EXPERIMENT 1
✦
ELECTRIC FIELDS

EQUIPMENT NEEDED

- Computer
- *Mathematica* software

PURPOSE

- To explore properties of electric fields due to point charges and the motion of various charged particles in uniform fields.

THEORY
Electric Field of Point Charges

The temperature has a definite value at every point in space in the room in which you are sitting. You can measure the temperature at each point in space by putting a thermometer at that point. We call such a distribution of temperatures a **temperature field.** The temperature field in a room is an example of a **scalar field**, the temperature being a scalar quantity.

We define the **gravitational field** in a similar way. Consider Figure 1 below showing a point mass m_0 located at a point that is a distance r from the center of the Earth. We imagine using this mass – the *test mass* – as a means of "testing" (i.e., measuring) the strength of the gravitational force due to the Earth at each point in the space surrounding the Earth. For example, Figure 1 shows a vector $\vec{F}_{grav}$ representing the gravitational force that the Earth exerts on the test mass when the test mass is placed at Point *A* in the figure.
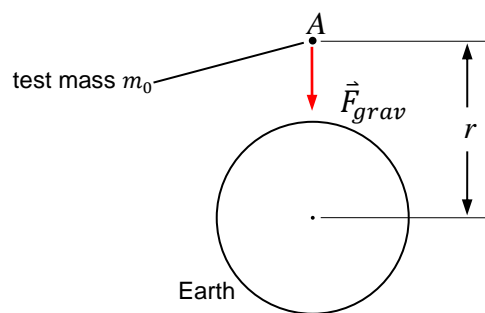

Figure 1

According to Newton's law of universal gravitation, the magnitude of the gravitational force exerted on the test mass by the Earth is given by:

$$F_{grav} = G\frac{m_0 M_E}{r^2},$$

(1)

in which M_E is the mass of the Earth and G is the gravitational constant ($G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$).

Now imagine moving the test mass to many different locations in the space surrounding Earth. As we do this, the gravitational force that the Earth exerts on the test mass will vary in magnitude and direction. In particular, the force will get weaker as the distance r is increased, as implied by Eq. (1), and the force will always point toward the center of the Earth. Thus we will get a collection of many gravitational force vectors – in principle, one for each point in space – as shown in Figure 2 below.
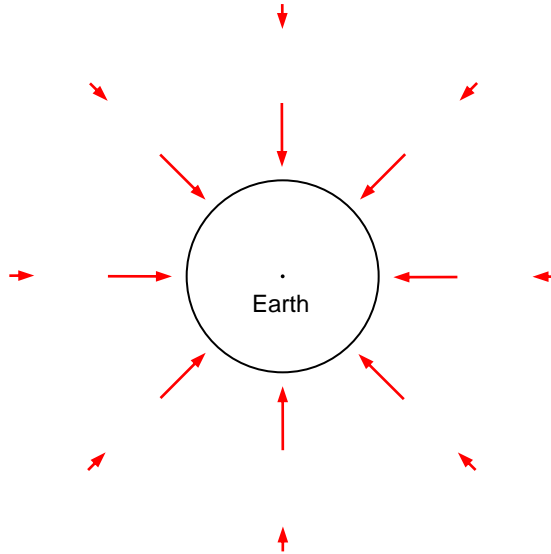

Figure 2

The gravitational field $\vec{g}$ is defined to be the force *per unit test mass*:

$$\vec{g} \equiv \frac{\vec{F}_{grav}}{m_0}. \tag{2}$$

Note that since the test mass m_0 is an intrinsically positive quantity, the gravitational field $\vec{g}$ is a vector that points in the same direction as $\vec{F}_{grav}$ at each point in space. Thus, a picture showing the gravitational field vectors at many locations in the space surrounding Earth would look essentially the same as Figure 2. This distribution of gravitational field vectors is one example of a *vector field*. The magnitude of the gravitational field at a distance r away from the center of Earth is:

$$g = \frac{F_{grav}}{m_0}$$
$$g = G\frac{M_E}{r^2} \tag{3}$$

The direction of the gravitational field is always toward the center of Earth.

We define the electric field $\vec{E}$ in a similar way. Consider, for example, a negative point charge $-Q$ (called the *source charge*) and a positive point charge $+q_0$ (called the *test charge*) located a distance r away from the source charge, as shown in Figure 3 below.
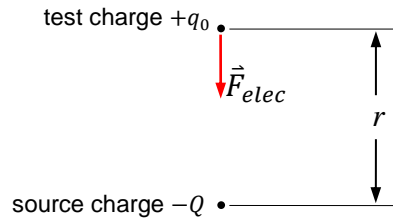
Figure 3

Because the source charge and test charge are of opposite sign in this example, the source charge will exert an attractive electrostatic force, $\vec{F}_{elec}$, on the test charge, as shown in Figure 3. The magnitude of this force is given by Coulomb's law:

$$F_{elec} = k\frac{|-Q|\,|+q_0|}{r^2}. \tag{4}$$

The direction of the electrostatic force on the test charge q_0 is *toward* the source charge if the source charge is *negative*. If the source charge is *positive*, the direction of $\vec{F}_{elec}$ would be *away* from the source charge.

As we did with the test *mass* for the case of the *gravitational* force, we can, for the case of the *electric* force, imagine moving the test *charge* to many different points in the space surrounding the source charge shown in Figure 3. As the distance r from the source charge varies, the magnitude of the electric force on the test charge will vary, as Eq. (4) implies. In addition, the direction of the electric force will vary so that the electric force vector always points *toward the source charge* $-Q$. Thus we can imagine an electric force vector associated with each point in the space surrounding the source charge, as shown in Figure 4 below.
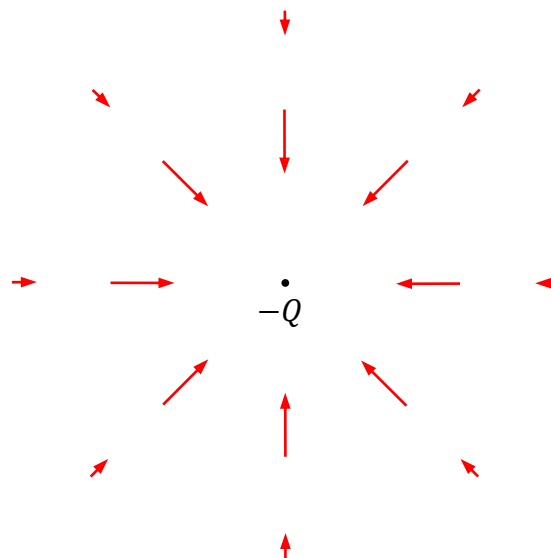

Figure 4

Note the striking similarity between this picture and the corresponding picture (Figure 2) for the gravitational force.

The *electric field* $\vec{E}$ is defined to be the electric force *per unit test charge*:

$$\vec{E} \equiv \frac{\vec{F}_{elec}}{q_0} \qquad (5)$$

The direction of the electric field is defined to be the direction of the electric force on a *positive* test charge. Thus, in Figure 4, the directions of the electric field vectors at the points shown would be exactly the same as the directions of the electric *force* vectors shown in the figure. The magnitude of the electric field at a distance *r* away from the source charge is given by:

$$E = \frac{F_{elec}}{|q_0|}$$
$$E = k\frac{|-Q|}{r^2} \qquad (6)$$

For a *positive* source charge $+Q$, the electric field would point *away* from the source charge at each point in space, as shown in Figure 5.
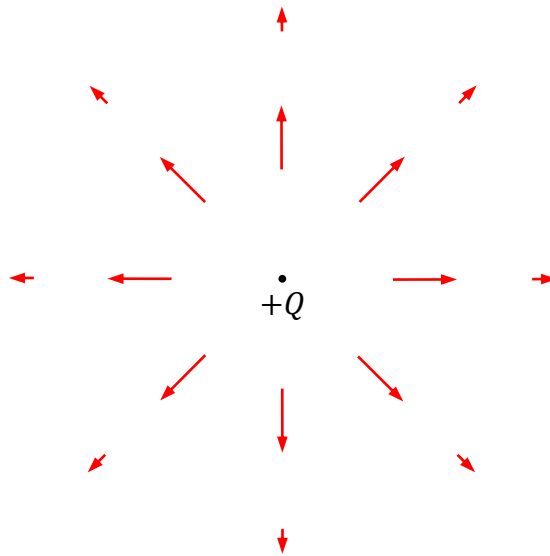

Figure 5

In this case, the magnitude of the electric field would be given by:

$$E = k\frac{|+Q|}{r^2}. \qquad (7)$$

Uniform Electric Field

The electric fields due to the point charges $-Q$ and $+Q$ considered thus far are not uniform in magnitude or direction. It turns out that it is possible to produce an electric field which is, to a good approximation, uniform in magnitude and direction over some region of space. A common way to do this is to construct a *parallel-plate capacitor*. A parallel-plate capacitor consists of two oppositely charged conducting sheets (called the *plates*) separated by some insulating material (e.g., air, mica, polyester film, Teflon, or a disc of ceramic material). This insulating material is called the *dielectric*. A diagram of a parallel-plate capacitor with air as the dielectric is shown in Figure 6.
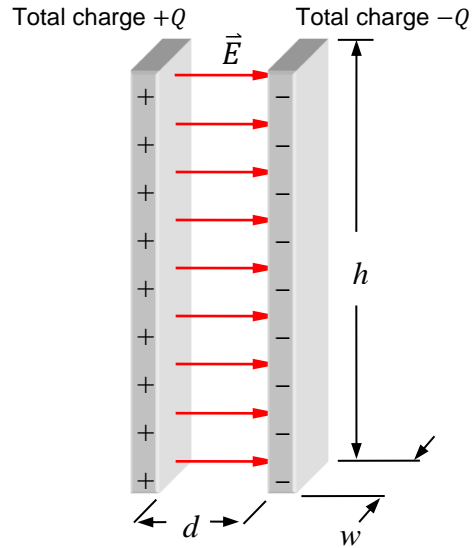
Total charge $+Q$ Total charge $-Q$

Figure 6

If the plate separation d is small compared to the height h and width w of the plates, then the electric field between the plates is approximately uniform in magnitude and direction, as shown in Figure 6. In this experiment, we will be dealing with such uniform electric fields.

Consider a particle with charge $+q$ moving vertically upward with velocity $\vec{v}$ into the region between the plates of the parallel-plate capacitor shown in Figure 6. This is shown in Figure 7, with the region between the plates shown expanded horizontally for clarity. In addition, to keep the figure from being too cluttered, the electric field $\vec{E}$ between the plates is indicated by a single vector, as shown in Figure 7. Once the charged particle enters the region between the plates, it
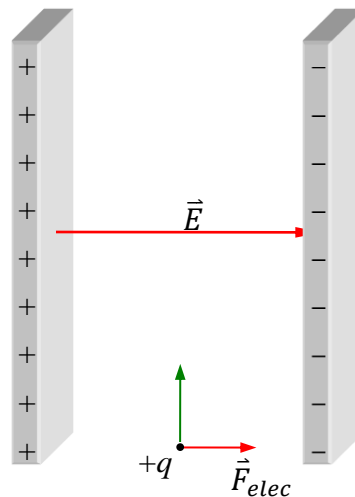
Figure 7

will experience an electric force due to the electric field $\vec{E}$ between the plates. From the definition of the electric field as the force per unit charge, it follows that the electric force on $+q$ will be:

$$\vec{F}_{elec} = q\vec{E} \qquad (8)$$

This force is depicted in Figure 7. Note that since the particle is assumed to be positively charged, the electric force on it points to the right, in the same direction as $\vec{E}$. By Newton's second law, the charged particle will thus experience an acceleration (to the right) of magnitude:

$$a = \frac{F_{elec}}{m},\tag{9}$$

in which *m* is the mass of the charged particle.

PROCEDURE
Part I: Setup

1. Open the folder called `Physics Folder` on your computer's desktop. Then open the folder called `Mathematica`.

2. In the `Mathematica` folder, open the file `ElectricFields`.   If you get a dialog box that says "Dynamic Content Warning", click "Enable Dynamic."

Section A: The Electric Field of Point Charges

1. The first interactive panel shows electric fields due to two point charges, Q_1, at $(-1\text{ m}, 0)$, and Q_2, at $(1\text{ m}, 0)$. The controls for this panel are at the top on the left.

2. The top line has two checkboxes: one to Show Axes and the other to Show Field Lines. The top line also has a slider labeled "Scale Factor"; this rescales the electric field vector arrows relative to the drawing. Click the checkboxes and move the slider to see what happens. To undo any changes, click the Reset button on the upper right of the panel.

3. The next line has buttons with three different values of the charges. Click these to see what happens.

4. The third line selects the point where the fields are evaluated. The five buttons give preset values for the *x*- and *y*-coordinates of this point. You can also drag the "locator" (crosshairs) to move the evaluation point to any position. Try this.

5. At the right of the control panel, the *x*- and *y*-components of the fields are shown. The vectors $\vec{E}_1$ and $\vec{E}_2$ are the electric fields due to Q_1 and Q_2, respectively; these are displayed with the green arrows in the picture. $\vec{E}$ is the total field, the vector sum of $\vec{E}_1$ and $\vec{E}_2$.

Proceed to Section A, Step 6 on your data sheet.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

Part II: Data Sheet

Data Recording Section A:

6. Select the first charge configuration, the *dipole*, ($Q_1 = -2$ μC and $Q_2 = +2$ μC) and check "Show Axes." Drag the locator to move the evaluation position along the *y*-axis. In the space below, **describe the direction of the field along the *y*-axis.**

7. Select the second charge configuration ($Q_1 = -2$ μC and $Q_2 = +3$ μC), check "Show Axes" and select the position (0, 1 m). In the space below, **record** $\vec{E}_1$, $\vec{E}_2$ and $\vec{E}$. These electric field vectors will be calculated in a later question.

8. Select the third charge configuration ($Q_1 = -2$ μC and $Q_2 = -3$ μC), check "Show Axes." Click and drag the locator to a position **along the *x*-axis** between the two charges. Find the position on the *x*-axis where the electric field equals zero. **Record this position** in the space below. (The best you will be able to do is to find where both components of $\vec{E}$ are small compared to the components of $\vec{E}_1$ and $\vec{E}_2$. It suffices for the components to be less than 0.5×10^3 N/C.) This position will be calculated in a later question.

Position: _____

Section B: Charged Particles in a Uniform Electric Field

1. Now scroll down to the second interactive panel. This shows the paths of various charged particles that are shot into a region of uniform electric field. The field points left-right; a positive value of E_x corresponds to a field to the right. The particle is shot in the +y-direction into this field with initial speed v_0.

2. At the top right are two buttons, a reset button and a U-shaped update button. The left of the control panel allows for the selection of the particle. The choices are electron, proton, neutron, alpha particle and positron.

3. In the middle of the control panel, you can choose the value of the initial speed v_0 and the electric field E_x. Anytime you change these values, you should then click the update button at the upper right.

4. There is also a checkbox to Animate Motion. Checking this box shows controls for animation. This may slow things down too much; if so, uncheck it.

5. The Exit Data is listed below the control panel.

Use $v_0 = 600,000$ m/s and $E_x = 15$ N/C for Steps 6 through 8 below.

6. Select the electron e^- and record the exit data.

    $x_f=$ _____ cm, $y_f=$ _____ cm, $t_f=$ _____ ns

7. Select the positron e^+ and record the exit data.

    $x_f=$ _____ cm, $y_f=$ _____ cm, $t_f=$ _____ ns

8. Select the proton p and record the exit data.

    $x_f=$ _____ cm, $y_f=$ _____ cm, $t_f=$ _____ ns

9. Experiment with different values of E_x, keeping $v_0 = 600,000$ m/s, to find the value needed for the proton to land at the same position, x_f, listed for the electron in step 6. Record this value of E_x below.

    $E_x=$ _____ N/C

10. Experiment with different values of v_0, using $E_x = 15$ N/C, to find the value of v_0 needed for the proton to land at the same position, x_f, listed for the positron in step 7. Record this value below.

    $v_0=$ _____ m/s

Part III: Questions (may be answered outside of class)

Questions for Section A:

A-1. Explain why the field of the dipole is perpendicular to the *y*-axis, as observed in Section A, Step 6.

A-2. Derive the result in Section A, Step 7. (Start with a sketch of the charges, draw a vector diagram, and compute $\vec{E}_1$, $\vec{E}_2$, and $\vec{E}$.)

A-3. Derive the result in Section A, Step 8. **Hint:** For the field $\vec{E}$ to be zero, the vectors $\vec{E}_1$ and $\vec{E}_2$ must be equal in magnitude and opposite in direction. Since both charges are negative, the fields $\vec{E}_1$ and $\vec{E}_2$ point toward the corresponding charges. The only points where the fields are in opposite directions are points between the two charges on the x-axis. This gives: $k \frac{|Q_1|}{r_1{}^2} = k \frac{|Q_2|}{r_2{}^2}$.

Use this equation to find the x-coordinate of the position where the net field is zero.

Questions for Section B:

B-1. Calculate the **components** of the acceleration vector $\vec{a}$ for the electron and positron in Section B, Steps 6 and 7. Record the accelerations in **component form** below.

Electron: $\vec{a} =$_____   Positron: $\vec{a} =$_____

B-2. Calculate the speed of the electron as it leaves the screen in Section B, Step 6.

B-3. Compare the paths of the electron and positron in Section B, Steps 6 and 7. Explain the differences and similarities.

B-4. Why is the proton's deflection in Section B, Step 8 so small?

B-5. Explain the results of Section B, Steps 9 and 10.

EXPERIMENT 2

✧

ELECTRIC POTENTIAL AND CONDUCTORS

EQUIPMENT NEEDED

- Computer
- *Mathematica* file - `ElectricPotential`

PURPOSE

- This lab is divided into two parts. In the first part, you will study the topic of electric potentials and examine how equipotentials can help visualize electric potentials.
- In the second part, you will explore how charge separation occurs in a conductor when a point charge is brought near it.

THEORY
Electric Potentials

The electric potential is equal to the electric potential energy (in joules) divided by the charge (in coulombs).

$$V = \frac{U}{q} \hspace{4cm} (1)$$

The units of electric potential are volts; 1 volt = 1 joule/coulomb. Recall that the gravitational potential energy of an object must be defined by setting an arbitrary "zero." The electric potential energy, and by extension, the electric potential, works the same way. There is no such thing as an absolute potential; instead, we often refer to a potential difference, ΔV. So if an equation presents you with voltage, V, we really mean potential difference, ΔV.

Why is this important? In the coming weeks you will often measure voltages, and every time you do, you will place the "ground" probe in one location and the "hot" probe in another, thus measuring a potential difference between the two probes.

The relationship between electric field and electric potential is similar to the relationship between elevation (height) and gravitational potential energy. Although the zero height must be defined, the gravitational potential energy of an object depends only on an object's height, *h*, not on the path traveled to get to its current position. If you move the object up, its potential energy increases. If you move it down the potential energy decreases; if you move it horizontally, the potential energy remains constant. We could define equipotential surfaces where the gravitational potential energy is constant. Near the surface of the Earth, these are horizontal planes. Notice that the gravitational force is normal (perpendicular) to the equipotential surfaces. Note: on maps, the locations where the landscape crosses the equipotential planes are denoted by contour lines.

In electric terms, the equipotential surfaces are surfaces where the electric potential is constant. For a point charge, these are spherical surfaces concentric about the charge. When drawn on a

2-D page, these appear as circular equipotential lines. (See Figure 1.) The electric field is always perpendicular to the equipotential lines. Furthermore, as you travel along the electric field line in the direction of the arrow, the potential decreases.
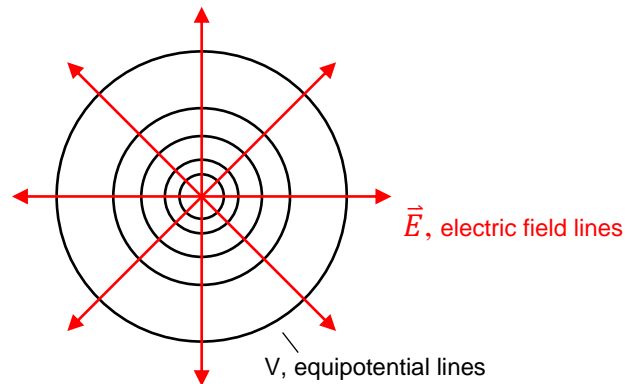

$\vec{E}$, electric field lines

V, equipotential lines

Figure 1

The relationship between the electric potential and the (average) electric field is

$$\Delta V = -E\Delta s \qquad\qquad (2)$$

where Δs is the magnitude of the displacement parallel to the electric field. For a point charge, the electric potential depends only on r, the distance from the charge. For convenience, we will set $V = 0$ at $r = \infty$.

Using a Mathematica file, you will "measure" the total electric potential at various positions due to two point charges. You will also be able to view a representation of the equipotential lines due to these point charges.

Conductors and Charges

Since charge is free to flow in a conductor, under electrostatic conditions the electric field inside a conductor is equal to zero. An electric field puts a force on free charges:

$$\vec{F} = q\vec{E}. \qquad\qquad (3)$$

Charges that are free to move in a conductor will do so until the electric field inside the conductor is canceled. Charge cannot be created or destroyed, so the net charge on the conductor will remain constant. But some charge will be redistributed on the surface of the conductor such that inside the conductor the external electric field is canceled by the charge distribution's electric field. To experiment with this concept, you will use a virtual conducting sphere and point charge. You will be able to see how the surface charge density of the sphere is affected by the point charge and, as a consequence of the charge redistribution, how the sphere and point charges exert forces on each other.

PROCEDURE
Part I. Setup

1. Open the folder called `Physics Folder` on your computer's desktop. Then open the folder called `Mathematica`.

2. In the `Mathematica` folder, open the file `ElectricPotential.` If you get a dialog box that says "Dynamic Content Warning", click "Enable Dynamic."

Section A: Electric Potential Due to Two Charges
Computer Setup for Section A

1. The first interactive panel shows different representations of the electric potential due to two point charges, Q_1, at (–1 m, 0), and Q_2, at (1 m, 0). The buttons at the top right give a choice between two different ways to display the electric potential: the Interactive 2D Plot button shows equipotentials and electric field lines and (*x*, *y*, *V*) Plot shows a 3D display of potential *V* as a function of *x* and *y*, with the equipotentials drawn in. Click through to see both displays for each set of charges. There is a small reset button at the upper right.

2. In the Interactive 2D Plot display, there is a second set of controls that appear. There are three check boxes: one to Show Axes, one to Show Field Lines, and one to Show $\vec{E}$. The top line also has a slider labeled "$\vec{E}$ Scale Factor"; this rescales the electric field vector arrows relative to the drawing. Click the checkboxes and move the slider to see what happens. To undo any changes here, click the other Reset button on the upper right of this inside panel. Note that holding the mouse over an equipotential (shown in green) gives its value in volts.

3. The next line selects the point where the potentials are evaluated. The five buttons give preset values for *x*- and *y*-coordinates of this point. You can also drag the "locator" (crosshairs) to move the evaluation point to any position. Try this.

4. At the right of the control panel, the electric potentials are shown. The values V_1 and V_2 are the electric potentials due to Q_1 and Q_2, respectively, and *V* is the sum of the two.

5. The upper interactive panel should look something like this:

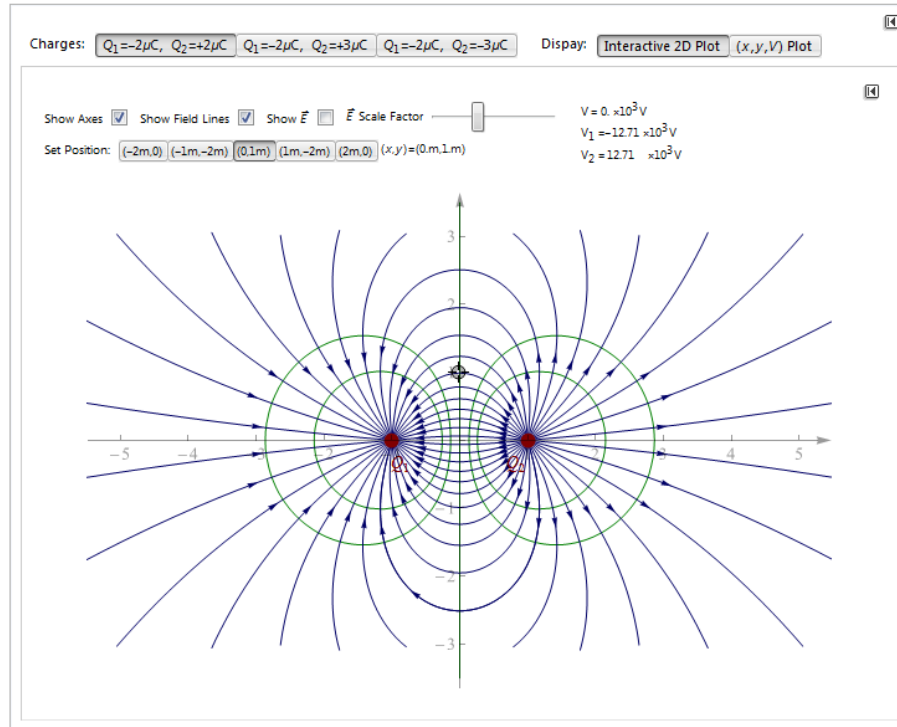**Figure 2**

6. Select the charge configuration ($Q_1 = -2$ µC and $Q_2 = +2$ µC) (called a *dipole*) and check Show Axes. Drag the locator to move the evaluation position along the y-axis. Notice that the y-axis is the zero equipotential. View this in the (x,y,V) Plot display as well.

