Physics 202 Lab Manual
Electricity, Magnetism and Light

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August 30, 2022

Contents

Introduction

Physics is an experimental science. In this laboratory, you will fight against experimental errors, find ways to minimize them, and (we hope) come to appreciate the need for clear and accurate record-keeping.

Physics is also a social activity. Discuss with your lab partners the purpose of each piece of apparatus; cooperate to choose who does what; critique the data as it is taken (is it as expected?); calculate independently, then compare results to check each others' work; debate the reliability of the results, and what may fairly be concluded from them.

Keep clear and accurate records, and record fair conclusions, in a laboratory notebook:

1. *Heading of the Experiment:*
   Copy from the manual the number and name of the experiment.
   Include both the current date and the name(s) of your partner(s).

2. *Original data:*
   "Original data" are the actual readings you have taken. Record them directly into your notebook as they are gathered. All partners should record all data: in case of doubt, the partners' lab notebooks can be compared to each other.
   Arrange data in tabular form when appropriate. Introduce each table with a phrase or sentence (so that you, or someone else, can make sense of it later).

3. *Housekeeping deletions:*
   Every hour or so, draw a box around any erroneous or unnecessary material and hatch three or four parallel diagonal lines across this box. Write a note explaining to yourself what was wrong *(sometimes, it turns out it wasn't wrong...).*

4. *Sketches and remarks:*
   Make simple, diagrammatic (rather than pictorial) sketches of apparatus.
   When a useful result occurs at any stage, describe it with at least a word or phrase.

5. *Graphs:*
   Affix a hand-drawn graph on graph paper with transparent tape; affix a computer-generated graph with transparent tape; or mark out and plot a simple graph directly in your notebook.
   Show points as dots, circles, or crosses, i.e., ·, ○, or ×.
   Show trends by drawing a smooth curve (that may actually miss most of the points) rather than connecting the points with lines.

6. *Units, coordinate labels:*
   Whenever you write down a physical quantity, *always* write down its units.
   Whenever you make a graph, always label the *abscissa* (horizontal coordinate) and *ordinate* (vertical coordinate), so that the reader (who might be yourself at a later time) knows what has been graphed.

7. *Final data, results and conclusions:*
   Write a neat summary of data and results at the end of each experiment. Any conclusions must be faithful to the data. Use phrases such as "the discrepancy between our measurements and the theoretical prediction was larger than the uncertainty in our measurements."

Errors and Uncertainties

All measurements are to some degree uncertain. It is good scientific practice to **include an estimate of the uncertainty of every measurement you make**. The uncertainty of a single measurement–such as, for example, the diameter of a cylinder–comes from multiple sources, which fall into two categories: *random uncertainties* and *systematic errors*:

- There may be **actual variations** of the quantity being measured, e.g. the diameter of a cylinder may actually be different in different places. This random uncertainty can be reduced by making measurements at different places and taking the average. The standard deviation of the measurements (see below) is a measure of the uncertainty.

- The **measuring device** itself may be in error. The systematic error thus introduced will not lie equally on both sides of the true value, so averaging a large number of readings is no help. To reduce such errors, we calibrate the measuring device. In the case of the micrometer caliper, for example, we measure the zero error (the reading when the jaws are closed) and the readings on selected precision gauges that are about as large as the cylinder to be measured.

- The **measuring technique** may be a source of systematic error. When used to measure the diameter of a cylinder, the micrometer will always measure the largest diameter between its jaws; hence if there are small bumps or depressions on the cylinder, the average of a large number of measurements will not give the true average diameter but a quantity somewhat larger. This error can be reduced by making the jaws of