Proceed to Section A, Step 7 on your data sheet.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

Part II: Data Sheet

Data Recording for Section A

7. Select the second charge configuration ($Q_1 = -2$ μC and $Q_2 = +3$ μC), check Show Axes, and select the position (–1 m, –2 m). **Record** the values of V_1, V_2 and V below. (Don't forget units.)

$V_1 = $ _____

$V_2 = $ _____

$V = $ _____

8. Continuing with the charge configuration ($Q_1 = -2$ μC and $Q_2 = +3$ μC), check Show Axes. Estimate the two positions *along the x-axis* where the potential is zero.
Note: These are the two points where the zero-volt equipotential line crosses the *x*-axis.
Drag the locator to each of these points and **Record** these positions below.

V = 0 on *x*-axis 1st Position: _____

V = 0 on *x*-axis 2nd Position: _____

9. Select the third charge configuration ($Q_1 = -2$ μC and $Q_2 = -3$ μC). Are there any positions where the electric potential is zero? Write "no" or list these positions in the space given below.

Section B: Point Charge Near a Conducting Sphere
Computer Setup for Section B

1. Now scroll down to the second interactive panel. This shows a movable positive point charge (blue dot) near a conducting sphere (gray disk). The surface charge densities on the conducting sphere are shown in red for negative and blue for positive.
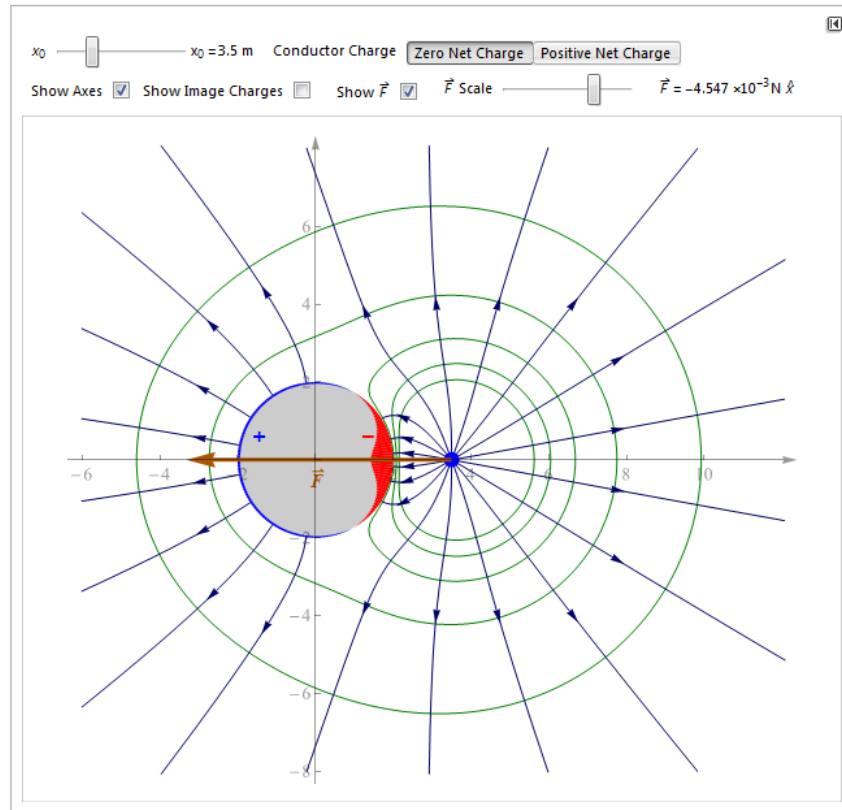

Figure 3

2. The blue (+) and red (–) "coatings" on the outer edges of the conducting sphere (gray disk) show the charge density in units of C/m^2. The units are not displayed but the thickness of the line shows the magnitude of charge density. Note that the charge distribution is completely on the surface; none of it is "inside" the conductor. For instance, on the initial display, the negative charge (red) is most dense near the x-axis.

3. You can change the position of the point charge, x_0, using the slider at the top left. The second row of controls allows you to display or hide various features. The "Show Image Charges" check box allows you to see the (hidden) trick used to draw these field and potential configurations. This is known as the *method of images*. Because this method is beyond the scope of this exercise, we won't go into detail about it.

4. The "Show F" check box will show the net force vector on the point charge. The "F Scale" slider allows you to resize the displayed vector in case it becomes too large or small. The actual value of $\vec{F}$ is also displayed.

Data Recording for Section B.

5. Select "Zero Net Charge" on the conductor. Vary the position and describe how the force changes. Describe how the surface charge densities change.

6. Select "Positive Net Charge" on the conductor. Vary the position and describe how the force changes and how the surface charge densities change.

Part III: Questions (can be answered outside of class)
Questions for Section A

A-1. For the dipole, explain why the potential is zero along the *y*-axis, as observed for charge distribution ($Q_1 = -2$ µC and $Q_2 = +2$ µC) in Section A, Step 6.

A-2. Derive the result in Section A, Step 7. That is, for the charge configuration ($Q_1 =$ -2 µC and $Q_2 = +3$ µC) find the net electric potential at position (–1 m, –2 m). Draw a diagram and show all your work.

A-3. For the charge configuration ($Q_1 = -2$ μC and $Q_2 = +3$ μC), calculate the two positions along the x-axis where the potential is zero. Compare this to what you found in Section A, Step 8.

A-4. Why is there nowhere, other than infinity, where the potential is zero in Procedure A, Step 9 ($Q_1 = -2$ μC and $Q_2 = -3$ μC)?

Questions for Section B

B-1. Explain why the force on any point charge (regardless of sign) should always be *towards* a neutral conductor.

B-2. Coulomb's law states $F = k\frac{|q_1||q_2|}{r^2}$. If we apply this to the positive point charge and the neutral conductor, the force should be zero. But it isn't. What's wrong with this logic? Why doesn't this simple application of Coulomb's law work here?

B-3. For the case of the conductor with the Positive Net Charge, why should the force on the point charge be attractive when close and repulsive when far?

EXPERIMENT 3

✧

OHM'S LAW

EQUIPMENT NEEDED

- *AC/DC Electronics Laboratory* circuit board
- Digital multimeters (2)
- Resistors (assorted values from ~ 100 Ω up to ~ 600 Ω)

PURPOSE

- To explore the relationship between voltage and current for discrete resistors and incandescent light bulbs.

THEORY

It is an experimentally observed fact that, for some materials, the current I that flows through the material when a voltage V is applied across it is simply proportional to V:

$$I = \frac{V}{R} \tag{1}$$

This relation, called *Ohm's law* after its discoverer, Georg Simon Ohm (1787-1854) is usually written in the form:

$$V = IR \tag{2}$$

If we make a plot of V versus I for an ohmic circuit component, it should follow Ohm's law, $V = IR$. That is, the plot should be linear, with a slope $m = R$ and an intercept of $V = 0$ when $I = 0$, as shown in Fig. 2.
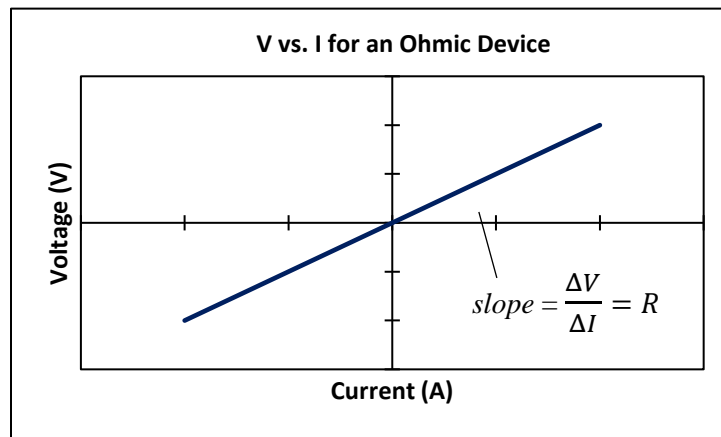

Figure 2

The constant of proportionality *R* in Eq. (2), called the *resistance*, depends on the material used and on geometrical parameters. The resistance of a material is a measure of the degree to which the material "resists" the flow of current through it. The larger the resistance, the smaller the current that runs through the material—for a given potential difference, *V*, across the material. The SI unit for resistance is called the *ohm* (Ω),

$$1 \ \Omega \equiv 1 \ \text{V/A}$$

Not all materials obey the simple relationship between voltage and current given by Ohm's law. Materials that generally obey Ohm's law are called *ohmic* materials. Ohmic materials include most metals (copper, gold, silver) and some materials that are nonmetals, such as carbon. Carbon is particularly important because it is very common and inexpensive to process into circuit components. It's quite common, for example, to make so-called *carbon-composition resistors* out of a mixture of carbon and an epoxy binder. Figure 1 shows a carbon-composition resistor.

Note the series of colored bands on the resistor in Fig. 1. These bands indicate the resistance of the resistor according to a code called the *resistor color code*. See Appendix A for an explanation of the resistor color code.
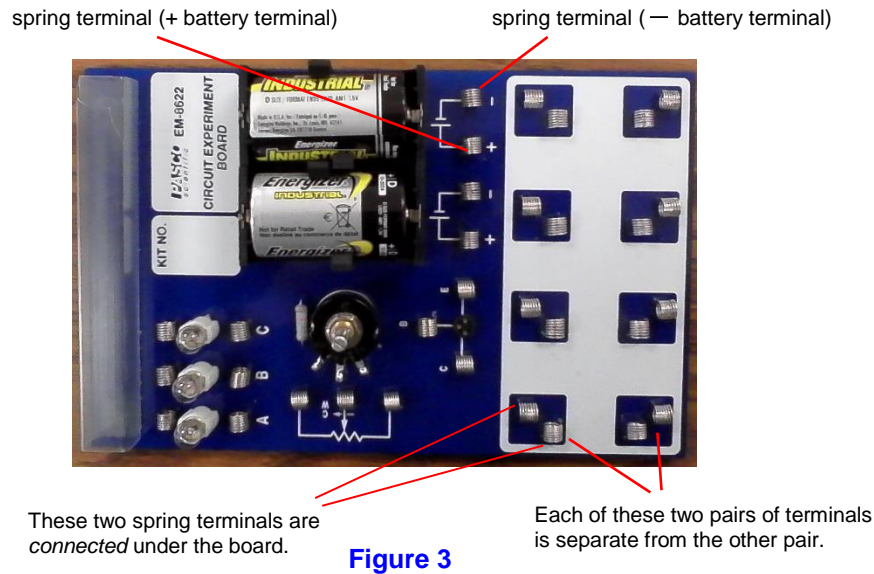

Figure 1

However, the resistance is not always constant in an ohmic material. Take the case of a tungsten filament in an incandescent light bulb, for instance. As the current through the filament is increased, the temperature of the filament increases. (That is, the average kinetic energy of atoms in the material increases.) As charge carriers (free electrons) "drift" through the filament (under the action of the electric field within the filament), they collide with tungsten atoms, and these collisions tend to slow down the charge carriers, limiting the current that flows. At higher temperatures (i.e., higher currents) these collisions can be more violent, with the consequence that the charge carriers are slowed down even more. Thus the additional current that flows (for a given change in the voltage) is lower at higher temperatures. This amounts to an effective increase in the resistance at higher temperatures. So when there is a *significant* change in temperature in an ohmic material, there can be a significant change in its resistance.

PROCEDURE

PART I: Setup

1. Obtain a circuit board and two multimeters. Make sure that your circuit board includes two batteries and that each multimeter includes a pair of test leads (one red and one black). Figure 3 below shows the *AC/DC Electronics Laboratory* circuit board you will use in this experiment.

spring terminal (+ battery terminal)   spring terminal (— battery terminal)

These two spring terminals are
connected under the board.

Each of these two pairs of terminals
is separate from the other pair.

Figure 3

2. To connect circuit components using this board, make connections between the *spring terminals* on the board. Note, for example, that the positive and negative terminals of each battery are brought out to the spring terminals adjacent to each battery holder. Also note that in the white area of the board, the two spring terminals in each pair of adjacent terminals are *connected* to one another (via solder traces on the bottom side of the board). This means that if you connect a circuit component such as a resistor between these two adjacent terminals, the circuit component will be "*shorted out.*" For this reason, you should *never* connect a circuit component between these two adjacent spring terminals. The correct way to connect circuit components using the spring terminals is shown in Fig. 4.

incorrect   correct   correct
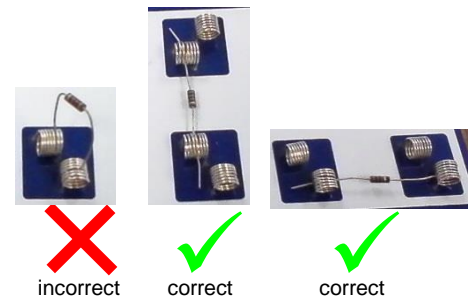
Figure 4

Part II: Data Recording
Section A: Ohmic Behavior I: Variation of Current with Resistance for Fixed Voltage

1. You will need eight different resistors within the range 100 Ω to 600 Ω. From the bag of resistors supplied, select one resistor and place it on the board between two terminals as shown in Fig. 4. Using one of your multimeters in the *resistance mode*, measure the resistance. The procedure for measuring resistances is discussed in Appendix B. If the resistance is not between 100 Ω to 600 Ω, set it aside and use another resistor. If it is in this range, record this as R_1 on Table A. Set it aside and check another resistor. Keep checking until you have eight resistors in the range 100Ω to 600Ω. Hint: place each resistor on its row (R_1 through R_8) as you record them so as not to get them mixed up. (Note: you can use the colored bands printed on the resistor to help you find the right resistors. For resistors in the range of 100s of ohms, the third band should be brown. See Appendix A for the resistor color code.)

2. Using your voltmeter, measure the voltage supplied by each of your two batteries under conditions of "*no load*" – i.e., with nothing connected to the batteries. Select the battery with the larger voltage and record this as "Fixed Voltage, V_{bat}" in Table A on your data sheet. On your circuit board, construct the circuit shown in Fig. 5 consisting of your chosen battery and resistor R_1. Put one of your multimeters in the *ammeter mode* and connect it in *series* with R_1, as shown in Fig. 5.
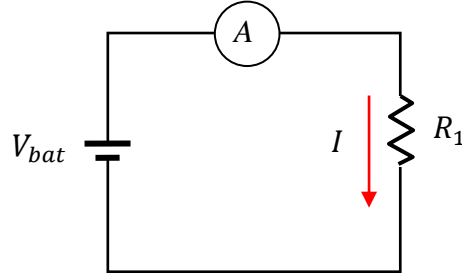

Figure 5. Circuit for Section A.

3. Record this current in Table A. Warning: the current will probably be in mA. Be sure you know what your meter is showing. All readings should have 3 significant figures (2 at the lowest). If your reading on the meter is showing only one significant figure (for example .003 A), check the range.

4. Replace R_1 with resistor R_2. Record the current through this resistor in Table A.

5. Continue replacing the resistor until you have readings for all eight resistors.

Section B: Ohmic Behavior I: Variation of Current with Voltage for Fixed Resistance

1. In this section, you will measure the current through and the voltage across resistor R_1 while using the other seven resistors as *biasing resistors* for changing the voltage across R_1. Record the value of R_1 at the top of table B.

2. On your circuit board, construct the circuit shown in Fig. 6 consisting of two batteries and two resistors, R_1 and any one of the other resistors. (This will be R_{bias}.) Put one of your multimeters in the *ammeter mode* and connect it in *series* with R_1 and R_{bias}, as shown in Fig. 6.
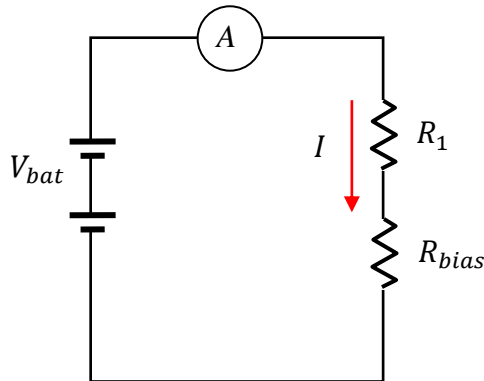

Figure 6. Circuit for Section B.

3. Put the other meter in the *voltmeter mode* and connect it *across* R_1 (i.e., in *parallel* with it), as shown in Fig. 7.
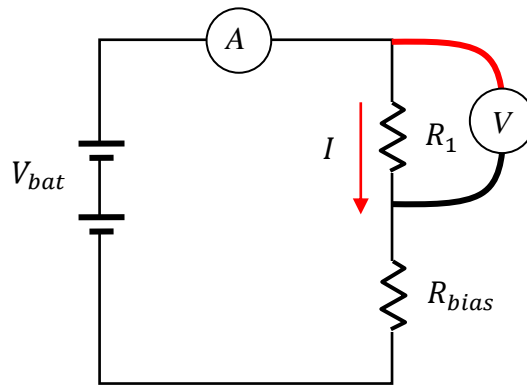

Figure 7. Voltmeter connected across R_1

4. Measure the current, I, in the circuit and the voltage, V_1, across R_1. Record these in column R_1, Trial 1 of Table B on your data sheet.

5. Now replace R_{bias} with a different resistor. **DO NOT change R_1!** Measure I and V_1 and record these in Table B. Repeat this until all of the bias resistors have been used.

6. For your last trial, remove the bias resistor and connect R_1 directly to the battery terminal. Measure I and V_1 and record these in Table A.

Section C: Nonohmic Behavior

1. In this section, we will investigate the relationship between current and voltage for an incandescent light bulb. To get started, you will need to construct on your circuit board the circuit shown in Figure 8. This circuit uses a *potentiometer* as a variable resistor. (For details on how to use the potentiometer, see the box below.)
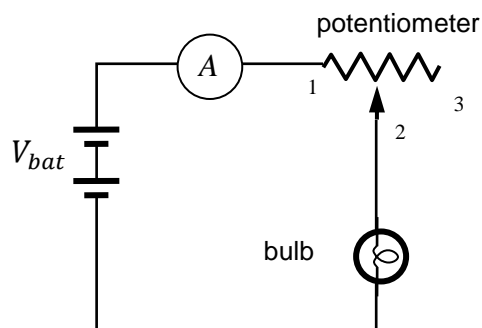

Figure 8

A note about the potentiometer:

A potentiometer (or "pot", for short) is a three-terminal device consisting of a resistor and a sliding contact called the *wiper*. The figure below shows a photograph of the pot that is mounted on your circuit board. The three terminals of the pot are brought out to the spring terminals labeled "1" through "3" in this figure.

Below is a diagram of the pot. The labels "1" through "3" on the three terminals (or "pins") of the pot in the figure below correspond to the spring terminals labeled "1" through "3" in the figure above.
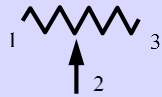
Between Pins 1 and 3, there is some *fixed* resistance (independent of the setting of the knob on the pot). For your pot, this fixed resistance should be about **25 Ω**. Pin 2 is the *wiper*. This contact can be *moved* (by turning the knob on the pot) all the way from Pin 1 to Pin 3. By making connections to Pins 1 and 2 *only*, we will use the pot as a *variable* resistor providing a resistance between about **3Ω** and **25 Ω**. Pin 3 will not be used.

---

2. Connect the voltmeter across the bulb (one lead to either side).   Record the current, I, through the bulb and the voltage, V, across the bulb as Trial 1 of Table C.

3. Calculate the ratio V/I and record it in Trial 1 of Table C. This ratio is the resistance of the bulb when the current through it is I. If the bulb were to behave as an *ohmic* device, its resistance should be *constant*, independent of the current through the bulb.

4. Take readings of the voltage across the bulb and the current through the bulb for a total of eight settings of the pot. Note: if the current is too high, you meter will read "1." which means "overload." Turn the potentiometer until a valid reading appears on the meter— generally less than 200mA. In particular, be sure to explore the region near about 100 mA. At least one of your data points should be for a current below 100 mA. Record your results in Table C and calculate the resistance for each trial.

Cleaning up

When you are done, remove the wires and resistors from your circuit board. Place the circuit board, wires and resistors in their bag(s). Roll up the leads on the meters. Put all equipment away in the assigned locations.

Part III: Data analysis (May be completed outside of class if time runs out)

Analysis section A

1. Calculate the reciprocal of each of the eight resistances R_1 through R_8. Record these in Table A.

2. Using the data from Table A, make a graph in Excel of I vs. $1/R$. Do a linear fit to the data. Have Excel display the equation of the best-fit line on the graph. Print this graph and turn in a copy with your completed lab report.

3. According to Ohm's law, the slope of your graph should equal the fixed supply voltage, V_{bat}. Record the slope from your graph and compare this to V_{bat} by computing the percent error.

Analysis section B

1. Using the data from Table B, make a graph in Excel of V_1 vs. I_1. Do a linear fit to your graph. Have Excel display the equation of the best-fit line on the graph. Print this graph and turn in a copy of the graph with your completed lab report.

2. Record the slope of the best-fit line in Table A as R_{meas}. Compare R_{meas} with R_1 by computing the percent error. Record this percent error in Table A.

Analysis section C

1. Using your data from Table C, make a graph in Excel of V vs. I for your light bulb. Fit the graph with a linear fit. Show the fit equation on the graph. According to Ohm's law, the slope should be equal to the resistance and the intercept should equal zero. Print out a copy of this graph and turn it in with your completed lab report. Answer the question in section C of your data sheet.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

DATA SHEET

Table A

Fixed Voltage (Battery Voltage) V_{bat} = _____ V

	measured Resistance R (Ω)	$\frac{1}{R}$ (Ω^{-1})	measured Current I (A)
R_1			
R_2			
R_3			
R_4			
R_5			
R_6			
R_7			
R_8			

attach graph

Slope of Best-fit Line: m = _____ V

% error = $\left| \frac{m - V_{bat}}{V_{bat}} \right| \times 100\%$ = _____ %

Table B

Trial	$R_1 =$ _____ Ω	
	measured $I_1(A)$	measured $V_1(V)$
1		
2		
3		
4		
5		
6		
7		
8		
	Slope of Best-fit Line $R_{meas} = m =$ _____ Ω	
	% error = _____ %	

percent error $= \left| \dfrac{R_{meas} - R_1}{R_1} \right| \times 100\%$

attach graph

Table C

Trial	measured I (A)	measured V (Volts)	$R = \dfrac{V}{I}$ (Ω)
1			
2			
3			
4			
5			
6			
7			
8			

attach graph

Question

Does your graph of V vs. I from Table C correlate to Ohm's law, $V = IR$, with $R = $ const? If not, describe any apparent discrepancies and discuss what might cause these discrepancies.

EXPERIMENT 4

✧

RESISTORS IN SERIES AND PARALLEL

EQUIPMENT NEEDED

- *AC/DC Electronics Laboratory* circuit board
- Digital multimeters (2)
- Resistors (assorted values from ~ 100 Ω up to ~ 600 Ω)

PURPOSE

- To measure currents, voltages and equivalent resistances for three different combinations of resistances:
    - series
    - parallel
    - series-parallel

  and compare the measured results with theoretical predictions.

THEORY

The three circuits we will consider in this experiment are shown in Figure 1 below. In Fig. 1, V_S is the source voltage (i.e., the battery voltage).

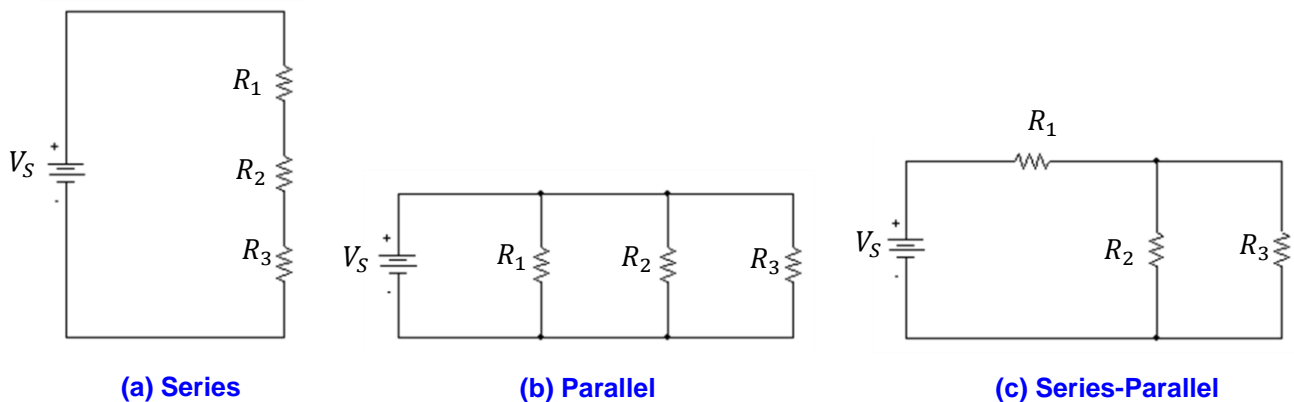| (a) Series | (b) Parallel | (c) Series-Parallel |

Figure 1

Resistors in Series

Consider the series combination of R_1, R_2 and R_3 shown in Figure 2. Because the resistors are in series, the current through each resistor is the same as the current through the other two resistors. This current is shown as I in Fig. 2.
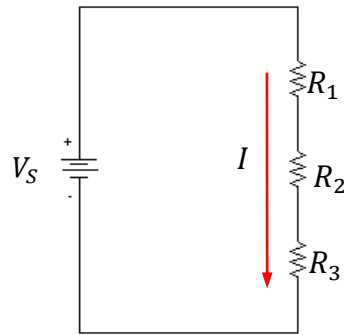
Figure 2

The equivalent resistance of the series combination of R_1, R_2 and R_3 is the sum of the individual resistances:

$$R_{eq} = R_1 + R_2 + R_3 \qquad (1)$$

Thus, the series combination of R_1, R_2 and R_3 could be imagined to be replaced by R_{eq} to yield an *equivalent circuit* (equivalent in the sense that the same current I would flow).

Resistors in Parallel

Consider the parallel combination of R_1, R_2 and R_3 shown in Figure 3.
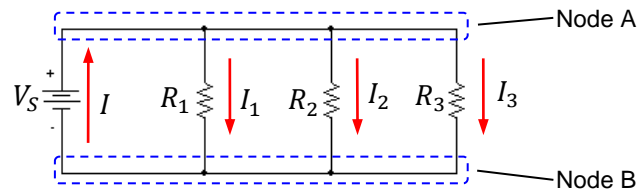

Figure 3

The voltage across each resistor is the voltage between Nodes A and B in Fig. 3. This is the same as the source voltage V_S:

$$V_1 = V_2 = V_3 = V_S$$

The equivalent resistance of the parallel combination of R_1, R_2 and R_3 is given by:

$$R_{eq} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)^{-1} \qquad (2)$$

Thus, the parallel combination of R_1, R_2 and R_3 could be imagined to be replaced by R_{eq} to yield an equivalent circuit.

The Series-Parallel Circuit

Consider the circuit shown in Figure 4 consisting of a resistor R_1 connected in series with the parallel combination of two other resistors, R_2 and R_3.
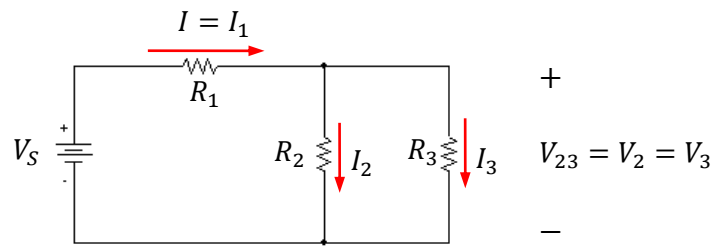
Figure 4

To find the equivalent resistance for this circuit, we first realize that R_2 and R_3 are in parallel, so the equivalent resistance of this combination of R_2 and R_3 (which will be referred to as "R_{23}") is given by:

$$R_{23} = \left(\frac{1}{R_2} + \frac{1}{R_2}\right)^{-1}$$ (3)

Thus the series-parallel circuit of Fig. 4 can be imagined to be replaced by an equivalent circuit, as shown in Figure 5.
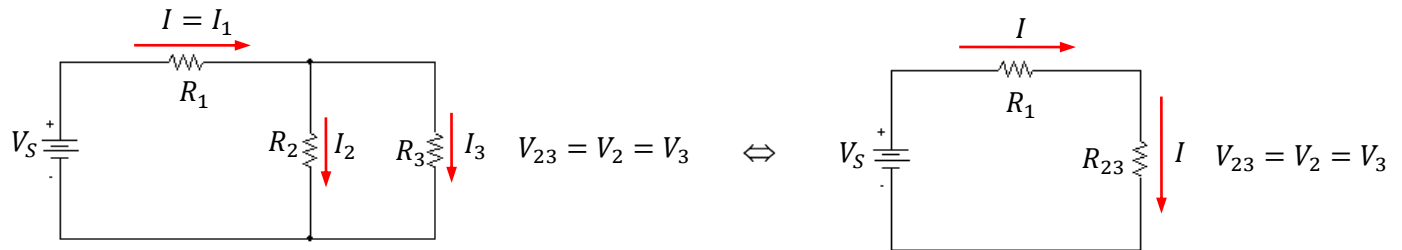
Figure 5

Note that R_{23} is in *series* with R_1 in the equivalent circuit of Figure 5. Thus, the equivalent resistance of the entire series-parallel circuit is given by:

$$R_{eq} = R_1 + R_{23}$$
$$R_{eq} = R_1 + \left(\frac{1}{R_2} + \frac{1}{R_2}\right)^{-1}$$ (4)

The entire series-parallel circuit could therefore be imagined to be replaced by the equivalent circuit shown below in Figure 6, with R_{eq} being given by Eq. (4).
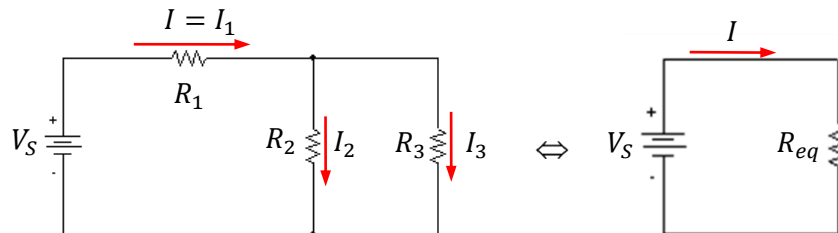

Figure 6

The total current I supplied by the battery is given by:

$$I = \frac{V_S}{R_{eq}}$$ (5)

This is also the current through R_1, that is,

$$I_1 = I = \frac{V_S}{R_{eq}} \tag{6}$$

To calculate the currents I_2 and I_3, we can first find the voltage V_{23} shown in Fig. 5 across R_2 and R_3. This voltage is evidently given by:

$$V_{23} = IR_{23} \tag{7}$$

Then we can find the currents I_2 and I_3 from:

$$I_2 = \frac{V_{23}}{R_2} \tag{8}$$

$$I_3 = \frac{V_{23}}{R_3} \tag{9}$$

PROCEDURE

PART I: Setup

1. Obtain a circuit board and two multimeters. Make sure that your circuit board includes two batteries and that each multimeter includes a pair of test leads (one red and one black).

2. From your supply of resistors, select three resistors within the range from about 100 Ω to about 600 Ω. **Use the colored bands** printed on the resistor to determine the nominal resistor values. See Appendix A for instructions on using the resistor color code to read the resistance.

Part II: Data Recording and Data Analysis
Section A: Measuring Your Three Resistances and Your Source Voltage

1. Using the resistor color code, read the resistance values for your three resistors and record these as the "theoretical" resistances in Table A on your data sheet.

    Important! Keep track of which resistor is R_1, R_2, and R_3. It will make a difference in you calculations later.

2. Now set one of your multimeters to the ohmmeter mode and *measure* each of your resistors R_1 through R_3. Record these values as the "measured" resistances in Table A. See Appendix B for a discussion of the proper way to measure resistances using the multimeter.

3. Calculate and record the percent errors between the measured and theoretical values.

Section B: The Series Circuit

1. On your circuit board, connect the three resistors R_1, R_2 and R_3 in series, as shown in Fig. 1(a). **Do not connect the battery yet!** Use one of your multimeters in the ohmmeter mode to *measure* the resistance of the series combination of R_1, R_2 and R_3. Record this *measured* equivalent resistance in Table B on your data sheet. Refer to Appendix B for details on the proper use of the ohmmeter.

2. Calculate the theoretical equivalent resistance R_{eq} of this series combination of R_1, R_2 and R_3. **On a separate sheet of paper, show your work in calculating this equivalent resistance.** Record your theoretical value of R_{eq} in Table B on your data sheet. (See the *Theory* section for a discussion of how to calculate R_{eq}.)

3. Now use this series combination of R_1, R_2 and R_3 to construct the series circuit shown in Figure 7.
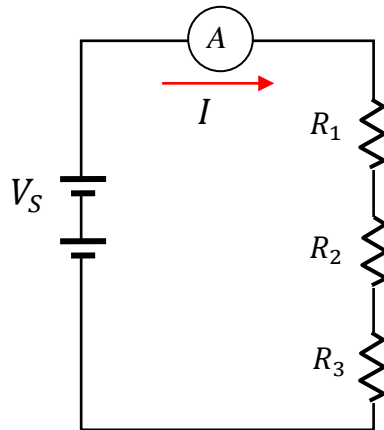
Figure 7. Series circuit setup

4. Set your second multimeter in the voltage setting and use it to measure the source voltage, V_S, across *both* batteries at once, as shown on the left side of Figure 8. It should read about 2.5V to 3.0V. Record this value as source voltage V_S on Table B.
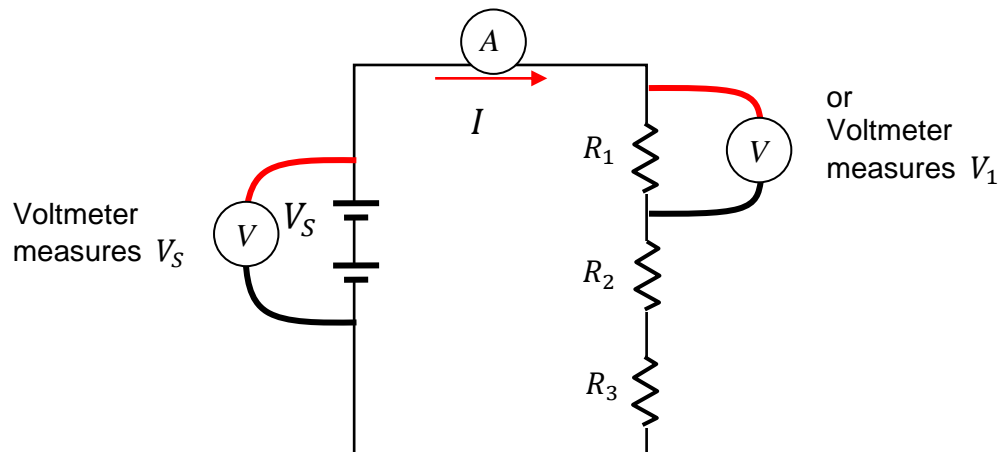
Figure 8. Measuring voltages

5. Read the total current I from the ammeter and record this as your *measured* value of current I. Move the voltmeter leads to place them across the resistors one at a time, as shown on the right side of Figure 8 for R_1. Read and record these as the *measured* values of voltage V_1, V_2 and V_3. When you are done, disconnect one lead from the battery so that you do not drain the battery while you are making calculations.

6. Calculate the theoretical total current I and voltages V_1, V_2 and V_3. Record these in Table B on your data sheet. Use the source voltage you measured along with the **theoretical** values of the resistances from Table A. **Show your work on separate paper!** (See the *Theory* section, if necessary, for a discussion of the proper way to carry out these calculations.)

7. Calculate the percent errors between your theoretical predictions and your measured results and record these in Table B on your data sheet.

8. According to Kirchhoff's voltage rule, the sum of the voltages $V_1 + V_2 + V_3$ should equal the source voltage V_S. Compute and record the sum $V_1 + V_2 + V_3$. Compare this to the theoretical value V_S (that you measured) by computing a percent error.

Section C: The Parallel Circuit

1. Disconnect the previous circuit. On your circuit board, connect your three resistors R_1, R_2 and R_3 in parallel, as shown in Fig. 1(b). **Do not connect the battery yet!**

2. Use one of your multimeters in the ohmmeter mode to *measure* the resistance of the parallel combination of R_1, R_2 and R_3. Record this as the measured equivalent resistance in Table C on your data sheet.

3. Calculate the theoretical equivalent resistance R_{eq} of this parallel combination of R_1, R_2 and R_3. On separate paper, **show your work in calculating this equivalent resistance.** Record your theoretical value of R_{eq} in Table C on your data sheet. (See the *Theory* section for a discussion of how to calculate R_{eq}.)

4. Now use this parallel combination of R_1, R_2 and R_3 to construct the parallel circuit shown in Figure 9, with the ammeter in series with the batteries so that it measures the total current I (the current through the batteries).
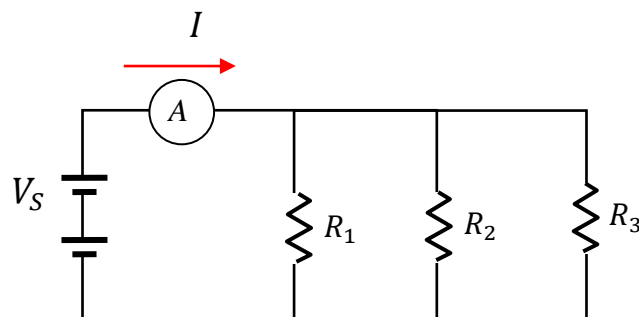
Figure 9. Parallel circuit setup

5. With the second multimeter set in the voltage setting, measure and record the source voltage on table C.

6. Record the total current, I, as your measured value on table C.

7. In order to measure the currents I_1, I_2, and I_3 you will need to move the ammeter. First disconnect the ammeter and replace it with a wire so that you have a complete circuit again. Now disconnect one side of R_1 and insert the ammeter into the circuit so that your

circuits looks like that shown in Figure 10. (You may need to rearrange some of your connections.)
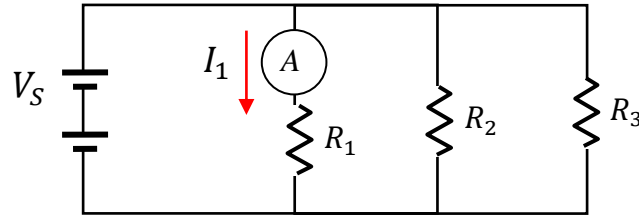
Figure 10. Current through R_1

8. Once you have recorded I_1, reconnect R_1 as it was originally connected and move the ammeter to measure I_2 and I_3 respectively. Record these in Table C. When you are done, disconnect one of the leads to the battery so you do not drain the battery while you are doing the following calculations.

9. Calculate the theoretical currents I, I_1, I_2 and I_3. Record these in Table C on your data sheet. Use the source voltage you just measured along with the **theoretical** values of the resistances from Table A to make your calculations. **Show your work on separate paper!** (See the *Theory* section for a discussion of the proper way to carry out these calculations.)

10. Calculate the percent errors between your theoretical predictions and your measured results and record these in Table C on your data sheet.

11. According to Kirchhoff's current rule, this sum of the currents $I_1 + I_2 + I_3$ should equal the total current I supplied by the battery. Calculate the sum of the measured currents $I_1 + I_2 + I_3$ and record this sum in Table C. Calculate and record the percent error between the sum of your measured currents and your *measured* total current I.

Section D: The Series-Parallel Circuit

1. Disconnect the previous circuit. On your circuit board, connect R_2 and R_3 in parallel, then connect this parallel combination of R_2 and R_3 in *series* with R_1, as shown in Figure 1(c). **Do not connect the battery yet!**

2. Use one of your multimeters in the ohmmeter mode to *measure* the resistance of the series-parallel combination of R_1, R_2 and R_3. Record this *measured* equivalent resistance in Table D on your data sheet.

3. Calculate the theoretical equivalent resistance R_{eq} of this series-parallel arrangement of R_1, R_2 and R_3. On separate paper, **show your work in calculating this equivalent resistance.** Record your theoretical value of R_{eq} in Table D on your data sheet. (See the *Theory* section for a discussion of how to calculate R_{eq}.)

4. Now use this combination of R_1, R_2 and R_3 to construct the series-parallel circuit shown in Figure 11, with the ammeter in series with the two batteries and R_1. Measure and record the current I_1 as the *measured* value in Table D.
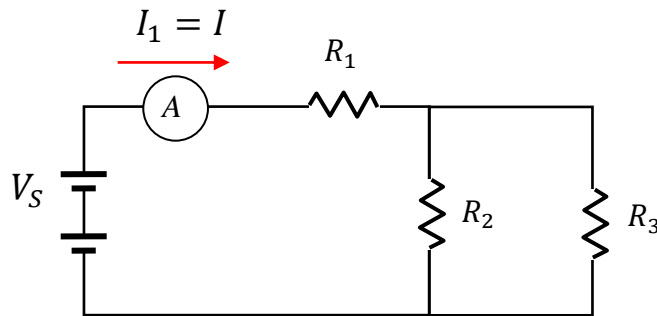
Figure 11. Series-Parallel circuit setup

5. Remove the ammeter from the circuit and replace it with a wire. Disconnect one side of R_2 and place the ammeter in series with R_2. Measure and record the *measured* value of current I_2. Remove the ammeter and reconnect resistor R_2. Place the ammeter in series with R_3. Measure and record I_3.

6. Using the other multimeter, measure and record the source voltage. Measure and record *measured* values of V_1 and $V_{23} = V_2 = V_3$. Disconnect one of the leads to the battery so you will not drain the battery while making the following calculations.

7. Calculate the theoretical values of $I_1 = I, I_2, I_3, V_1$ and $V_{23} = V_2 = V_3$. Record these in in the theoretical column on Table D on your data sheet. Use your **measured** source voltage and the **theoretical** values of the resistances listed in Table A for these calculations. **Show your work on separate paper!** (See the *Theory* section for a discussion of the proper way to carry out these calculations.)

8. Calculate and record percent errors between your theoretical predictions and your measured results.

9. According to Kirchhoff's voltage rule, the sum $V_1 + V_{23}$ should equal the source voltage V_S. Calculate the sum of the *measured* voltages $V_1 + V_{23}$ and record this sum in Table D. Calculate the percent error between the sum of your measured voltages and your measured source voltage.

10. According to Kirchhoff's current rule, the sum $I_2 + I_3$ should equal the total source current $I = I_1$. Calculate the sum $I_2 + I_3$ of the measured currents through R_2 and R_3. Record this sum in Table G. Calculate the percent difference between the value $I_2 + I_3$ and your measured source current I.

Cleaning up

When you are done, remove the wires and resistors from your circuit board. Place the circuit board, wires and resistors in their bag(s). Roll up the leads the meters. Put all equipment away neatly in its proper assigned location.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

DATA SHEET
Section A: Measuring Resistance

Table A

	Theoretical Resistances	Measured Resistances	% Error
$R_1(\Omega)$			
$R_2(\Omega)$			
$R_3(\Omega)$			

$$percent\ error = \left|\frac{Theoretical-Measured}{Theoretical}\right| \times 100$$

Section B: The Series Circuit

Table B

	Theoretical Value	Measured Value	% Error
Equiv. Resistance $R_{eq}(\Omega)$			
Source Voltage $V_S(V)$	measured		
Total Current: I (A)			
Voltage Across R_1: $V_1(V)$			
Voltage Across R_2: $V_2(V)$			
Voltage Across R_3: $V_3(V)$			
Voltage check		$=\ V_1 + V_2 + V_3$	

$$percent\ error = \left|\frac{Theoretical - Measured}{Theoretical}\right| \times 100$$

Attach Calculations

Section C: The Parallel Circuit

Table C Parallel

	Theoretical Value	Measured Value	% Error
Equiv. Resistance $R_{eq}(\Omega)$			
Source Voltage $V_S(V)$	measured		
Total Current: $I(A)$			
Current Through R_1: $I_1(A)$			
Current Through R_2: $I_2(A)$			
Current Through R_3: $I_3(A)$			
Current check $I = I_1 + I_2 + I_3$		$= I_1 + I_2 + I_3$	

$$percent\ error = \left|\frac{Theoretical - Measured}{Theoretical}\right| \times 100$$

Attach Calculations

Section D: The Series-Parallel circuit

Table D Series-Parallel

	Theoretical Value	Measured Value	% Error
Equiv. Resistance $R_{eq}(\Omega)$			
Source Voltage $V_S(V)$	measured		
Current Through R_1: $I_1(A)$			
Current Through R_2: $I_2(A)$			
Current Through R_3: $I_3(A)$			
Voltage Across R_1: $V_1(V)$			
Voltage Across R_2 & R_3: $V_{23} = V_2 = V_3 (V)$			
voltage check $V_S = V_1 + V_{23}$		$= V_1 + V_{23}$	
current check $I_1 = I_2 + I_3$		$= I_2 + I_3$	

$$percent\ error = \left| \frac{Theoretical - Measured}{Theoretical} \right| \times 100$$

Attach Calculations

Questions

Suppose the resistors in the three circuits studied in this experiment were light bulbs. When a bulb burns out, the bulb filament *breaks*, and the bulb becomes an *open circuit*. This means that the bulb's resistance is essentially *infinite*. (There's no longer any connection between the two terminals of the bulb, so it's as though the bulb were replaced by an *open switch*.) Use this information to answer all parts of this question. **You must give complete, correct answers for full credit!**

1. If any bulb in the series circuit of Section B burns out, what happens to the other bulbs? Specify whether the other bulbs *go dark*, *stay the same in brightness*, *burn brighter*, or *burn more dimly*. Explain why this happens.

2. If any bulb in the parallel circuit of Section C burns out, what happens to the other bulbs? Specify whether the other bulbs *go dark*, *stay the same in brightness*, *burn brighter*, or *burn more dimly*. Explain.

3. In the series-parallel circuit of Section D, if R_2 burns out, what happens to R_1 and R_3? Specify whether the other bulbs *go dark*, *stay the same in brightness*, *burn brighter*, or *burn more dimly*. Explain.

EXPERIMENT 5
✧
RC CIRCUITS

EQUIPMENT NEEDED

- *Pasco* interface
- *RC* circuit board kit, including *RC* circuit board, AA battery, hook-up wire, and an additional capacitor
- voltage probe
- multimeter

PURPOSE

- To explore how the voltage across a capacitor depends on time as the capacitor is charged and discharged.

THEORY

Charging a Capacitor

Consider the circuit in Figure 1 below showing a capacitor C being "charged up" through a resistor R. The capacitor is assumed to be completely discharged until $t = 0$, when the switch S is closed. At $t = 0$, the capacitor begins to charge up and a current I begins to flow, as indicated in the figure.
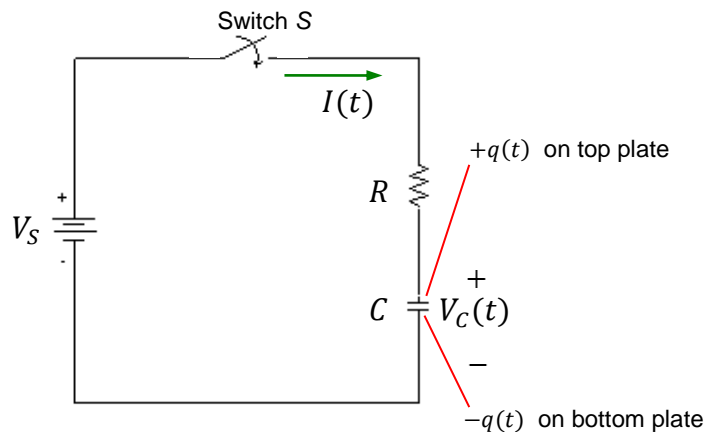
Figure 1

The current, the magnitude of the charge on each plate of the capacitor, and the voltage across the capacitor will vary with time as the capacitor charges up. Accordingly, in Fig. 1, these are shown as $I(t)$, $q(t)$, and $V_C(t)$, respectively. Note that the notation "$V_C(t)$" does ***not*** mean "V_C times t." Rather, it means "the voltage across the capacitor at time t." For example, $V_C(5.4)$ means the voltage across the capacitor at time $t = 5.4$s. Similarly, $I(t)$ and $q(t)$ represent the current and charge at time t.

Using the methods of calculus for solving first-order ordinary differential equations, we can derive theoretical formulas for $q(t)$ and $I(t)$. These derivations will not be presented here, but the results are as follows:

$$q(t) = Q_{max}\left(1 - e^{-t/\tau}\right) \tag{1}$$

and

$$I(t) = I_0 e^{-t/\tau}, \tag{2}$$

in which:

$$Q_{max} = CV_S, \tag{3}$$
$$I_0 = \frac{V_S}{R}, \tag{4}$$

and

$$\tau = RC. \tag{5}$$

Q_{max} is the *maximum* charge on the capacitor (the magnitude of the charge on each plate when the capacitor is *fully charged*). I_0 is the initial current (the current immediately after the switch is closed). The constant $\tau = RC$, called the *RC time constant*, characterizes the time required for the capacitor to charge up. In a time equal to RC, the capacitor charges up to about 63% of its maximum charge and the current drops to about 37% of its initial value. In a time equal to $5RC$, the capacitor charges up to about 99% of its maximum charge and the current drops to about 0.7% of its initial value. This observation is called "*The 5-RC Rule*":

<div style="border:1px solid blue; padding:10px;">

"5-RC Rule" (Charging): When charging up an initially uncharged capacitor, after a time equal to five RC time constants, the following will be true:

- The charge on the capacitor will be ~99% of its maximum value:
$$q(5RC) \approx (0.99)Q_{max}$$
- The current will have fallen to ~0.7% of its initial value:
$$I(5RC) \approx (0.007)I_0$$

</div>

The 5-RC rule gives a good "rule of thumb" to use in determining how long you should wait before you can be assured that the capacitor is essentially fully charged: If you wait for five RC time constants, the capacitor will be within about 1% of its full charge.

In order to get a formula for the voltage across the capacitor as a function of time, we use the defining equation for the capacitance C:

$$q(t) = CV_C(t)$$

So:

$$V_C(t) = \frac{q(t)}{C} = \left(\frac{1}{C}\right)CV_S\left(1 - e^{-t/\tau}\right)$$

$$V_C(t) = V_S\left(1 - e^{-t/\tau}\right) \tag{6}$$

Figure 2 shows a graph of $V_C(t)$ versus t. Note that the voltage across the capacitor approaches the source voltage V_S as time progresses.
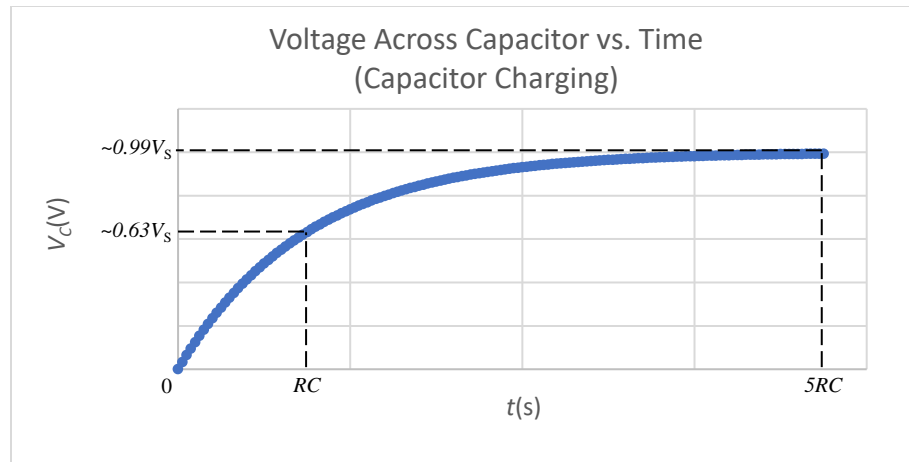
Figure 2

One of the major goals of this experiment is to measure the voltage across the capacitor at various times and use these experimental V_C vs. t data values to get an experimental measure of the time constant τ. In principle, this could be done by plotting a graph of the experimentally obtained values of V_C versus time, as in Fig. 2, then fitting an exponential curve to the data. The equation of the exponential fit would contain parameters from which τ could be determined. However, it's much easier for the human eye to detect when a set of data fits a *linear* curve fit than it is to determine when a set of data fits an *exponential* curve. But how can we take this exponential set of data and transform it to make it look linear? Well, consider rearranging Eq. (6) as follows:

$$V_S - V_C = V_S e^{-t/\tau}$$
$$\ln(V_S - V_C) = \ln\left(V_S e^{-t/\tau}\right)$$

$$\ln(V_S - V_C) = \ln V_S + \ln\left(e^{-t/\tau}\right)$$

$$\ln(V_S - V_C) = -\left(\frac{1}{\tau}\right)t + \ln V_S \tag{7}$$

If we plot $\ln(V_S - V_C)$ versus t, Eq. (7) will have the form:

$$y = -\left(\frac{1}{\tau}\right)x + \ln V_S, \tag{8}$$

which we can recognize to be the slope-intercept form of a straight line:

$$y = mx + b$$

with slope:

$$m = -\frac{1}{\tau} = -\frac{1}{RC} \tag{9}$$

and y-intercept:

$$b = \ln V_S$$

Figure 3 shows a graph of $\ln(V_S - V_C)$ versus t.
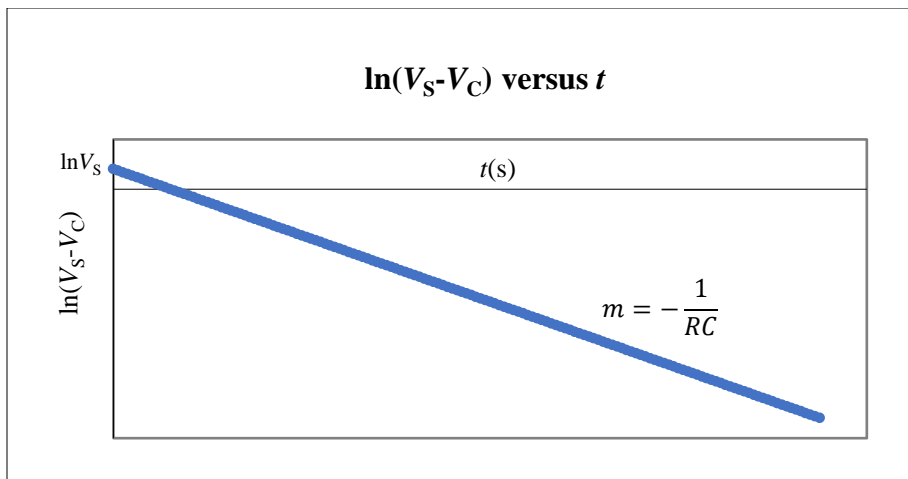
Figure 3

In this experiment, you will make a graph of $\ln(V_S - V_C)$ versus t using your measured values of $V_C(t)$. You will then do a linear fit to your graph and record the slope of the best-fit line. The negative of the reciprocal of this slope is your experimentally determined time constant τ_{exp}:

$$\tau_{exp} = -\frac{1}{m} \qquad (10)$$

Discharging a Capacitor

Now consider a capacitor that is initially charged up to some charge Q_0 and allowed to discharge through a resistor R, as shown in Figure 4. At $t = 0$, the switch S is closed and positive charge starts to flow *off of* the *top* plate of C, through R, and *onto* the *bottom* plate of C. Clearly, the current and the magnitude of the charge on each plate of the capacitor will depend on time as the capacitor discharges.

Figure 4

Using the methods of calculus for solving first-order ordinary differential equations, we can derive theoretical formulas for $q(t)$ and $I(t)$. The results are as follows:

$$q(t) = Q_0 e^{-\frac{t}{\tau}} \tag{11}$$

and

$$I(t) = I_0 e^{-\frac{t}{\tau}}, \tag{12}$$
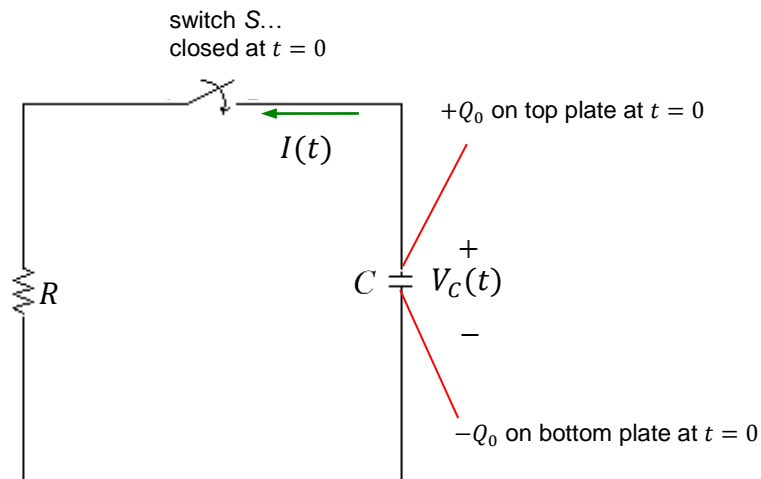
in which Q_0 is the initial charge on the capacitor. I_0 is the initial current and is given by:

$$I_0 = \frac{Q_0}{RC} \tag{13}$$

and, once again,

$$\tau = RC \tag{14}$$

The RC time constant characterizes the time required for the capacitor to discharge. In a time equal to RC, the capacitor discharges to about 37% of its initial charge and the current drops to about 37% of its initial value. In a time equal to $5RC$, the charge on the capacitor and the current fall to about 0.7% of their initial values. Thus, the "5-RC Rule" for capacitor discharging may be stated as follows:

> **"5-RC Rule" (Discharging):** When discharging a capacitor, the following will be true after a time equal to five RC time constants:
>
> - The charge on the capacitor will have fallen to ~0.7% of its initial value:
> $$q(5RC) \approx (0.007)Q_0$$
> - The current will have fallen to ~0.7% of its initial value:
> $$I(5RC) \approx (0.007)I_0$$

The 5-RC rule gives a good "rule of thumb" to use in determining how long you should wait before you can be assured that the capacitor is essentially fully discharged.

To get a formula for the voltage across the capacitor $V_C(t)$, we can again use the defining equation for the capacitance:

$$V_C(t) = \frac{q(t)}{C} = \left(\frac{1}{C}\right) Q_0 e^{-\frac{t}{\tau}}$$
$$V_C(t) = V_0 e^{-\frac{t}{\tau}}, \tag{15}$$

in which we recognize from $Q = CV$ that Q_0/C is the initial voltage across the capacitor, V_0. Figure 5 shows a graph of V_C versus t for a discharging capacitor.
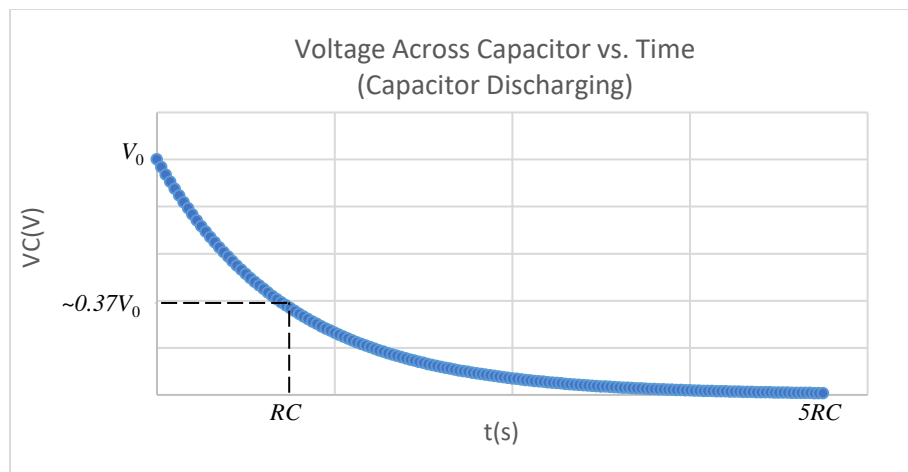

Figure 5

In this experiment, you will measure the voltage V_C across a discharging capacitor at various times. As for the case of the *charging* capacitor discussed earlier, one of your goals will be to extract from your V_C-vs.-t data an experimental measure of the time constant τ. To do this, first notice that Eq. (15) can be rearranged to give:

$$\ln V_C = -\left(\frac{1}{\tau}\right)t + \ln V_0 \qquad (16)$$

According to Eq. (16), if you graph $\ln V_C$ versus t, the graph would have the form:

$$y = -\left(\frac{1}{\tau}\right)x + \ln V_0,$$

which we recognize to be the slope-intercept form of a line with slope:

$$m = -\frac{1}{\tau}$$

and *y*-intercept:

$$b = \ln V_0.$$

In this experiment, you will make a graph of $\ln V_C$ versus t using your measured values of $V_C(t)$ for the discharging capacitor. You will then do a linear fit to your graph and record the slope of the best-fit line. The negative of the reciprocal of this slope is your experimentally determined time constant τ_{exp}:

$$\tau_{exp} = -\frac{1}{m} \qquad (17)$$

Figure 6 shows a graph of $\ln V_C$ versus t for a discharging capacitor.
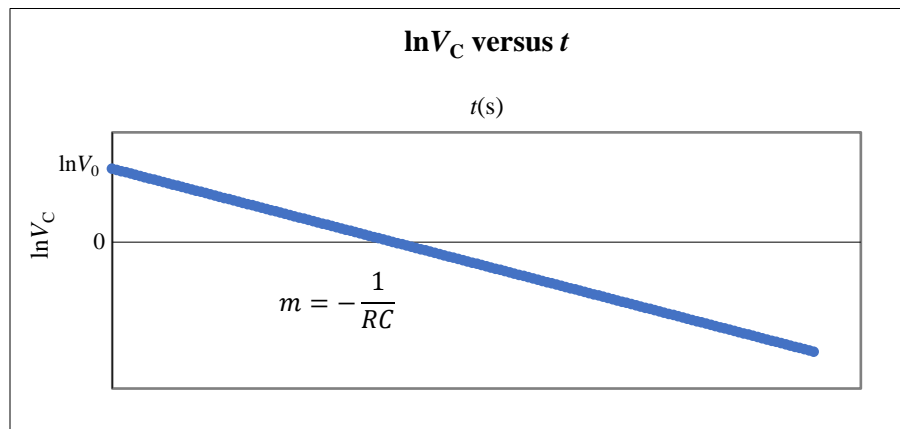
Figure 6

PROCEDURE
PART I: Setup

1. Make sure your computer and the *Pasco* interface are turned on.

2. Open the `Physics Folder` on your computer's desktop. Open the *Capstone* file called `RC`. This should start *Capstone* and load this file.

3. Plug the voltage probe's 5-pin DIN plug (Figure 7) into Analog Channel A.

Figure 7

Connect the two alligator clips at the other end of the voltage probe across the capacitor on your *RC* circuit board, as shown in Figure 8. Insert the AA battery into its holder, if it isn't already in place. Also, make sure your board has a fuse installed in the fuse holder located just below the battery holder. If your board does not have a fuse installed, notify your instructor. The switch to the left of the battery should be set to "Battery." The switch below the battery should be set to "Discharge."
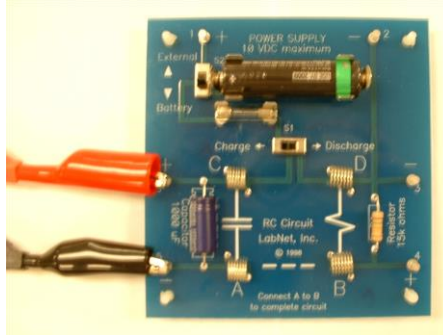
Figure 8

Part II: Data Recording
Section A: Charging the Capacitor

1. Using your *RC* circuit board, construct the circuit shown in Figure 9. To do this, **all you need to do is use the hook-up wire included to connect terminals *A* and *B* on the circuit board. All of the other connections shown in Fig. 9 are already made by solder traces on the board.**
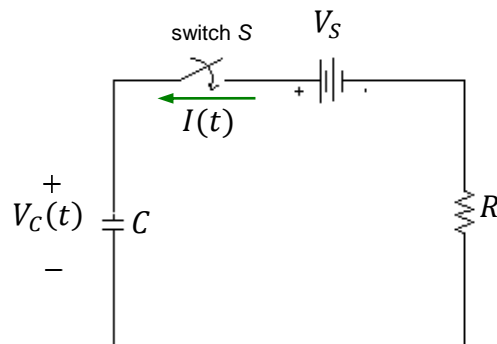
Figure 9

When you have successfully connected the circuit, it should look similar to Figure 10 below.
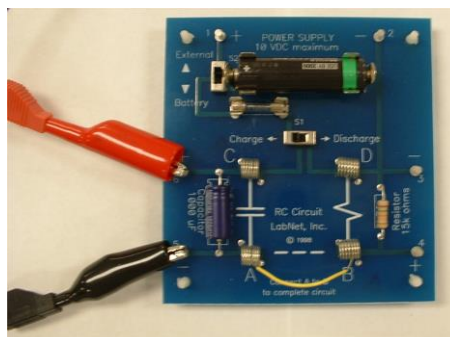
Figure 10

2. Using your multimeter in the voltmeter mode, measure your source voltage V_S (the battery voltage). Record it in Table A on your data sheet.

3. Read the resistance and capacitance values printed on the circuit board and record them in Trial 1 of Table A on your data sheet.

4. Using the values of R and C you just recorded, calculate your theoretical RC time constant in seconds and record it in Trial 1 of Table A.

5. Before you begin charging up the capacitor, make sure you start with the capacitor *completely discharged*. To do this, make sure the Charge/Discharge switch is set to Discharge, and move the hook-up wire to "short out" the capacitor. After a few seconds, reconnect the hook-up wire between terminals A to B so that the circuit again looks as shown in Figure 10.

6. In *Capstone*, identify the **Record** button on the lower left. Click the **Record** button, then immediately switch the **Charge/Discharge** switch to the **Charge** position. In your **Graph** window, you should see the voltage start to rise as the capacitor charges up.

7. Continue recording data until you are reasonably sure the capacitor is mostly charged (i.e., for a time of about 5 RC time constants.), then click stop. Leave the switch in the Charge position.

8. On the table in the Capstone display, right click No Data Selected> and select your run number (most likely "Run 1"). Your table should populate with times and voltage readings.

9. Starting at time $t = 0$, $V = 0$ (it may not be exactly zero), copy the time and voltage for times listed about every two seconds, until Trial 1 Charging table is filled. **Important**: it's very important that the rise on your graph (the increase in V) starts *right* after time $t = 0$. If you clicked record after the voltage started to climb or if the voltage reads 0 (or constant, nearly zero) for more than 0.8 seconds before rising, you may want to delete this data and try again.

10. Use Excel (or some other spreadsheet) to make a graph of $\mathbf{ln}(V_S - V_C)$ versus t from your measured data values. If you are unsure about how to do this, ask your instructor for help. Do a linear fit to your data. Remember to use scatter plot and do not connect the data points with lines. Be sure to put the fit equation and axis labels on your graph. Turn in the graph with your completed lab report.

11. Read off the slope of the best-fit line and record it near the bottom of the **Charging** column in Trial 1 of Table A.

12. Referring to Eq. (10) from the *Theory* section, calculate your experimentally determined RC time constant τ_{exp} and record it in seconds in the **Charging** column in Trial 1 of Table A.

Section B: Discharging the Capacitor

1. In this section of the experiment, you will discharge your capacitor through the resistor on your *RC* circuit board, as shown in the schematic diagram of Figure 13.
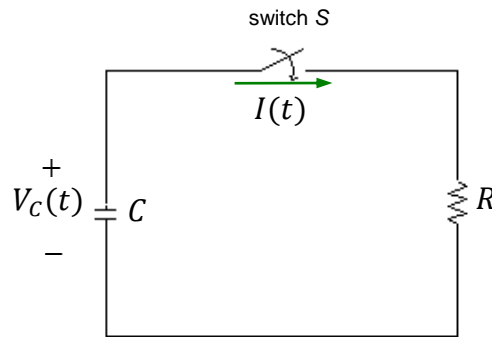

Figure 13

2. Make sure the capacitor is nearly fully charged before proceeding with the rest of this section of the experiment. (It is sufficient to have the capacitor charging for several minutes before you discharge it.)

3. Start discharging the capacitor just *before* you click record in *Capstone*.

4. Let the capacitor discharge until it is mostly discharged (about 5 *RC* time constants).

5. In the table in the *Capstone* display, right click <No Data Selected> and select the run number.

6. Starting with $t = 0$, record the time and Voltage for times listed about every two seconds in Trial 1, Discharging section of Table A, until this section of the table is full.

7. Use Excel to make a graph of **ln V_C** versus **t** from your measured data values. BE CAREFUL—this is different from the charging graph! Do a linear fit to your data. Display the fit equation of the graph, include labels, and print the graph. Turn in the graph with your completed lab report.

8. Read off the slope of the best-fit line and record it near the bottom of the **Discharging** column in Trial 1 of Table A. Calculate your experimentally determined *RC* time constant τ_{exp} and record it in seconds in the **Discharging** column in Trial 1 of Table A.

9. Now calculate and record the average of your two values of τ_{exp} in Trial 1 of Table A.

    This average τ_{exp} should be close to the *theoretical* value of the *RC* time constant you calculated earlier and recorded near the top of Trial 1 of Table A. Calculate and record the percent error of the average τ_{exp} to the theoretical *RC* time constant, $\tau_{theo} = RC$.

Section C: Changing the *RC* Time Constant

1. For Trial 2, you will repeat the measurements and data analysis in Sections A and B, but with a different *RC* time constant. To change the time constant of your *RC* circuit, first find the additional capacitor in your *RC* circuit board kit. (If you don't have one, just ask the instructor.) Read the value of the capacitance from the capacitor. Place this capacitor in parallel with the capacitor on the circuit card by connecting it between the spring

terminals on the board. The new capacitance is the sum of the original plus the parallel capacitance:

$$C_{eq} = C_1 + C_2 \qquad\qquad (18)$$

2. Now repeat the procedures given in Sections *A* and *B* above. Record your data in Trial 2 of Table A. If you are running short on time, you can finish the graphs and questions outside of class.

Cleaning up

When you are done, be sure the charge/discharge switch is set to discharge. Short the capacitors to discharge them, then remove the spare capacitor and hook-up wire and place them in the bag with the *RC* circuit board. Put all equipment away neatly in its proper location.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

DATA SHEET

Table A

Source Voltage: $V_S =$_____ V

Trial 1				Trial 2			
$R ==$_____ Ω $C =$_____ F				$R ==$_____ Ω $C =$_____ F			
$\tau_{theo} = RC =$_____ s				$\tau_{theo} = RC =$_____ s			
Charging		Discharging		Charging		Discharging	
t(s)	V_C (V)	$t(s)$	V_C (V)	$t(s)$	V_C (V)	t(s)	V_C (V)
Slope =_____ s^{-1}		**Slope** =_____ s^{-1}		**Slope** =_____ s^{-1}		**Slope** =_____ s^{-1}	
$\tau_{exp}=$_____ s		$\tau_{exp}=$_____ s		$\tau_{exp}=$_____ s		$\tau_{exp}=$_____ s	
$\left(\tau_{exp}\right)_{av}=$_____ s				$\left(\tau_{exp}\right)_{av}=$_____ s			
% Error = _____				**% Error =** _____			

Attach 4 Excel graphs

Questions

1. In the space below, starting with Eq. (15) in the *Theory* section, do the necessary algebra
    to show how Eq. (16) can be derived.

2. For the series circuit shown below, the capacitor is initially uncharged. When the switch
    is connected to position 1, the capacitor starts to charge. After 8.00 s, the switch is
    abruptly switched to position 2 and the capacitor starts to discharge. What is the voltage
    across the capacitor 6.00 s *after* the switch is connected to position 2?

EXPERIMENT 6

✧

CHARGED PARTICLES
IN MAGNETIC AND ELECTRIC FIELDS

EQUIPMENT NEEDED

- Computer
- *Mathematica* software

PURPOSE

- To investigate properties of the motion of various charged particles in uniform magnetic and electric fields.

THEORY

Motion of a Charged Particle in a Uniform Magnetic Field

Consider a particle with mass m and charge $+q$ moving with velocity $\vec{v}$ in a region of uniform magnetic field $\vec{B}$ directed into the page, as shown in Figure 1.
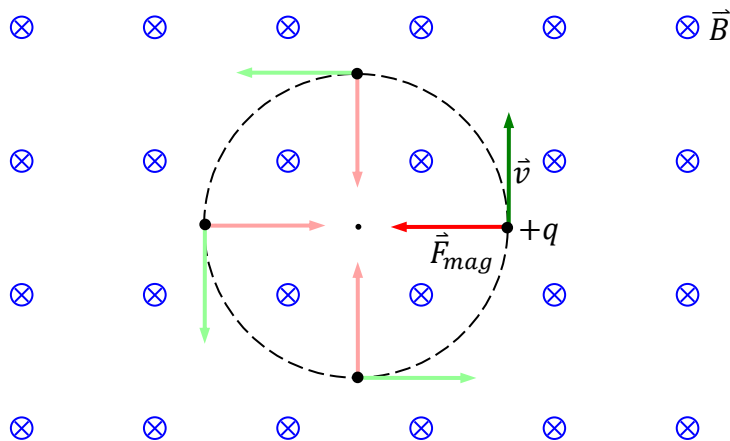

Figure 1

The magnitude of the magnetic force on the particle is given by:
$$F_{mag} = |q|vB \sin\theta, \qquad (1)$$
in which θ is the angle between $\vec{v}$ and $\vec{B}$. In the situation shown in Fig. 1, $\theta = 90°$, so:
$$F_{mag} = |q|vB \sin 90° = |q|vB \qquad (2)$$
The magnetic force vector $\vec{F}_{mag}$ always points perpendicular to both $\vec{v}$ and $\vec{B}$, as shown in Fig. 1. Its direction is given by a "right-hand rule":

> **Right-hand rule for direction of $\vec{F}_{mag}$:**
> - Point fingers of right hand in direction of $\vec{v}$.
> - Curl fingers toward $\vec{B}$.
> - Thumb points in direction of $\vec{F}_{mag}$ for a *positive charge*. For a *negative* charge, $\vec{F}_{mag}$ points in the opposite direction.

Applying Newton's second law to the centripetal direction in Fig. 1 gives the following expression for the radius of the circular path in which the particle moves:

$$r = \frac{mv}{|q|B} \tag{3}$$

The Velocity Filter

The velocity filter, also called a *velocity selector*, is a device for "filtering out" of a beam of particles all those except particles which have a certain *chosen* speed. Figure 2 below shows a diagram of a velocity filter.
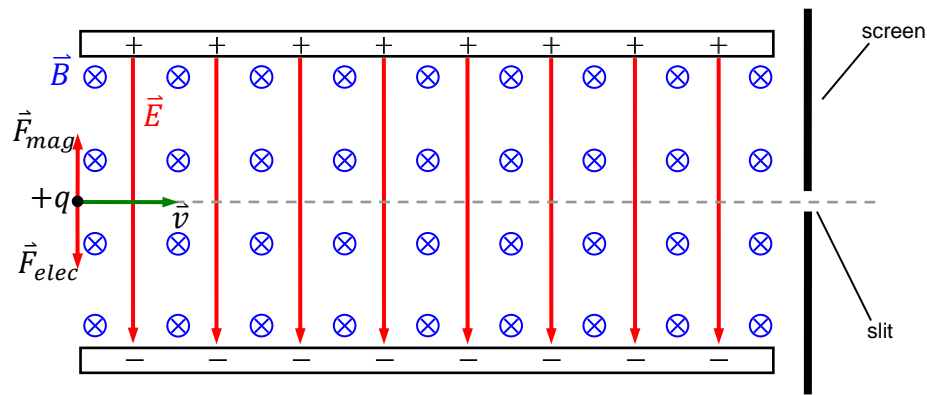

Figure 2

As shown in Fig. 2, a velocity filter consists of a parallel-plate capacitor placed in a region of uniform magnetic field. If the dimensions of the plates of the capacitor are *large* compared to the distance *between* the plates, the electric field produced by the capacitor will be approximately *uniform* and will point *from* the *positively* charged plate *to* the *negatively* charged plate, as shown in the figure.

Now suppose a positively charged particle moves into the velocity selector with a speed v, as shown in Fig. 2. The particle will experience an *electric* force of magnitude
$$F_{elec} = |q|E$$
and a *magnetic* force of magnitude
$$F_{mag} = |q|vB \sin 90° = |q|vB.$$
The direction of the electric force is downward, *in the direction of $\vec{E}$*, since the particle is positively charged. By the right-hand rule, the direction of the magnetic force is *upward*.

If the net force on the particle is zero, it will pass through the velocity selector *undeflected*. In order for this to happen, the magnetic and electric forces must be equal in magnitude:
$$F_{mag} = F_{elec}$$

$$|q|vB = |q|E$$
Thus the speed for which the particle goes through undeflected is:
$$v = E/B \hspace{4cm} (5)$$
Particles with this speed will make it through the slit shown at the right end of the velocity selector in Fig. 2. Particles with speeds greater than or less than E/B will be blocked by the screen. By adjusting E and B, we can *select* the velocity of the particles we want to let through.

PROCEDURE
Part I: Setup
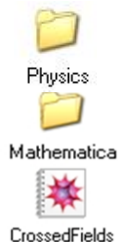
1. Open the folder called `Physics Folder` on your computer's desktop. Then open the folder called `Mathematica`.

2. In the `Mathematica` folder, open the file `CrossedFields`. *Mathematica* should start up.

Computer Setup

1. The interactive panel shows the paths of various charged particles that are shot into a region of uniform electric field and uniform magnetic field. The electric field points left-right; a positive value of E_x corresponds to a field to the right. The magnetic field points *out of* the screen or *into* the screen; a positive value of B_z corresponds to a magnetic field pointing out of the screen. The particle is shot in the $+y$-direction with initial speed v_0.

2. At the top right are two buttons, a reset button and a U-shaped update button. The left of the control panel allows for the selection of the particle. The choices are: electron, proton, neutron, alpha particle and positron.

3. In the middle of the control panel you can choose the value of the initial speed v_0, the electric field E_x, and the magnetic field B_z. Anytime you change these values, you should then click the update button at the upper right. Note that the magnitudes of the fields B and E are the absolute values of B_z and E_x.

4. In the middle there is also a checkbox to Animate Motion. Checking this shows controls for animation. If you get a dialog box that says "Dynamic Content Warning", click "Enable Dynamic." Enabling animation may slow things down too much; if so, uncheck the checkbox.

5. The Exit Data is listed below the control panel.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

Part II: Data Recording
Section A: Electron in Uniform Magnetic Field

1. Use $v_0 = 600,000$ m/s, $E_x = 0$ and $B_z = -0.00015$ T. Select the electron e^- and record the exit data.

    $x_f =$ _____ cm, $y_f =$ _____ cm, $t_f =$ _____ ns

Questions

A-1. What is the direction of the magnetic force on the electron as it enters the field?

A-2. Calculate the radius of the circular path from the initial data and compare with the exit data. **Show your work in the space below.**

A-3. Which way (*into* the screen or *out of* the screen) should the magnetic field be directed in order to make the electron go *counterclockwise*? (Circle your answer.)

- into the screen
- out of the screen

A-4. Referring to Eq. (3), calculate the magnitude of the magnetic field (in teslas) needed to cause the electron to move in a counterclockwise circular path of radius 4 cm. **Show your work in the space below.**

Section A: Electron in Uniform Magnetic Field (cont'd)

2. We want the electron to move in a counterclockwise circle of radius 4 cm. Use the results of Questions A-3 and A-4 to do this, remembering that the sign of B_z gives the direction of the B-field. If the radius of the path is not 4 cm, review your calculation in Question A-4, if necessary, to correct any errors. Record the exit data.

$x_f =$ _____ cm, $y_f =$ _____ cm, $t_f =$ _____ ns

Section B: Positron in Uniform Magnetic Field

1. Now keep all values set as they were but select the positron e^+ instead of the electron. The positron is the antiparticle of the electron. Record the exit data.

$x_f =$ _____ cm, $y_f =$ _____ cm, $t_f =$ _____ ns

Question
B-1. Describe and explain the similarities and differences between the electron and positron paths.

Section C: Alpha Particle in Uniform Magnetic Field

1. Use $v_0 = 600,000$ m/s, $E_x = 0$ and $B_z = -0.00015$ T. Select the alpha particle α and record the exit data.

    $x_f = $ _____ cm, $y_f = $ _____ cm, $t_f = $ _____ ns

2. Section C is similar to Section A. This time, though, the particle is an *alpha particle* (a helium nucleus). You are to use a magnetic field to cause the alpha particles to move clockwise in a semicircular path of approximately 4-cm radius. You should **not** use an electric field. Before proceeding, answer Question C-1 below.

Questions
C-1. Which way (into the screen or out of the screen) should the magnetic field be directed? (Circle your answer.)

- into the screen

- out of the screen

Section C: Alpha Particle in Uniform Magnetic Field (cont'd)

3. Now experiment with changing the magnetic field until you get the alpha particles to move clockwise in a semicircle of 4-cm radius. When you are successful, record your value of the magnetic field magnitude B in teslas in the space below.

$B = $_____ T

Section D: Electric and Magnetic Fields I

1. Use $v_0 = 600,000$ m/s, $E_x = 20$ N/C and $B_z = -0.00015$ T. Select the positron e^+.
   With an electric field in the x-direction and magnetic field in the z-direction a charged
   particle moving in the x-y plane will stay in that plane. With this choice of parameters an
   odd motion is observed. **Sketch the trajectory in the space below.**

Questions

D-1. Consider two positions in the trajectory: a point we will refer to as **L** at the far left,
     where the radius of curvature is the smallest, and a point **R** at far right where the radius
     of curvature is largest. Draw these points and label them in the above diagram. For
     each of these points, draw vectors showing the directions of the electric force, $\vec{F}_{elec}$,
     and the magnetic force, $\vec{F}_{mag}$.

D-2. At which of the two positons, **L** or **R**, is the speed the largest? **Explain. Hint:**
     Consider the electric potential energy and remember that electric field lines point
     toward lower potential. Also remember that magnetic forces do no work and therefore
     cannot change the speed. **Answer in the space below.**

Section E: Electric and Magnetic Fields II – The Velocity Filter

1. Here we will set up a velocity filter as discussed in the theory section.
   Use $v_0 = 600{,}000$ m/s, $B_z = 0.0002$ T, and select the electron e^-.

Questions

E-1. Which direction (left or right) should the electric field point in order for the velocity filter to work properly? (Circle your answer.)

- to the left

- to the right

E-2. Given the above values of v and B, calculate the value E required for particles to go through without being deflected. **Show work in the space below.**

Section E: Electric and Magnetic Fields II – The Velocity Filter (cont'd)

2. Input the appropriate value of E_x, being careful about the sign.

3. Record x from the Exit Data for the electron.

Exit Data: e^-: $x_f =$ _____ cm

4. Now try the rest of the particles (proton, neutron, alpha particle and positron) and record their exit values.

Exit Data:

p: $x_f =$ _____ cm

n: $x_f =$ _____ cm

α: $x_f =$ _____ cm

e^+: $x_f =$ _____ cm

Additional Questions (can be answered outside of class)

1. In the space below, give a derivation of Eq. (3). **Hint:** Apply Newton's second law to the centripetal direction, $(\Sigma F)_{cp} = ma_{cp}$.

2. In Section A, what happens to the speed of an electron as it moves in its semicircular path? **Explain.**

3. In Section C, do you need a *larger* or *smaller* B-field magnitude than in Section A? **Explain.**

    Calculate the B-field needed in Section C and compare this with the value of B you found in Step 3 of Section C. Calculate the percent error. **Show your work in the space below.**

EXPERIMENT 7

✧

ELECTROMAGNETIC INDUCTION

EQUIPMENT NEEDED

- Bar magnets (2)
- Solenoid
- Photogate
- Voltage probe (with alligator clips)
- *Pasco* interface

PURPOSE

- To explore the current and electromotive force induced in a solenoid when a bar magnet is dropped through the solenoid.

THEORY

It is observed experimentally that when a changing magnetic flux passes through a solenoid, a current is induced in the solenoid and an electromotive force (emf) is induced *across* the solenoid. This fact was first demonstrated in 1831 by the English physicist and chemist Michael Faraday (1791-1867). Faraday's law states that the average emf induced across the solenoid is directly proportional to the rate at which the magnetic flux is changing and to the number of turns of wire in the solenoid. The mathematical statement of Faraday's law is as follows:

$$\mathcal{E}_{av} = -N \frac{\Delta \Phi_{mag}}{\Delta t}, \qquad\qquad (1)$$

in which $\mathcal{E}_{av}$ is the average induced emf (over the time interval Δt), N is the number of turns in the solenoid, and Φ_{mag} is the magnetic flux through each turn of the solenoid. The ratio $\Delta \Phi_{mag}/\Delta t$ represents how rapidly (on average) the magnetic flux changes over the time interval Δt.

The polarity of the induced emf is given by Lenz's law, named in honor of Heinrich Lenz (1804-1865), who formulated the law in 1833:

> **Lenz's law (polarity of induced emf):**
> The induced emf is always of such a polarity as to *oppose* the *change* in magnetic flux which *caused* the emf.

The *polarity* of the emf refers to whether *one* end of the solenoid (the *top* end, let's say) or the *other* end (the *bottom*) is at the higher potential.

Alternatively (and equivalently), Lenz's law can be stated in terms of the sense of circulation of the induced current:

> **Lenz's law (sense of induced current):**
> The induced current always flows in such a sense as to *oppose* the *change* in magnetic flux which *caused* the induced current.

The *sense of circulation* of the induced current refers to whether the induced current circulates around the solenoid in the *clockwise* sense (as viewed from the top end of the solenoid, for example) or whether the induced current circulates around the solenoid in the *counterclockwise* sense (as viewed from the same end of the solenoid).

Consider, for example, a permanent bar magnet falling with speed v toward a solenoid, as shown in Figure 1.
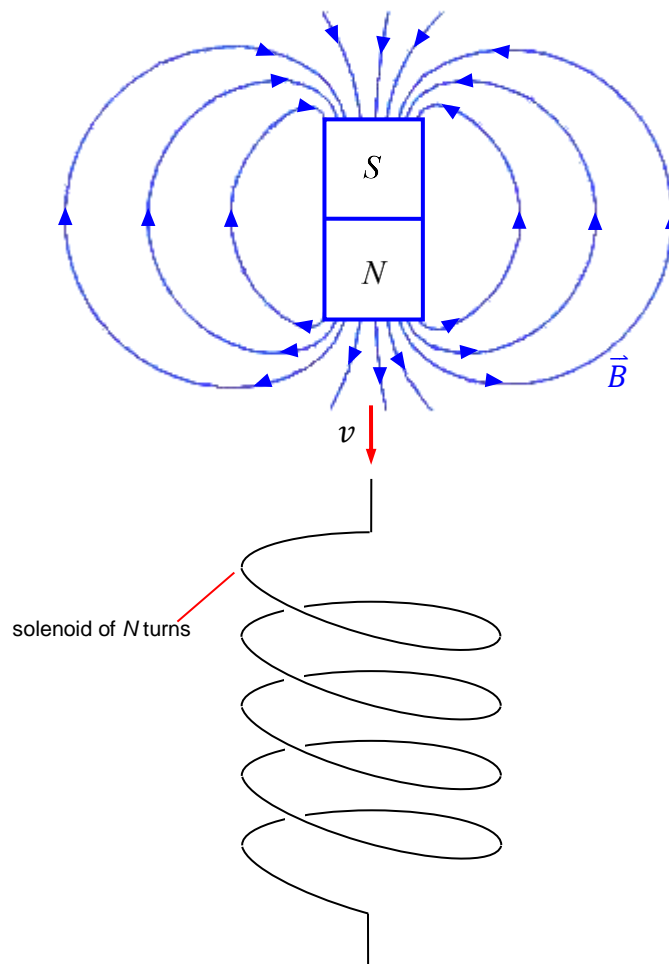

Figure 1

If the magnet is dropped with its *north* pole facing *downward*, as shown in Fig. 1, there will be a downward magnetic flux through the solenoid. This magnetic flux is, by *definition*, given by:
$$\Phi_{mag} = BA \cos \theta, \qquad\qquad (2)$$
in which B is the magnitude of the magnetic field, A is the cross-sectional area of the solenoid, and θ is the angle between the magnetic field vector $\vec{B}$ and the *normal* to the cross-sectional area. As the magnet falls into the solenoid, B will increase, resulting in an increase in the downward

magnetic flux through the solenoid. According the Lenz's law, this increasing downward flux will induce a current in the solenoid flowing in such a sense as to *oppose* the *increase* in the downward flux. That is, the induced current will flow in such a sense as to produce a magnetic flux *of its own* – an *induced* magnetic flux – that will point *upward*, in order to cancel some of the increase in the downward flux due to the falling magnet. This upward *induced* flux thus causes the downward flux through the solenoid to increase *not as much as it otherwise would.* By the right-hand rule for the *B*-field produced by a current-carrying wire, in order to produce this upward induced flux, the induced current must circulate around the solenoid in the
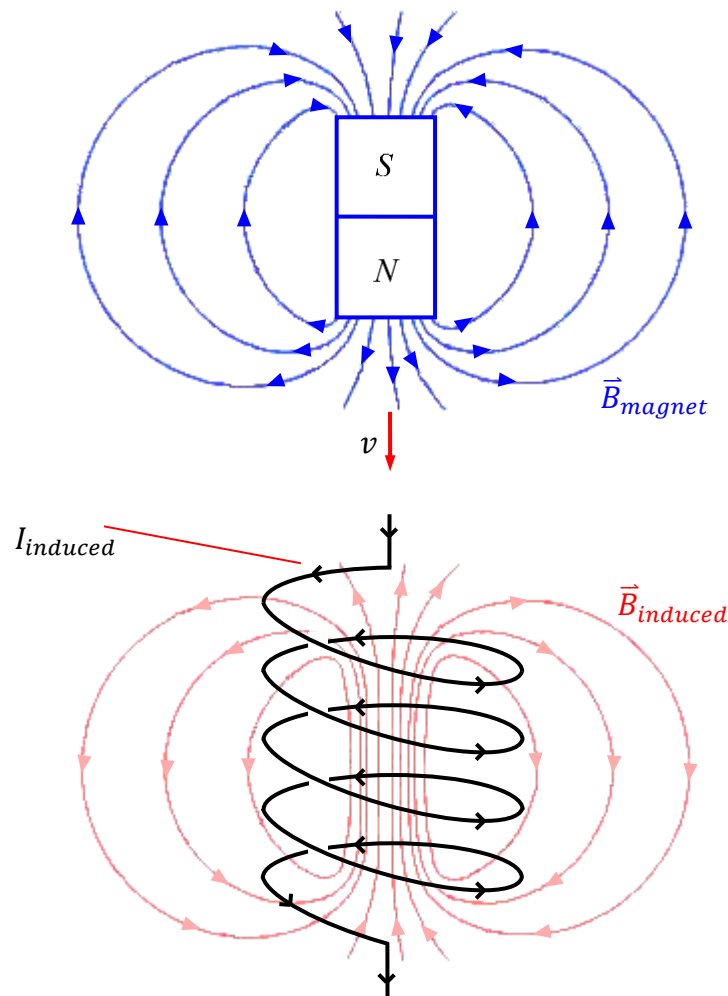

Figure 2

counterclockwise sense when viewed from the top of the coil, as shown in Figure 2.
If the solenoid is connected to an external circuit, the induced current will flow *out of* the *bottom* end of the solenoid, through the external circuit, and back *into* the *top* end of the solenoid, as shown in Figure 3.
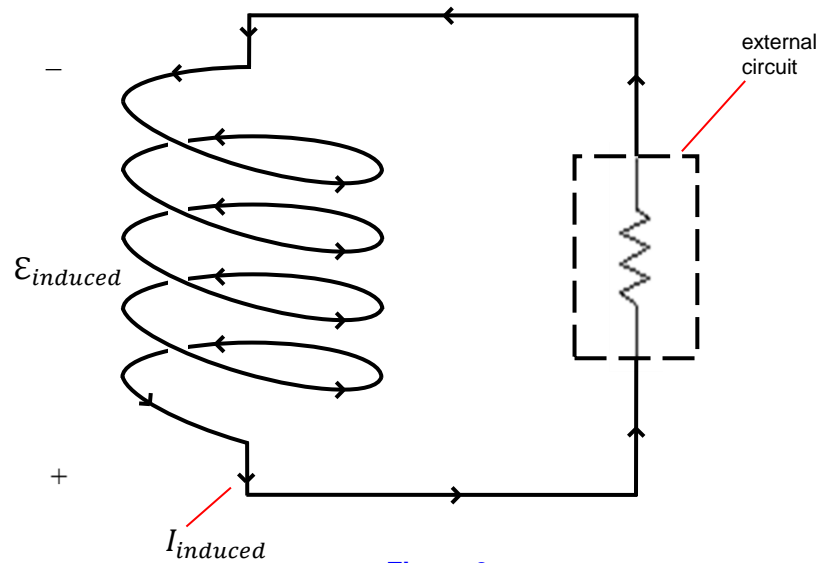
Figure 3

In order for the current $I_{induced}$ shown in Fig. 3 to flow, there must be some source of emf. According to Faraday, the solenoid *itself* is the source of this emf! The solenoid does positive work on positive charges, forcing them to go *from* a region of *low* potential *to* a region of *higher* potential. With regard to Fig. 3, this means that the *top* end of the solenoid is at a *lower* potential than the *bottom* end, as indicated by the polarity of $\mathcal{E}_{induced}$ shown in the figure. As far as the external circuit is concerned, it's as though the solenoid were replaced by a *battery*, as shown in Figure 4.

The induced emf continues to have this polarity as long as the magnet is falling in toward the
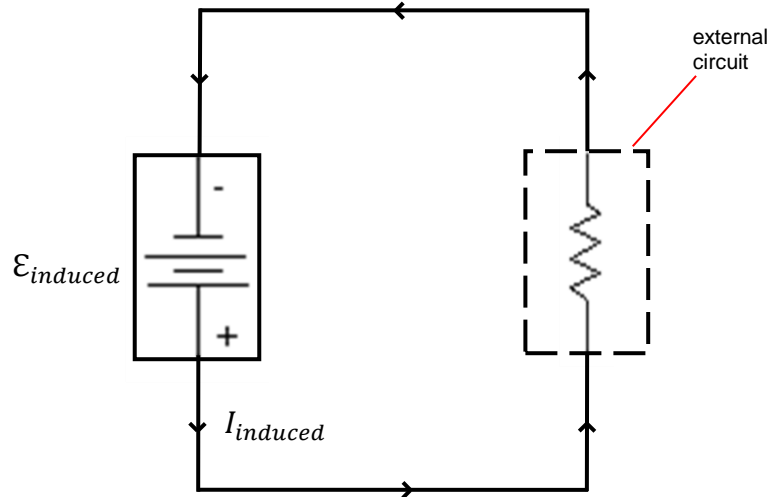

Figure 4

center of the solenoid, causing the downward magnetic flux to increase. However, after the magnet passes through the *center* of the solenoid, the downward magnetic flux caused by the magnet starts to *decrease*, as shown in Figure 5.
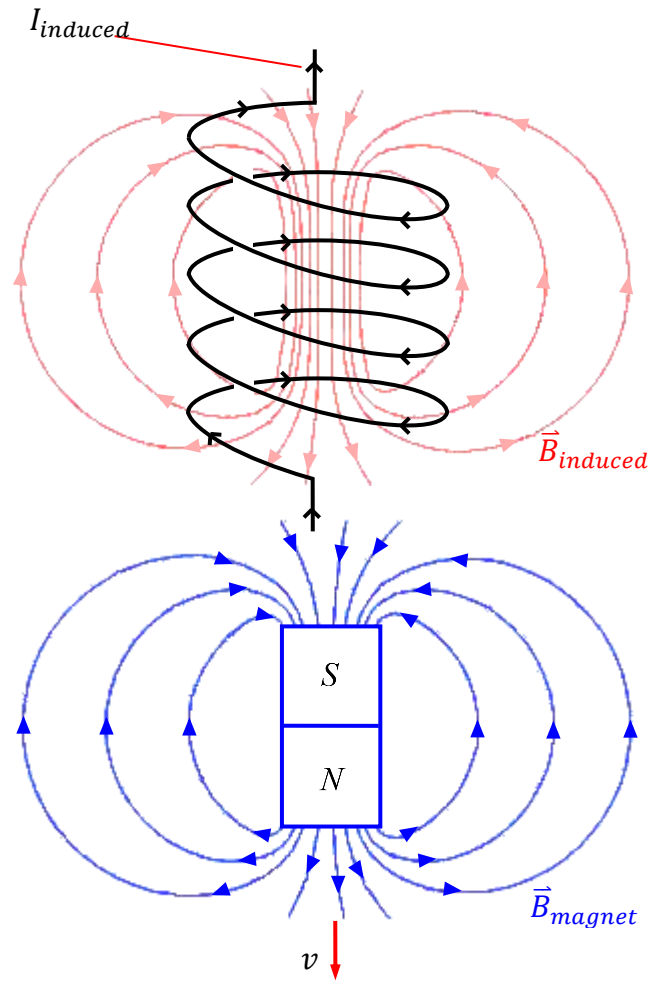
Figure 5

The induced current in the solenoid *now* produces an induced *B*-field which is *downward*, as shown in Fig. 5, in an attempt to *keep* magnetic flux going downward through the solenoid. (The solenoid "fights against" any attempt to *change* the magnetic flux through it. Before the magnet reached the center of the solenoid, there was a net magnetic flux *downward* due to the magnet, so the solenoid "doesn't want" this downward magnetic flux to change.) In order to produce this downward $\vec{B}_{induced}$, the induced current must now flow in the *opposite* sense, *clockwise* when viewed from the top of the solenoid, as shown in Fig. 5, as you can verify by the right-hand rule for the *B*-field produced by a current-carrying wire.

This change in the sense of circulation of $I_{induced}$ implies that the polarity of the induced emf must be inverted, as shown in Figure 6.
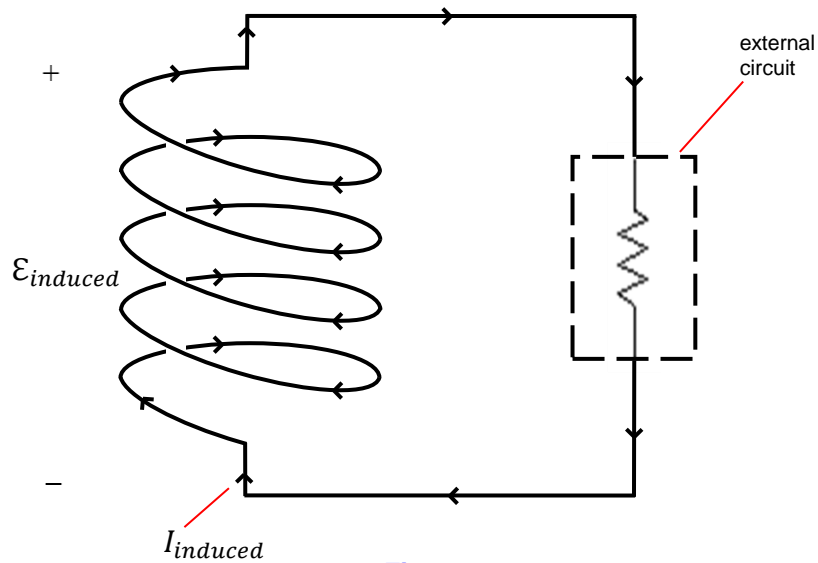
Figure 6

A graph of $\mathcal{E}_{induced}$ versus time thus shows a change in sign at the time when the magnet passes through the center of the solenoid. A typical graph of $\mathcal{E}_{induced}$ versus time is shown in Figure 7.
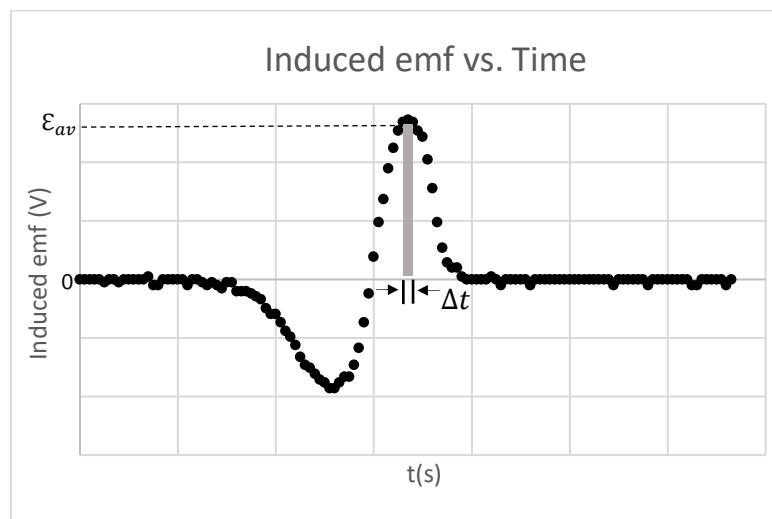

Figure 7

Consider the time interval Δt shown in Fig. 7. If the average emf during this time interval is $\mathcal{E}_{av}$, as shown in Fig. 7, then the product $\mathcal{E}_{av}\Delta t$ represents the *area under the graph* during the time interval Δt (the area of the shaded rectangle in Fig. 7). Rearranging Eq. (1) slightly, we find:
$$\mathcal{E}_{av}\Delta t = -N\Delta\Phi_{mag} \qquad (3)$$

Thus the area under the graph is proportional to the *change in the magnetic flux* through the solenoid. For the first peak in Fig. 7 (the *negative* peak), the area between the $\mathcal{E}_{induced}$ curve and the horizontal axis represents the total change in flux during the time that the magnet is falling *into* the solenoid, *toward* the *center* of the solenoid. For the second peak in Fig. 7 (the *positive* peak), the area under the graph represents the total change in flux during the time that the magnet is falling *out of* the solenoid, *away from* the center. Because magnetic field lines

always form *closed loops*, *all* of the flux that *enters* the solenoid (while the magnet is falling *in*) must *leave* the solenoid (while the magnet is falling *out*). Thus, we expect the corresponding areas in the graph of Fig. 7 to be *equal to one another*. In this experiment, you will make measurements of this kind using data you obtain by dropping your magnets through your solenoid.

As a final note, it's important to realize that the polarity of the induced emf depends not only on whether the magnet is falling *into* the solenoid or *out of* it, but also on *how the solenoid is wound*. For example, the solenoid pictured in Figs. 1–3, as well as Figs. 5 and 6, is wound in such a way that if a current flows from the *top* end to the *bottom* end, the current circulates around the solenoid in the *counterclockwise* sense, as viewed from the top end. But it's also possible for the solenoid to be wound in the *opposite* sense, as shown in Figure 8.
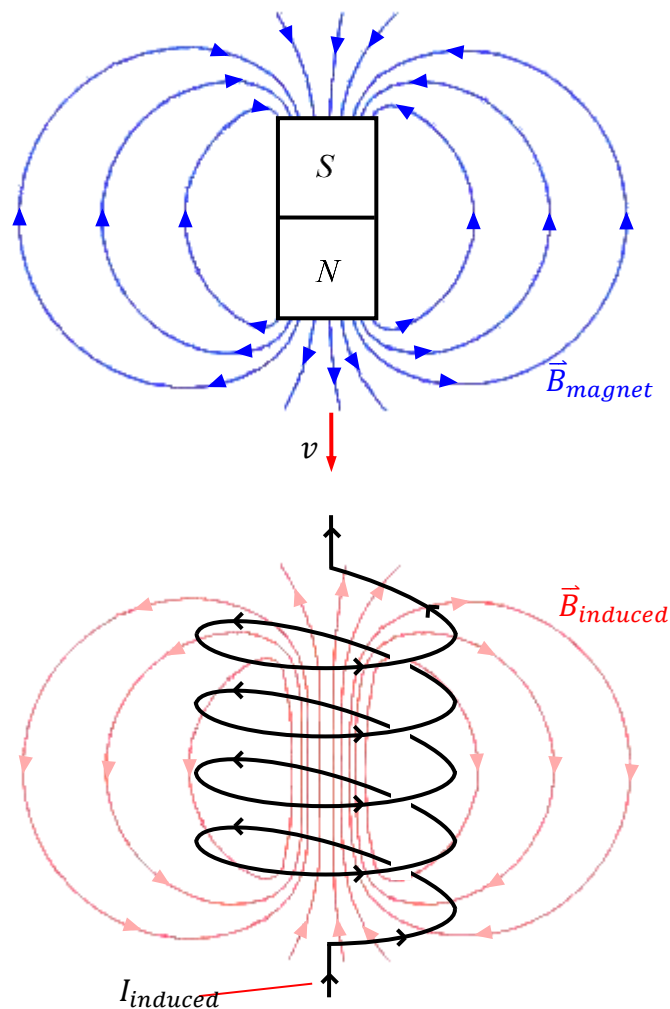

Figure 8

Figure 8 shows the magnet being dropped with its north pole downward, as was done in Figs. 1-3. Notice that, as in Figs. 1-3, $\vec{B}_{induced}$ is still *upward*, as it must be to partially cancel the increase in downward flux caused by the falling magnet. In order to produce this upward $\vec{B}_{induced}$, the induced current must still circulate around the solenoid in the counterclockwise sense, as viewed from the top end of the solenoid. (See Fig. 8.) But now, because of the way in which the turns of the solenoid are wound, as $I_{induced}$ flows around the solenoid, it flows from

the *bottom* end to the *top* end. This means that the polarity of the induced emf is *reversed*: the *bottom* end is at a *lower* potential than the *top* end. This polarity is shown in Figure 9, with the solenoid connected to an external circuit.
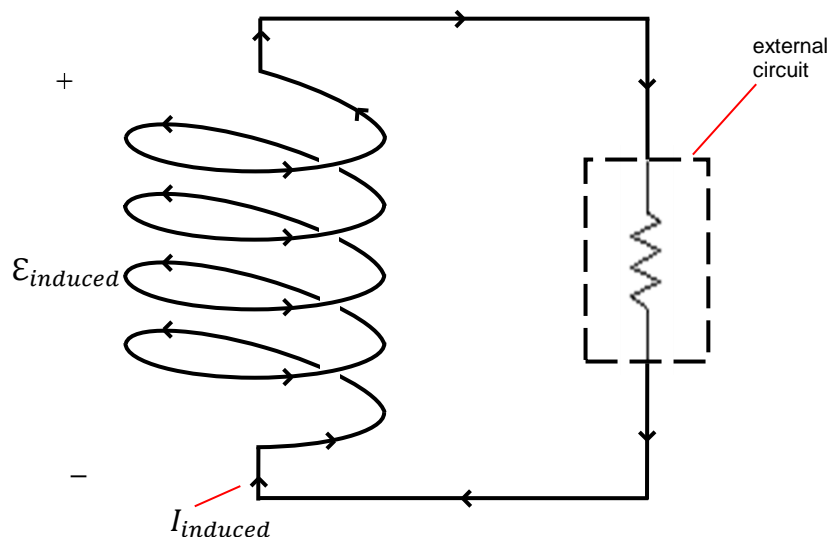

Figure 9

Thus, even though the magnet is dropped in the same orientation (north pole down) as in Figs. 1-3, the polarity of the emf obtained is reversed. For this reason, it's important to keep track of whether your solenoid is wound in the sense shown in Figs. 1-3 or in the sense shown in Figs. 8 and 9.

PROCEDURE
Part I: Setup

1. Make sure your computer and the *Pasco* interface are turned on.

2. Open the `Physics Folder` on your computer's desktop. Open the *Capstone* file called `Induction.` This should start *Capstone* and load this file.

3. Plug the voltage probe's 5-pin DIN plug (Figure 10) into *Analog Channel A* on your *Pasco* interface box.

Figure 10

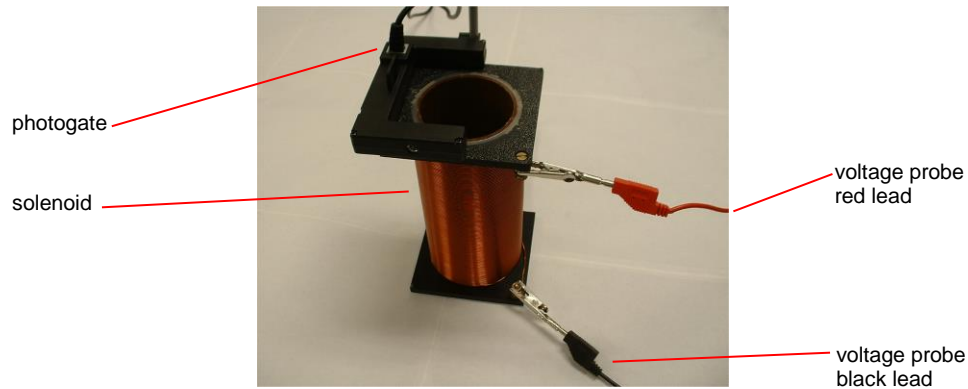4. Set up the solenoid and photogate as shown in Figure 11.

Figure 11

Part II: Data Recording
Section A: One Magnet, N Pole Down

1. Look closely at the way the turns of your solenoid are wound. From the *bottom* of your solenoid to the *top*, in which sense, clockwise or counterclockwise, are the turns wound, as viewed from the *above* the solenoid? Circle your answer on your data sheet. (Current flowing in this sense would give a **positive** reading on the voltmeter.)

2. Now hold the solenoid and photogate over the edge of the table so that the magnet can fall all the way through the solenoid without hitting the table. **Position a chair underneath the solenoid so that the magnet will fall into the chair. Do not let the magnet hit the floor!**

3. In *Capstone*, click **Record.**

4. Hold one of your magnets just above the photogate with its north pole facing down. Drop the magnet through the photogate so that the broad side of the magnet blocks the photogate as the magnet passes through. Data recording should stop automatically after the magnet falls through the solenoid. In *Capstone*, you should see a **Graph** that looks something like Figure 12. Note: the sign of your peaks may be opposite to those shown.
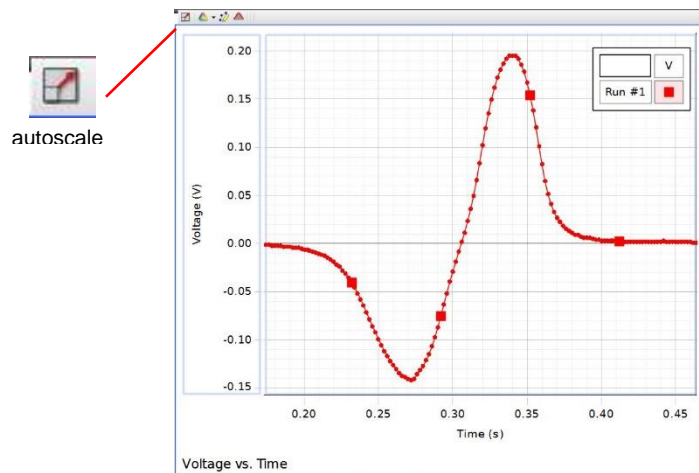

Figure 12

If you need to see your graph better, follow these instructions: To move your graph: click within the graph window and drag. To see the entire graph: click the "autoscale" button (above graph, left most button). To resize the horizontal axis, hover your mouse pointer above the numbers on the horizontal axis until your pointer becomes a double arrow ($\Longleftrightarrow$), then click and drag.

5. When you can see the entire graph, **print it. Label this "*Graph A*" and turn it in with your completed lab report.**

6. Click on the graph. Now click the **Area** tool located above the graph window. The area listed in the information box is the *total* area under the graph, including both the *negative* and *positive* peaks. We would like to measure the area under each peak separately. Click the Selection tool above the graph. Drag the selection box to the first peak. Resize it by dragging the corners of the selection box so that only the first peak is selected. Your graph should resemble that shown in Figure 13. This area represents the change in magnetic flux for the first peak. Record this area in Table A on your data sheet.
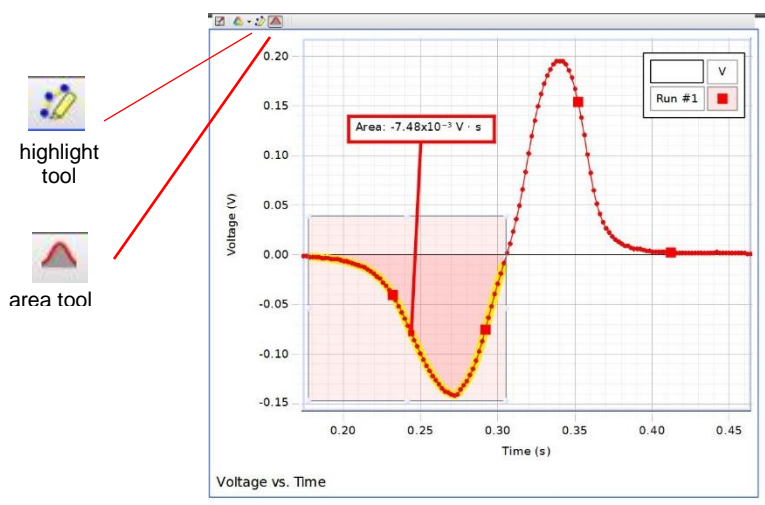

Figure 13

7. Now measure the area for the second peak and record it in Table A on your data sheet.

8. Calculate the percent difference between your areas for the first and second peaks. The correct way to do this is as follows:

$$\text{percent difference} = \left| \frac{|Area_{1st\,peak}| - |Area_{2nd\,peak}|}{\left[\frac{|Area_{1st\,peak}| + |Area_{2nd\,peak}|}{2} \right]} \right| \times 100\%$$

Note the use of absolute value signs! Record this percent difference in Table A on your data sheet.

9. Determine the sense of circulation of $I_{induced}$ for the first and second peaks. (You should be able to do this from the observed polarity of $\mathcal{E}_{induced}$ for each peak and your observations regarding the sense in which your solenoid is wound.) In Table A on your data sheet, record the sense of $I_{induced}$ (clockwise or counterclockwise, as viewed from the above the solenoid) for your first and second peaks.

Section B: One Magnet, S Pole Down

1. In this section you will drop the south end of the magnet through the solenoid.

2. Answer Question B-1 on your data sheet.

3. Now repeat Steps 2 through 9 from Section A, but this time with the *south* pole of the magnet facing down. Print copies of this graph. **Label your printed graph "*Graph B*" and turn it in with your completed lab report.**

4. Answer question B-2 on your data sheet.

Section C: Two Magnets, Both N Poles Down

1. Using tape supplied by your instructor, tape your two magnets together so that the two north poles are together at one end. In this section of the experiment, you will repeat Steps 2 through 8 of Section A, but with both north poles facing down. **Before proceeding further,** answer C-l your data sheet.

2. Now repeat Steps 2 through 8 of Section A, but with both north poles facing downward. Record your results in Table C on your data sheet. Print this graph. **Label your printed graph "*Graph C*" and turn it in with your completed lab report.**

3. **Do not delete your data from this run! You will need it in the next section.**

4. Answer question C-2 on your data sheet.

Section D: Two Magnets, One N Pole Down, One S Pole Down

1. Now place your two magnets together so that the two north poles are at opposite ends. (You shouldn't need any tape for this.) In this section of the experiment, you will again drop both magnets, but now with one north pole and one south pole facing downward. **Before proceeding further,** answer Question D-l on your data sheet.

2. Drop the two stuck-together magnets through the solenoid while recording your $\varepsilon_{induced}$-vs.-t data. You will want to display the new graph (section D) and section C graph simultaneously. Use the down arrow on the Data Selection tool (rainbow triangle above the graph) select the data that you had for section C and D at the same time. Print this graph. **Label your printed graph "*Graph D*" and turn it in with your completed lab report.**

Data
Selection
tool

3. Answer question D-2 on your data sheet.

Cleaning up

When you are done, remove the voltage probe, place the alligator clips back on the tips (if you removed them), roll this up and place it in its bag. Put the solenoid, magnets, and voltage probe in their assigned locations. **These each go** in a different location; please put the equipment away neatly so the next class can find it.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

DATA SHEET

Section A: One Magnet, N Pole Down
Sense of Winding of Solenoid
From the *bottom* of your solenoid to the *top*, in which sense, clockwise or counterclockwise, are the turns wound, as viewed from the *above* the solenoid? Circle your answer below.

- clockwise (CW)

- counterclockwise (CCW)

Table A: One Magnet, N Pole Down

	First Peak	Second Peak	% Difference
Area $(V \cdot s)$			
Sense of $I_{induced}$ (CW or CCW)			

Section B: One Magnet, S Pole Down
Question

B-1. What effect(s) do you expect inverting the magnet to have on your graph of $\varepsilon_{induced}$ versus t? **Answer in the space below.**

Table B: One Magnet, S Pole Down

	First Peak	Second Peak	% Difference
Area $(V \cdot s)$			
Sense of $I_{induced}$ (CW or CCW)			

Questions

B-1. Look at your graph of $\mathcal{E}_{induced}$ versus t. Do your results agree with the predictions you made in Question B-1? Discuss how well your results agreed with your predictions. **Answer in the space below. Be sure to give as *complete* an answer as possible!**

Section C: Two Magnets, Both N Poles Down
Question

C-1. In what way(s) do you expect the graph of $\mathcal{E}_{induced}$ versus t that you get with *two* magnets (north poles facing down) to be similar to the graph you got in Section A with only *one* magnet dropped in the same orientation? In what way(s) do you expect the graphs to be different? **Answer in the space below.**

Table C: Two Magnets, Both N Poles Down

	First Peak	Second Peak	% Difference
Area $(V \cdot s)$			
Sense of $I_{induced}$ (CW or CCW)			

Questions

D-1. What effect(s) do you expect to see in comparing the graph of $\varepsilon_{induced}$ versus t that you get in *this* section with the graph you got in Section C (with both north poles facing down)? **Answer in the space below.**

D-2. Look at the graph you just printed out. Do the results implied by this graph agree with the predictions you made in Question D-1? Discuss how well your results agreed with your predictions. **Answer in the space below. Be sure to give as *complete* an answer as possible!**

Additional Questions (can be answered outside of class if time runs out)

1. Looking at your graphs from Sections A through C, you should notice that for each graph, the first and second peaks always have opposite signs. **Discuss why you should expect this to be true. Be sure to give as *complete* an answer as possible!**

2. Looking at your graphs from Sections A through C, you should notice that for each graph the first and second peaks have different shapes. That is, one is always short and wide, the other taller and narrower. **Why do you think this is true? Be sure to answer** *completely***!**

3. Look at your data for the areas of your first and second peaks from Tables A through C. If things have gone well, you should have discovered that the area of the first peak is approximately *equal to* the area of the second peak. **Discuss why you should expect this to be true. Be sure to give as** *complete* **an answer as possible!**

4. Suppose a magnet is initially held at rest above a solenoid with its north pole facing downward. Referring to Lenz's law, **explain** the sense of circulation of the current induced in the solenoid if the magnet is then moved *upward*, *away from* the solenoid.

EXPERIMENT 8

✧

THE SERIES RLC CIRCUIT

EQUIPMENT NEEDED

- *RLC Circuit Board*
- Multimeter, Banana leads (2)
- Pasco Interface, Voltage probe
- *Capstone* file – RLC scope.cap

PURPOSE

- To measure AC currents and voltages in an *RLC* series circuit and compare the measured results with theoretical predictions.
- To explore the phenomenon of *electrical resonance* in an *RLC* series circuit.

THEORY

RLC Series Circuit with *Ideal* Inductor

An *RLC* series circuit consists of a resistor, inductor, and capacitor connected in series. Figure 1 shows an *RLC* series circuit connected across an AC voltage source.
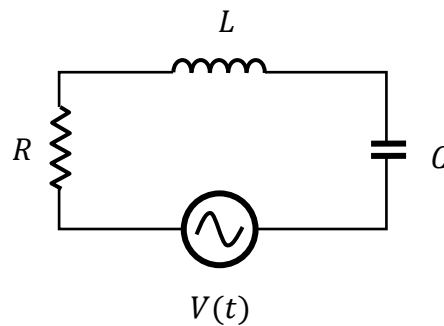

Figure 1

When the AC voltage source is connected across the series combination of R, L, and C, as shown in Fig. 1, an AC current $I(t)$ will flow, as shown in the figure. We will assume that the current is sinusoidal and given by

$$I(t) = I_{max} \sin(\omega t) \tag{1}$$

where I_{max} (also known as the peak current) is the amplitude of $I(t)$ and ω is the angular frequency of the source. Using the methods of calculus for solving second-order ordinary differential equations, it can be determined that the source voltage must be a sinusoid of the same frequency given by:

$$V(t) = V_{max} \sin(\omega t + \phi), \tag{2}$$

where V_{max} is the amplitude of $V(t)$ and ϕ is the *phase angle* of $V(t)$ with respect to the current $I(t)$. To determine $V(t)$, we need to determine V_{max} and ϕ in terms of I_{max}, ω, and the circuit components R, L, and C. By using *phasors* to represent $I(t)$ and $V(t)$, it is found that v_{max} is related to I_{max} by Ohm's law:

$$V_{max} = I_{max}Z, \tag{3}$$

in which Z, called the *impedance* of the RLC series circuit, is given by:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \tag{4}$$

where R is the resistance of the circuit,

$$X_L = \omega L \tag{5}$$

is the reactance of the inductor and

$$X_C = \frac{1}{\omega C}, \tag{6}$$

is the reactance of the capacitor.

In this experiment, you will use a voltage probe to measure the voltages across components of a series LRC circuit. The current through the circuit will be measured directly by a current sensor in the power source (the Pasco interface). Both current and voltage will be displayed on a simulated oscilloscope display on your computer screen. So you will actually be able to view voltage vs time and current vs time for the system.

The impedance Z is the "effective resistance" of the RLC series circuit. That is, to an AC source, the RLC circuit "looks like" a *resistor* with resistance Z. Thus, Eq. (3) represents the "AC form" of Ohm's law for the RLC series circuit. However, unlike the case of a resistor *by itself* connected across and AC source, for the case of the RLC series circuit, the voltage $V(t)$ and the current $I(t)$ are *not in phase*. In fact, from phasor analysis, we find:

$$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \tag{7}$$

Thus, $V(t)$ *leads* $I(t)$ by the angle ϕ, called the *phase angle*. Using a simultaneous display of voltage vs time and current vs time, you will measure the phase angle and compare it to the computed value.

Note that since this is a series circuit, the current $I(t)$ is the same throughout the circuit. Thus we will always compare the phase of the voltage across each component to the phase of the current. For instance, the voltage across the resistor is in phase with the current. That is, $V_R(t)$ is in phase with $I(t)$ (neither leads nor lags).

The symbol X_L in Eq. (5) represents the *inductive reactance* of the inductor L. The inductive reactance of an inductor is the "effective resistance" of the inductor to an AC current. From phasor analysis, it is found that the voltage across an inductor and the current through the inductor are related by X_L as follows:

$$V_{max,L} = I_{max}X_L, \tag{8}$$

in which $V_{max,L}$ is the peak voltage across the inductor and I_{max} is the peak current in the circuit.

Equation (8) represents the "AC form" of Ohm's law for an inductor. Notice that the peak current through the inductor is the *same* as the peak current through the *entire RLC series circuit*. This is because, for any number of components connected in *series*, the current flowing through *one* component *must* be the same as the current through all the *others*. If this were not true, then the total amount of charge in the circuit would not be conserved.

In addition, it is found by phasor analysis that the AC voltage $V_L(t)$ across the inductor leads the current $I(t)$ by 90°.

The symbol X_C in Eq. (4) represents the *capacitive reactance* of the capacitor C. This is the "effective resistance" of the capacitor to an AC current. From phasor analysis, it is found that:

$$V_{max,C} = I_{max}X_C, \tag{9}$$

in which $V_{max,C}$ is the peak voltage across the capacitor.

Equation (9) represents the "AC form" of Ohm's law for a capacitor. From phasor analysis, it is also found that the current $I(t)$ flowing *to* the capacitor and the voltage $V_C(t)$ *across* the capacitor are not in phase. The voltage $V_C(t)$ *lags* the current $I(t)$ by 90°.

Finally, notice (with reference to Fig. 1) that, because Kirchhoff's voltage rule *must* be obeyed at each instant in time, it must be true at any time *t* that:

$$V(t) = V_R(t) + V_L(t) + V_C(t) \tag{10}$$

However, the same statement *cannot* be made for the *amplitudes* of the source voltage and the voltages across R, L, and C. That is, because of phase differences,

$$V_{max} \neq V_{max,R} + V_{max,L} + V_{max,C} \tag{11}$$

The reason is that the AC voltages $V(t)$, $V_R(t)$, $V_L(t)$, and $V_C(t)$ *do not* reach their maximum values *at the same time*! They are *out of phase*! Note: since $V_{rms} = \frac{1}{\sqrt{2}}V_{max}$, it also follows that the RMS voltages do not add, that is: $V_{rms} \neq V_{rms,R} + V_{rms,L} + V_{rms,C}$.

RLC Series Circuit with *Real* Inductor

The analysis just completed assumed (*tacitly*, i.e., without saying so) that the inductor L was an *ideal inductor*, an inductor having *zero resistance*. This is only an idealization. *Real* inductors always have some resistance. For example, a solenoid made of 500 turns of wire has some non-zero resistance because the turns of wire used to make the inductor have some resistance.

It turns out that we can model a real inductor by thinking of it as an *ideal* inductor *in series with some resistance R_L*. For the case of the solenoid of 500 turns, R_L would be the resistance of 500 turns of the wire used to wind the solenoid.

With this model in mind, the schematic diagram for a *real RLC* series circuit being driven by an AC source would look as shown in Figure 2.
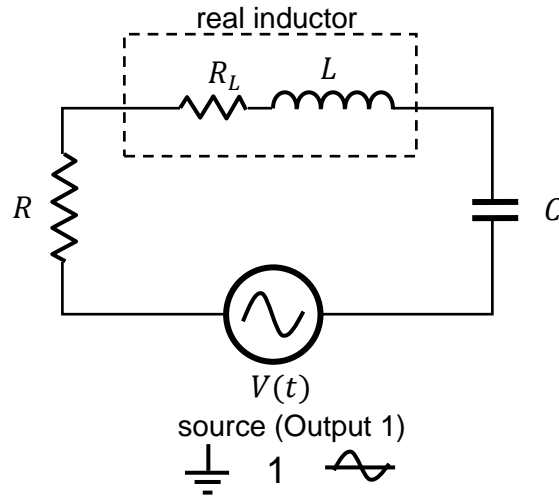

Figure 2

One effect of the intrinsic resistance R_L of the inductor is clearly to modify the impedance of the inductor. The impedance is no longer just $Z_L = X_L$, as it was for the pure inductor. For a *real* inductor:

$$Z_L = \sqrt{R_L^2 + X_L^2} \tag{12}$$

With this modification, the "AC form" of Ohm's law still holds for the inductor, namely:

$$V_{max,L} = I_{max}Z_L \tag{13}$$

Additionally, the impedance Z of the entire *RLC* series circuit must be modified. If we notice that R_L appears *in series* with R in Fig. 2, it becomes clear that we could simply replace R with the equivalent series resistance $R_{eq} = R + R_L$ in the expression for the impedance Z. Thus:

$$Z = \sqrt{R_{eq}^2 + (X_L - X_C)^2} \tag{14}$$

With this modification, the "AC form" of Ohm's law still holds, namely:

$$V_{max} = I_{max}Z \tag{15}$$

Resonance

Resonance (of *any* kind, whether in *electrical* systems or in *mechanical* ones) occurs when a system is "driven" (by some source) *at the natural frequency of oscillation of the system.* This natural frequency of oscillation of the system is called the *resonant frequency, f_0.* By considering a capacitor with initial charge Q_0 in series with an ideal inductor, it can be shown that an *RLC* series circuit has a resonant frequency given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (16)$$

Equation (16) implies that resonance occurs when $\omega L = \frac{1}{\omega C}$, that is $X_L = X_C$.

Thus, at resonance, the impedance Z of the RLC series circuit is a *minimum*. For the case of an RLC series circuit with a *real* inductor L, the impedance at resonance is thus:

$$Z = \sqrt{R_{eq}^2 + 0^2} = R_{eq} \qquad (17)$$

Thus the resistance in the circuit is REAL. In addition the phase angle between the source voltage and the current is $\phi = \tan^{-1}\left(\frac{X_L - X_C}{Z}\right) = \tan^{-1}\left(\frac{0}{R_{eq}}\right) = 0$.

You will use this property to explore resonance in this system in two different ways.

PART I: PROCEDURE
Procedure Section A: Preliminary Calculations

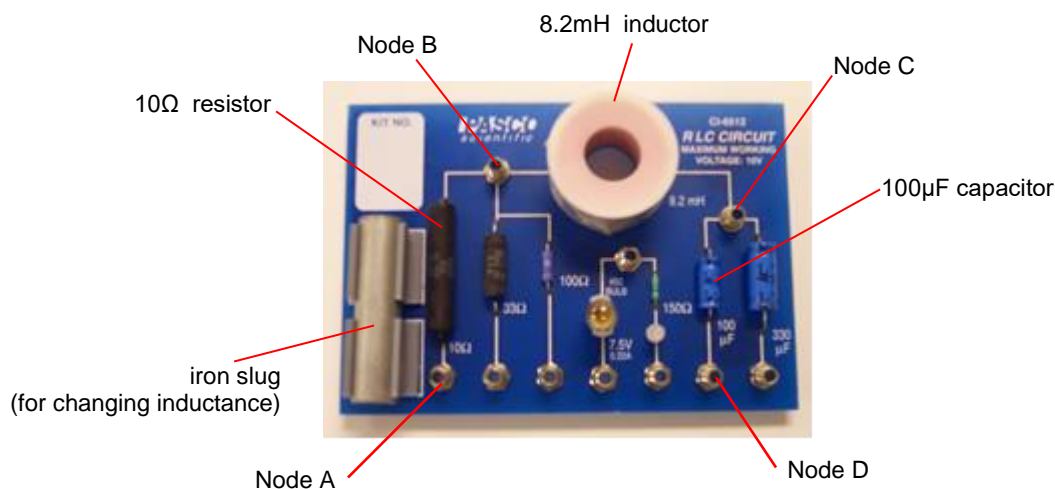**Figure 5**

On the RLC circuit board identify the following components:

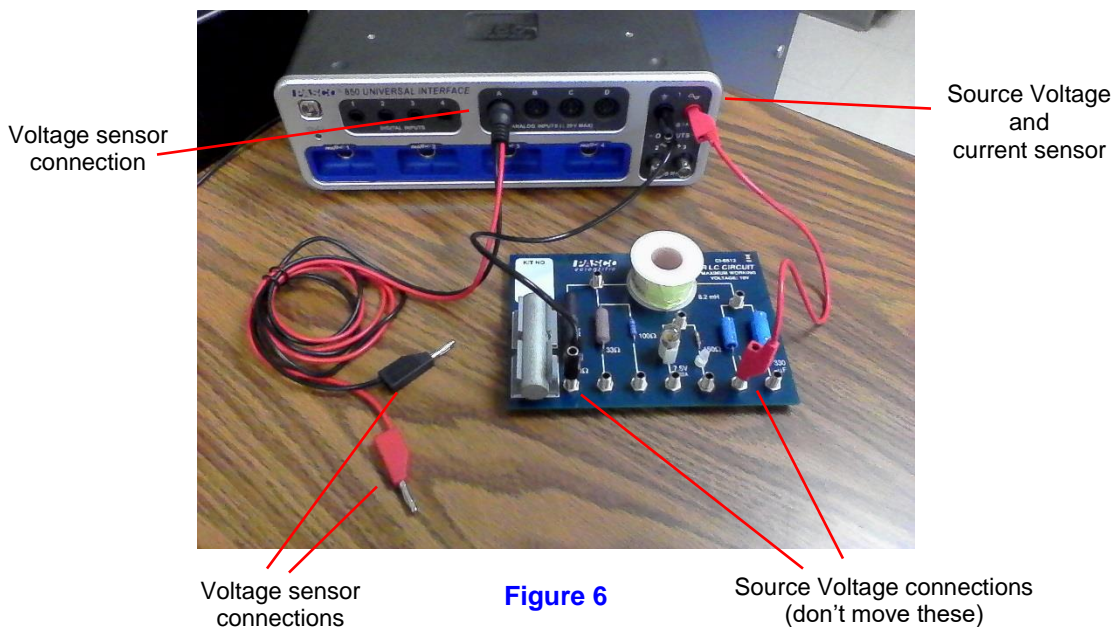$R = 10\ \Omega \qquad L = 8.2\ \text{mH} \qquad C = 100\ \mu\text{F}$

Use a multimeter with *banana* leads to measure the internal resistance, R_L, of the inductor (put leads at node B and node C). Record this in Section A of the Data Sheet. Put the multimeter away, you won't need it again.

Procedure Section B: Ohm's Law for AC circuits
You will connect a variable frequency AC source across a series RLC circuit, and compare measurement of peak current, peak voltages, and phase angles to expected values.
1. Check your Computer, if there is an instance of Capstone already running, close it. Turn on the Pasco 850 interface. Open the `Physics Folder` on your computer's desktop. Open the *Capstone* file called `RLC scope.`

2.   Using the banana leads, connect output 1 on the Pasco interface (upper far right on
      Pasco interface) across the chosen RLC circuit. Connect the black banana lead from
      ground on the interface to Node A on the RLC circuit board. Connect the red
      banana lead from red output to Node D on the RLC circuit board. This is your
      source voltage. The ammeter is also contained in the Pasco interface. You will
      leave these leads connected throughout the rest of the experiment. **Don't move
      them.**

3.   Connect the **voltage probe** to Analog Input A on the interface. This is your
      voltmeter. You will connect these leads across various locations on the RLC circuit
      board. Note: the direction in which you connect these leads is very important. Pay
      close attention to the instructions.

4.   Your set up should resemble this.

Voltage sensor connection

Source Voltage and current sensor

Voltage sensor connections

Figure 6

Source Voltage connections (don't move these)

5.   **SOURCE VOLTAGE**: Connect the voltage probe leads across the source voltage.
      Plug the red lead to Node D (plug it into the back of the red source lead).   Plug the
      black lead into Node A (into the back of the black source lead).

6.   On the Capstone display, click Signal Generator (on left). Change the frequency to
      120 Hz. Click "**on**" to turn the generator on. Click "Monitor" and monitor the
      signal for a few seconds.

7.   On the dual trace oscilloscope display (onscreen graph), identify the voltage trace
      and the current trace. Move the Data Selection tool (box with cross-hairs) on your
      display to measure the peak voltage (amplitude) of the source. Record this as the
      experimental peak voltage, V_{max} in section B of the data sheet.

8.   Measure the peak current and record this as *experimental* peak current, I_{max}, in
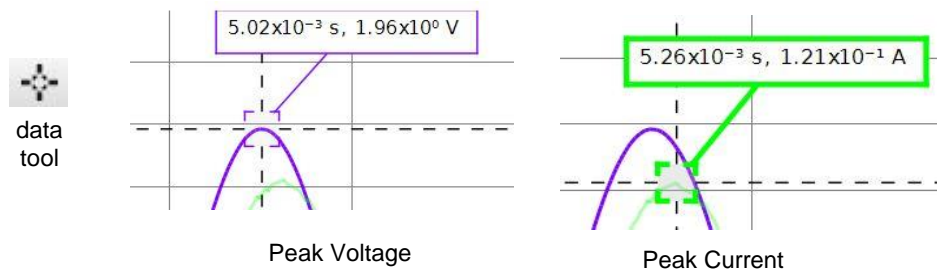   Table B on your data sheet. (See Figure 7.)

Figure 7

9. Phase analysis: Look at the two peaks, which peaks first in time, voltage or current? If voltage peaks first then voltage *leads* current. If voltage peaks after current, then voltage *lags* current. If they peak at the same time then they are *in phase*. Record this in section B of the Data sheet.

10. Ninety degrees or $\frac{\pi}{2}$ radians is one quarter of a cycle. Look at the peaks. Is the difference in the peaks about 90° or less than 90°? Record this in section B of the data sheet.

11. **RESISTOR**: Leaving the source voltage connected as is, move the voltage probe leads so you can measure the voltage across the resistor alone. Leave the black lead connected to Node A. Move the red lead to B. (Fig 5.). Monitor for a few seconds.

12. Measure the peak voltage and record this in Table B as the *experimental* peak voltage across the resistor, $V_{max,R}$.

13. Does $V_{max,R}$ *lead* or *lag* current, or are they *in phase*? Record your answer in section B of the data sheet.

14. **INDUCTOR**: Leaving the source voltage connected as is, move the voltage probe leads to measure the voltage across the inductor alone. Move the black lead to Node B. Move the red lead to Node C. Monitor for a few seconds.

15. Measure the peak voltage. Record this in Table B as *experimental* peak voltage across the inductor, $V_{max,L}$.

16. Does $V_{max,L}$ *lead* or *lag* current? By 90° or less than 90°? Record your answers in section B of the data sheet.

17. **CAPACITOR**: Leaving the source voltage connected as is, move the voltage probe leads so you can measure the voltage across the capacitor alone. Move the black lead to Node C. Connect the red lead to Node D (into the back of the red lead from the source). Monitor for a few seconds. Measure the peak voltage and record this as the *experimental* peak voltage across the capacitor, $V_{max,C}$.

18. Does $V_{max,C}$ *lead* or *lag* current? By 90° or less than 90°? Record your answers in section B of the data sheet.

19. Skip to section C. Later, you will have to compute theoretical values of these voltages and currents and compare them to your measured values, and you can then answer the questions listed for section B. But don't do that now, finish getting experimental data first.

Procedure Section C: Changing the Inductance

1.   Unclip the iron core from your RLC circuit board and insert it into the center of the inductor. This will change the inductance to an unknown value. Move your voltage probe to measure the voltage across the inductor. Place the black lead on Node B and the red lead on Node C. Monitor the system for a few seconds.

2.   On the Capstone display, measure the peak current and record this as I_{max} in section C of your Data sheet.

3.   Measure the peak voltage and record this as $V_{max,L}$ in section C on your data sheet.

4.   Later you will use these measured values to compute the new value of inductance in your circuit.

Procedure Section D: Resonance

1.   Leave the iron core in place. Move the voltage probe leads to the Source voltage. Connect the black lead to Node A and the red lead to Node D. Click monitor and leave it on. Note: you can adjust the scale of the vertical axes *separately* by grabbing and dragging at the axes on left or right respectively.

2.   With the signal generator open, adjust the frequency until the Voltage and current peaks occur at the same time, that is V_{max} and I_{max} are in phase. Your circuit is now in resonance. **Record this frequency** as *experimental* resonance frequency in Section D of the data sheet. Stop monitoring.

A more accurate way to find the resonance frequency is to display current $I(t)$ on the vertical axis while displaying source voltage $V(t)$ on the horizontal axis. This will result in an oval shaped figure called a lissajous. This is a plot of $I(t) = I_{max} \sin(\omega t)$ vs. $V(t) = V_{max} \sin(\omega t + \phi)$. At resonance, the phase angle, $\phi = 0$, and the oval collapses into the form of a diagonal line.

Leave your setup as it was, with the iron core still in place.

1.   On the left of the screen, click to turn "off" the Signal generator. Select "x-y scope" tab (top left, 2nd tab). Select the signal generator and turn it "on".
2.   Monitor the signal. Adjust the frequency of the Signal Generator until the oval on the oscilloscope display collapses into a diagonal line. **Record this frequency** as the *theoretical* value of the resonance frequency, f_0, in section D of the Data Sheet.

Cleaning up

When you are done, remove the voltage probe, place the alligator clips back on the tips, roll this up and place it in its bag. Remove the banana leads. Put the RLC circuit board in its bag. Put the pointed test leads back on the multimeter and roll them up. Put the multimeter, RLC circuit board, banana leads and voltage probe in their assigned locations. **These each go** in a different location, please put equipment away neatly so the next class can find it.

This completes the Data recording part of your lab. You may now proceed to analyze the data on your Data Sheet. If you run out of time, you can complete this part at home.

Name: _____   Section: _____   Group #: _____

ID: _____   Date: _____

Part II: DATA SHEET

Data Section A: Preliminary Calculations
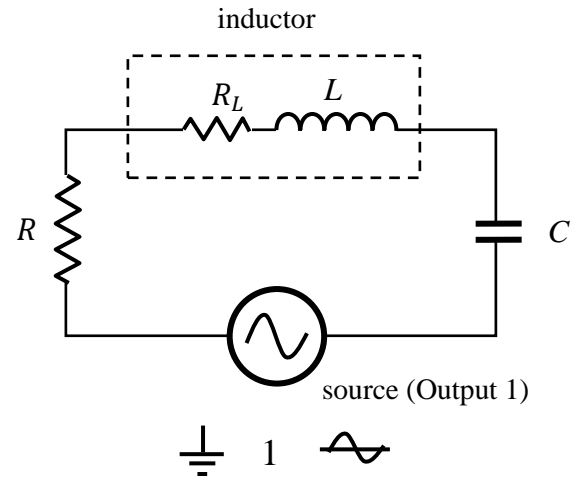
Preliminary calculations

inductor

$R = 10\ \Omega$ $L = 8.2$ mH $C = 100\ \mu$F

Resistance of Inductor

$R_L = $ _____ Ω

Total resistance of circuit

$R_{eq} = R + R_L = $_____ Ω

Calculate the theoretical values of the reactance and impedance of the system given $f = 120$ Hz. Remember to use the equivalent resistance, R_{eq}, when calculating impedance.

$X_L = $ _____ Ω $X_C = $ _____ Ω $Z = $ _____ Ω
Show work.

Data Section B: Ohm's Law for AC circuits

Using the data you took in Section B, fill out the experimental column of Table B1 below.

Peak source voltage: V_{max}_____ V

Phase Analysis. (Circle your answers.)

Source voltage	• leads • lags	current by	• 90° • less than 90°
Voltage across the resistor	• leads • lags • is in phase with	current	
Voltage across the inductor	• leads • lags	current by	• 90° • less than 90°
Voltage across the capacitor	• leads • lags	current by	• 90° • less than 90°

Table B

	Theoretical (calculated)	Experimental (measured)	% Error
I_{max} (A)			
$V_{max,R}$ (volts)			
$V_{max,L}$ (volts)	*		
$V_{max,C}$ (volts)			

Compute the theoretical values and percent errors. Use the measured peak source voltage V_{max} (listed above) for all your theoretical calculations.

Recall: $percent\ error = \left| \dfrac{theoretical - experimental}{theoretical} \right| \times 100\%$

* Remember, the inductor has resistance. You will need to compute the impedance of your inductor $Z_L = \sqrt{R_L^2 + X_L^2}$ to compute the voltage across the inductor.

Show all your calculations on the next page.

Questions Section B: Ohm's Law for AC circuits

Question B.1: Do the peak values add up to the peak value of the source, that is, does $V_{max} = V_{max,R} + V_{max,L} + V_{max,C}$? Should they add this way?   Explain why or why not.

Question B.2: Using your theoretical results, find the total power dissipated in this circuit. *Show work.*

Question B.3: Look at the phase differences between $V_{max,R}$ and I_{max}, between $V_{max,L}$ and I_{max}, and between $V_{max,C}$ and I_{max}. Are they what you expected? Discuss the rules for phase differences.

Data Section C: Changing the Inductance

Copy the current and maximum voltage across the inductor from Data Recording section C.

I_{max} = _____A $V_{max,L}$ = _____ V

Using these values, calculate the new value of the inductance. Remember when you compute the impedance that there is still a resistance here. So the impedance across the inductor is
$Z_L = \sqrt{R_L^2 + X_L^2}$.

Experimental value of inductance (with core) L = _____ H

Show your work.

Data Section D: Resonance
Record your data from section D.

Experimental resonance frequency f_0 _____ Hz

Theoretical resonance frequency f_0 _____ Hz

compute an error for the resonance frequency f_0: % error _____

Using the theoretical **resonance frequency**, compute the inductance. Record this as the theoretical value of inductance below (show calculations).

Theoretical value of inductance (with core) $L =$ _____ H
Show work:

Compare the measured value of inductance found in part (C) above to this theoretical value found in part (D).

Inductance with core L: % error _____

EXPERIMENT 9
✧
GEOMETRIC OPTICS

EQUIPMENT NEEDED

- Light source
- Optics Kit Including:
    - Concave-Convex-Planar Mirror
    - Thin Convex and Thin Concave Lenses
    - Prism
- Ruler and Protractor, several blank sheets of paper

PURPOSE

- To understand the fundamental principles of reflection and refraction of light rays.
- To understand the behavior of light rays incident on mirrors and thin lenses.
- To measure the focal length of mirrors and thin lenses using actual light rays.

THEORY

Geometric optics is the description of optical phenomena using light *rays*. When light rays are incident on a mirror, the rays are reflected. When light rays pass from one medium to another, the speed of light is changed, with the result that the light rays change direction. These two phenomena are described by the *law of reflection* and *law of refraction*, respectively. Using these principles, the effects that mirrors and thin lenses have on the path of light rays may be understood and measured.

The Law of Reflection
Consider a light ray incident on a plane mirror, as shown in Figure 1. The dashed reference line perpendicular to the surface of the mirror is called the *normal*. The *incident* and *reflected* light
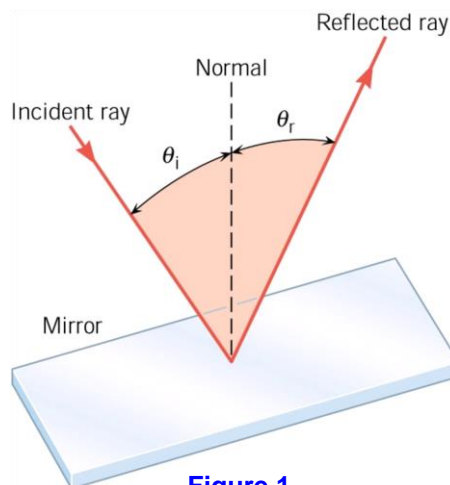

Figure 1

rays are measured with respect to the normal by the *angle of incidence*, θ_i, and *angle of reflection*, θ_r.

The law of reflection states that these two angles are equal:

> **Law of Reflection:** The angle of incidence equals the angle of reflection, $\theta_i = \theta_r$.

The Law of Refraction

Consider a light ray incident upon an air-water interface, as shown in Figure 2. The result is a reflected ray and a *refracted* ray. The incident and refracted rays are measured with respect to the normal by the angle of incidence, θ_1, and the *angle of refraction*, θ_2. The reflected ray is
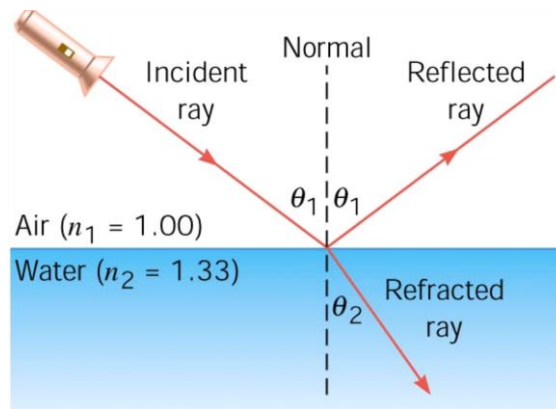

Figure 2

governed by the law of reflection. As the ray passes through the interface, the speed of light is changed. The result is that the ray changes direction—**the ray is refracted**. In vacuum, the speed of light is $c = 3.00 \times 10^8$ m/s. In any other optical medium, the speed of light is less than c. The *index of refraction* for each medium is defined as the ratio of the speed of light in vacuum to the speed of light in that medium:

$$n = \frac{c}{v}. \tag{1}$$

The speed of light in air is approximately equal to that in vacuum, so $n_1 \approx 1$ in Fig. 2. In water, the speed of light is less than that in vacuum. The index of refraction for water is about 1.33, so $n_2 = 1.33$ in Fig. 2. In 1621, Dutch astronomer and mathematician Willebrord van Roijen Snell derived a relationship between the angle of incidence and angle of refraction, which has since come to be known as *Snell's Law*:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2. \tag{2}$$

The law of refraction may be stated as follows:

> **Law of Refraction:** The incident and refracted rays lie in the same plane, and the angle of incidence and angle of refraction are related by Snell's law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$.

Concave and Convex Mirrors

The law of reflection may be used to describe the behavior of light rays reflected from *concave* and *convex* mirrors. Figure 3 shows the distinction between (a) concave and (b) convex mirrors. Each mirror is of circular cross-section, with *center of curvature* at point *C*. The *radius of*
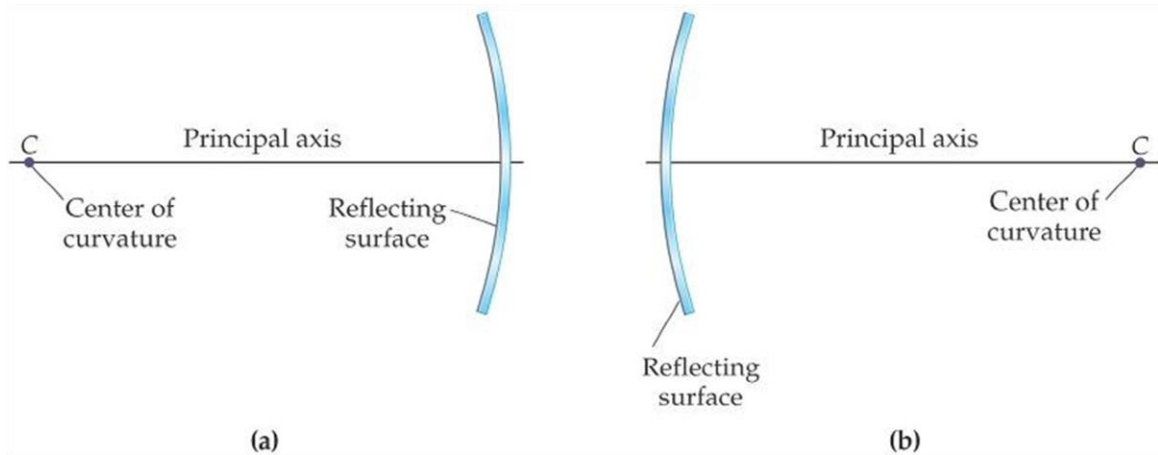

Figure 3

curvature is the distance from *C* to the mirror. The concave mirror has its center of curvature on the same side as the reflecting surface while the convex mirror has its center of curvature on the side opposite the reflecting surface. The *principal axis* is defined as a straight line passing through the center of curvature and intersecting the mirror perpendicular to its center.

Consider light rays, parallel to the principal axis, reflecting from a concave mirror, as shown in Figure 4. Each ray is governed by the law of reflection. For example, the topmost ray is incident at angle θ measured with respect to a normal at the point of incidence and reflected by angle θ
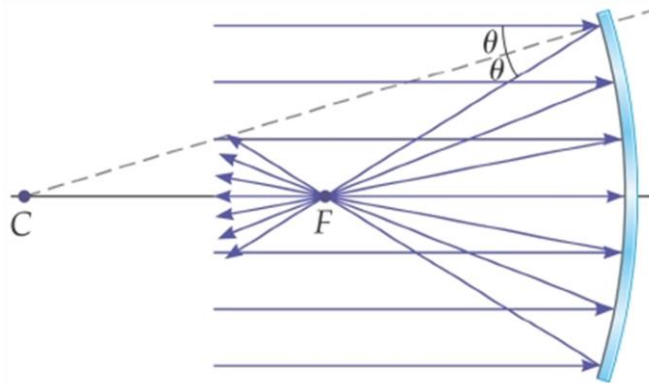

Figure 4

measured from the same normal. Each parallel incident ray may be analyzed in the same manner. The net result is that all *paraxial rays* – rays very near and parallel to the principal axis – arrive at a single point upon reflection: **Paraxial rays incident on a concave mirror converge at the *focal point F* upon reflection**. The distance from the focal point to the mirror is the magnitude of the *focal length*. In this case, the focal point is on the same side as the reflecting surface so that the focal length is positive and equal to:

$$f = +\frac{R}{2}. \tag{3}$$

Application of the law of reflection to each of several paraxial rays incident upon a convex mirror is shown in Figure 5. The net result is that the reflected rays diverge, appearing to
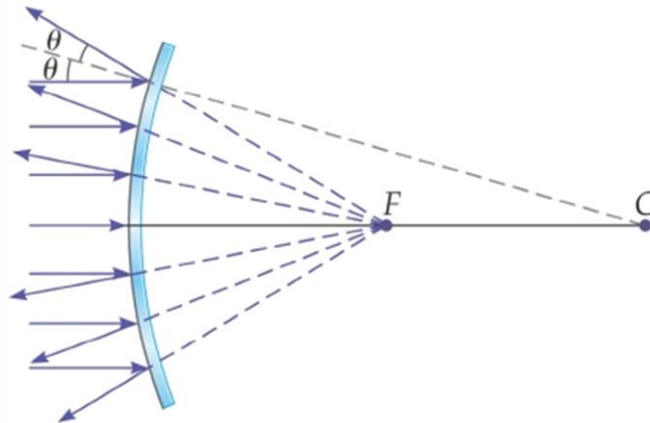

Figure 5

emanate from a single point behind the mirror: **Paraxial rays incident on a convex mirror appear to diverge from the focal point F upon reflection**. In this case, the focal point is on the side opposite the reflecting surface so that the focal length is negative and equal to:

$$f = -\frac{R}{2}. \tag{4}$$

Convex and Concave Thin Lenses
The law of refraction may be used to describe the behavior of light rays passing through *convex* (converging) and *concave* (diverging) lenses. Rays passing through a thin lens are refracted upon entering the lens at the air-lens interface and refracted again upon exiting the lens at the
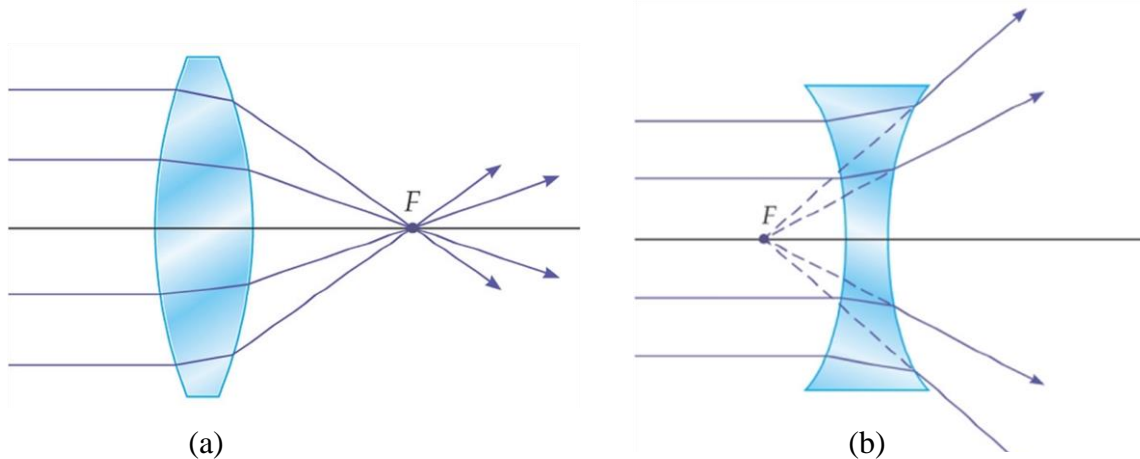

(a)   (b)

Figure 6

lens-air interface. Rays passing through a convex lens are refracted *toward* the principal axis upon entering the lens and once again *toward* the principal axis upon exiting the lens, as shown in Figure 6(a): **Paraxial rays passing through a thin convex lens converge at the focal point F**. Rays passing through a concave lens are refracted *away* from the principal axis upon entering the lens and once again *away* from the principal axis upon exiting the lens, as shown in Figure

6(b): **Paraxial rays passing through a thin concave lens appear to diverge from the focal point _F_.**

PROCEDURE

PART I: Reflection, Mirrors, and Focal Length Measurements

Section A: Reflection from a Plane Mirror

1. Rotate the dial on the front of the light source to select **one** ray of light.

2. Place the mirror on a blank sheet of paper and reflect the single ray from the _flat_ side of the mirror. Hint: larger angles of reflection work best.

3. While one group member holds the mirror in place, trace the interface of the mirror (the flat side where the reflection occurs). Trace the incident ray and the reflected ray as follows:

   - Make one dot at the point of incidence—right where the light ray is reflected from the mirror.
   - Make several dots along the incident ray (in the center of the ray) and several dots along the reflected ray.
   - Remove the light ray and the mirror. Use a ruler to draw the incident and reflected rays. Use arrows to show the direction the light is traveling.
   - Label the interface, incident ray, and reflected ray.

4. Using a protractor, draw a dashed line indicating the normal to the mirror. Measure the angles of incidence and reflection. Record these angles in Table A _and_ on the drawing.

5. Repeat these steps twice more on the same page so that you have tracings for three _different_ reflections. Change the angle each time.

   Important: Include all your drawings with your lab report. If lab members are turning in individual lab reports, you may need to make photocopies. Consult your instructor for specific instructions.

Section B1: Reflection from a Concave Mirror

1. Rotate the dial on the front of the light source to select **five** rays of light.

2. On a clean sheet of paper, use the ruler to draw a single straight line (at least 8 cm long).

3. Position the light source so that the center ray follows the line you just drew. Place the mirror on the paper so that the **concave** side of the mirror faces the light source. The five rays should reflect back in a way similar to that shown in Figure 4. The reflected light rays should all meet a one point, the focal point, which should be along the centerline you drew on the page.

4. While one group member holds the mirror in place, trace the interface (curved side of the mirror.) Trace the rays as follows:

   - Make a dot at each of the five points of incidence (the place where each ray reflects from the mirror).
   - Make a dot at the place where the reflected rays meet (the focal point).

- Make several dots along each incident ray.
- Remove the mirror and light source and use a ruler to trace all the rays.
- Label the interface. Label the focal point, *f*.

5. Measure the distance along the middle ray from the point of incidence to the focal point. Record this focal length on the drawing and on the data sheet. (Be sure to include the correct sign.)

6. Compute and record the radius of curvature of your mirror.

Section B2: Reflection from a Convex Mirror

1. Continue using **five** rays from the light source.
2. On a blank sheet of paper, use the ruler to draw a straight line (about 20 cm long).
3. Position the light source so that the center ray follows the line you just drew. Place the mirror on the paper so that the **convex** side of the mirror faces the ray box. The five rays should reflect outward, as in Figure 5. You will need room to trace these lines back, so make sure there is about 10 cm *behind* your mirror.
4. While one group member holds the mirror in place, trace the interface (curved side of the mirror.) Trace the rays as follows:
    - Make a dot at each of the five points of incidence (the place where each ray reflects from the mirror).
    - Make several dots along each *reflected* ray. (The rays spread out, so make the dots near the center of each ray.)
    - Don't trace the incident rays.
    - Remove the mirror and light source and use a ruler to trace the reflected rays.
    - Using your ruler, extend each reflected ray behind the mirror so that it crosses the principal axis.
    - These extended (virtual) rays may not all meet in the same place. Do your best to choose a center of interception of the virtual rays. Put a dot here and label it as the focal point, *f*.

5. Measure the distance along the middle virtual ray from point of incidence to the focal point. Record this focal length on the drawing and on your data sheet. (Be sure to include the correct sign.)

6. Compute and record the radius of curvature of the mirror.

7. Compare the radii of curvature of your two mirrors by computing a percent difference.

PART II: Refraction, Thin Lenses and Focal Length Measurements

Section C1: Thin Convex Lens

1. Continue using **five** rays from the light source.
2. On a blank sheet of paper, use the ruler to draw a straight line about 30 cm long.
3. Place the thin **convex** lens on the line close to the light source. Adjust the lens so that it is centered and not tilted. The middle ray should pass undeflected through the lens. The focal point should be on the central line you drew.

4. While holding the lens in place, trace around the perimeter of the lens.

5. Mark the incident rays by placing dots at the points of incidence and several dots along each ray. Mark the refracted rays by placing dots where the rays leave the lens and a dot where the refracted rays intersect (the focal point). Note: if the five rays don't meet at one location, choose the best center you can. Label this focal point "f."

6. Remove the lens and the light source and trace the incident and refracted rays.

7. Mark the center of the lens and measure the focal length from the center of the lens to the focal point. Record this focal length on your drawing and on your data sheet. (Be sure to include the correct sign.)

Section C2: Thin Concave Lens

1. Continue using **five** rays from the light source.

2. On a blank sheet of paper, use the ruler to draw a straight line about 30 cm long.

3. Place the thin **concave** lens on the line. Adjust the lens so that it is centered and not tilted. The middle ray should pass undeflected through the lens. The rays should refract outward, as in Figure 6b.

4. You will have to trace virtual rays back to where they intersect. You need to make sure you have enough room for this. If your lens has a long focal length, you will need to put it a large distance (as much as 20 cm) away from the light source.

5. WARNING: you may see a set of reflected rays that intersect (on the side of the lens nearest the light source.) **DON'T TRACE THESE**. You are looking for *refracted* rays.

6. While holding the lens in place, trace around the perimeter of the lens.

7. Don't mark the incident rays, as they will clutter the drawing. Mark the refracted rays by placing a dot at the point where each ray emerges from the lens and several dots along each ray.

8. Remove the lens and the light source and trace the refracted rays. Use the ruler to extend these rays back through the lens. Use dashed lines to mark these virtual rays. Estimate the point where the virtual rays cross. Mark this focal point and label it "f."

9. Mark the center of the lens and measure the focal length from the center of the lens to the focal point. Record this focal length on your drawing and on your data sheet. (Be sure to include the correct sign.)

PART III: Measurement of the Index of Refraction

Design a short, simple experiment to measure the index of refraction of a prism using a single light ray. Carry out this experiment and determine the index of refraction of the acrylic prism included in the Optics Kit. Record the value of the index of refraction on the data sheet. On a separate sheet of paper, give a short summary of the experiment, including the following elements. Use only one page if possible.

- Title this page: **Measurement of the Index of Refraction of a Prism**. Write the names of all lab group members directly below this title.

- Give a short description of how the index of refraction was measured, the equipment used, physical principles, and formulas. A *very* short description is sufficient as long as it is written in complete, grammatically correct sentences.

- Attach your drawing showing the prism and ray tracing. Be sure it is properly labeled and has measurements marked on the page.

- Organize and tabulate any data collected.

- Show any calculations you perform using your data.

- Write a short conclusion stating the measured value of the index of refraction. A *very* short conclusion is sufficient as long as it is written in complete, grammatically correct sentences.

Record your value for index of refraction of acrylic on the data sheet and compare this to the expected value of 1.5 by computing a percent error.

Name: _____ Section: _____ Group #: _____

ID: _____ Date: _____

DATA SHEET
PART I: Reflection, Mirrors, and Focal Length Measurements
Section A: Reflection from a Plane Mirror

Table A

	θ_i	θ_r	percent error
trial1			
trial 2			
trial 3			

percent error = $\left|\frac{\theta_i - \theta_r}{\theta_i}\right| \times 100\%$

Section B1: Reflection from a Concave Mirror

Focal Length of the Concave Mirror: f_{B1}= _____

Radius of Curvature of the Concave Mirror: R_{B1}= _____

Section B2: Reflection from a Convex Mirror

Focal Length of the Convex Mirror: f_{B2}= _____

Radius of Curvature of the Convex Mirror: R_{B2}= _____

percent difference = $\left|\frac{R_{B1} - R_{B2}}{average}\right| \times 100\%$ = _____

PART II: Refraction, Thin Lenses and Focal Length Measurements
Section C1: Thin Convex Lens

      Focal Length of the Thin Convex Lens: $f_{C1}=$ _____

Section C2: Thin Concave Lens

      Focal Length of the Thin Concave Lens: $f_{C2}=$ _____

PART III: Measurement of the Index of Refraction

      Index of Refraction of the Prism: $n=$ _____

      percent error $= \left| \frac{1.5-n_{meas}}{1.5} \right| \times 100\%$ = _____

Questions

1. Given that the index of refraction of water is $n = 1.33$, calculate the speed of light in water.
   Give your answer to three significant figures.

2. Do the rays reflected from the plane mirror obey the Law of Reflection? Explain.

APPENDIX A
The Resistor Color Code

The resistor color code is used to indicate the resistance of a resistor by means of a series of colored bands printed on the body of the resistor, as shown in Fig. A-1.

Figure A-1

Each color stands for a number, as shown in Table A-1.

Table A-1

| Color	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Because resistors cannot be made with arbitrary precision, the actual values of resistance in any given "batch" of resistors supplied by the manufacturer vary over some range. To specify the range within which the actual value of resistance for a given resistor will fall, the manufacturer indicates the *tolerance* by a colored band (the rightmost band on the resistor in Fig. A-1). Colors used to indicate common tolerances are shown in Table A-2.

Table A-2

Color	Tolerance
Brown	1%
Gold	5%
Silver	10%

For example, a gold band indicates that the actual value of resistance will fall within $\pm 5\%$ of the value given by the colored bands on the resistor.

One color-code system in common use today utilizes a total of 4 bands. The first two bands are significant figures, the third is a power-of-ten multiplier, and the fourth is the tolerance. An example of this system is shown in Fig. A-2.

Figure A-2

red	yellow	brown	gold
2	4	$\times\,10^1$	

$$240\ \Omega \qquad \pm\quad 5\%$$
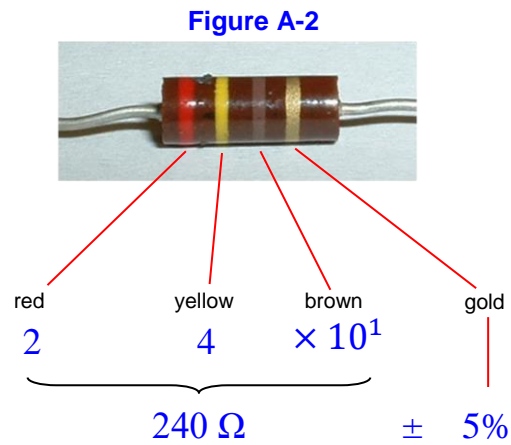
Note that there is no implied decimal point between the two significant figures. That is, the correct way to read the above resistance is $24 \times 10^1\ \Omega = 240\ \Omega$, **not** $2.4 \times 10^1\ \Omega = 24\ \Omega.$

APPENDIX B
Using the Multimeter

Figure B-1 below shows the multimeter you will use in this and several other experiments in this course. The meter should include a pair of *test leads* (not shown). The multimeter can be used as an ammeter, a voltmeter, or an ohmmeter.
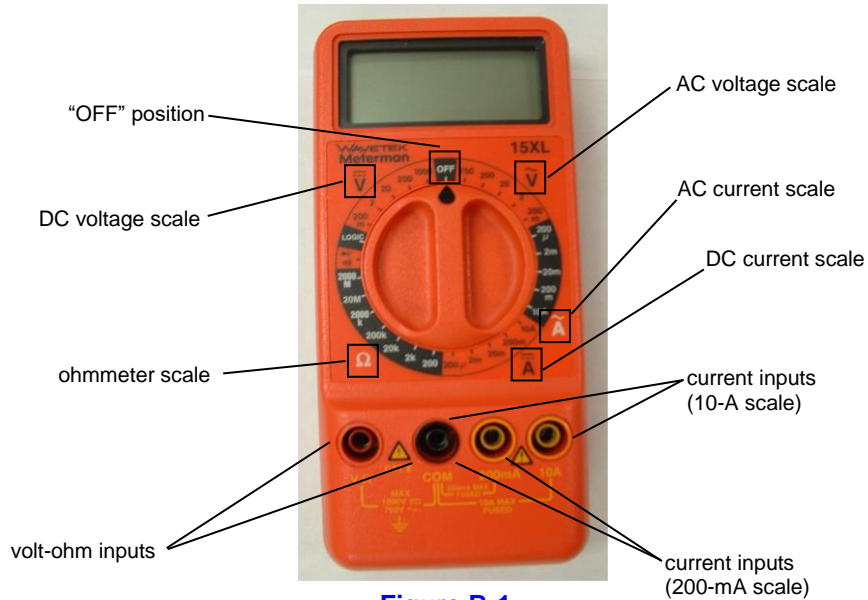

Figure B-1

General Comments

- Note the "OFF" position of the rotary switch. To avoid running down the battery unnecessarily, **always return the rotary switch to the "OFF" position when you finish using the meter!**

- On the current, voltage, and resistance scales on the meter, the letter "*m*" stands for "*milli-*", "*k*" stands for "*kilo-*", and "μ" stands for "*micro-*". If you select, for example, the "200m" DC voltage scale, the meter will display the measured voltage in *millivolts*.

- No matter whether you are measuring current, voltage, or resistance, if you ever see the readout shown in Fig. B-2, it means that the value you are trying to measure is *out of range*. Turn the knob to successively higher range settings until the out-of-range indicator disappears.

Figure B-2

Measuring Current: Using the Multimeter as an Ammeter

Remember that the internal resistance of any good ammeter is *very small* (i.e., close to *zero ohms*). For this reason, to use the multimeter as an ammeter, you must **always** put the ammeter in *series* with the component through which you want to measure the current. (If you put the meter *in parallel* with the component you're trying to measure the current through, you will have effectively *shorted out* that component!) Fig. B-3 shows correct and incorrect ways to measure the current through a resistor.
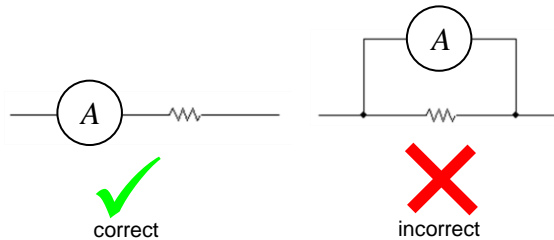

correct   incorrect

Figure B-3

To use the multimeter as an ammeter, you connect the test leads to the current inputs. If the current you wish to measure is in excess of 200 mA, you will need to use the 10-A inputs and select the 10-A range on the DC or AC current scale. If the current you wish to measure is not greater than 200 mA, use the 200 mA inputs.

To measure DC currents, turn the knob to one of the ranges on the DC scale. When you want to measure AC currents, use the AC scale. When in the AC mode, the multimeter measures *root-mean-square* (*rms*) voltages and currents.

Measuring Voltage: Using the Multimeter as a Voltmeter

Remember that the internal resistance of any good voltmeter is *very large* (at least 10 MΩ). For this reason, you **always** connect the voltmeter *in parallel* with the component you wish to measure the voltage across. (If you put the voltmeter in *series* with this component, you'll drastically decrease the current through it!) Fig. B-4 shows correct and incorrect ways to measure the voltage across a resistor.
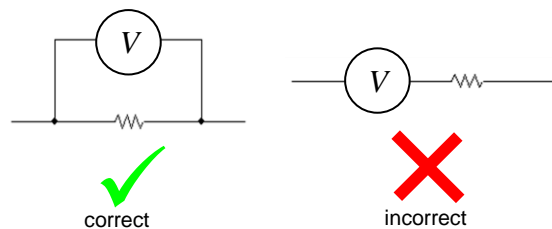

correct   incorrect

Figure B-4

To use the multimeter as a voltmeter, you connect the test leads to the volt-ohm (V-Ω) inputs. To measure DC voltages, turn the knob to one of the ranges on the DC scale. When you want to measure AC voltages, use the AC scale.

Measuring Resistance: Using the Multimeter as an Ohmmeter

To measure resistances, connect the test leads to the volt-ohm inputs. The multimeter measures resistances by applying a known voltage between the two test leads and measuring the current that flows (*into* the *red* input, through the meter, and back out of the *black* input). If you try to use the multimeter to measure resistances *while those resistances are connected to voltage sources other than the meter itself, such as batteries*, the ohmmeter will read a voltage between its two terminals which is not just the voltage that *it put there*. Thus, the ohmmeter will give an erroneous reading. (It's as though the meter were effectively "fooled" into believing that the resistance that's "out there" between its two terminals is not what it *really* is.) For this reason, when you measure the resistance of a component, **you should always disconnect the component from any voltage sources before you measure the resistance.** You then connect the multimeter **across** the component whose resistance you want to measure, as shown in Fig. B-5.
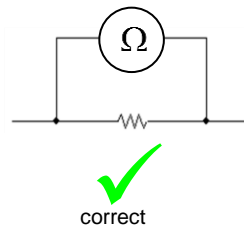

correct

Figure B-5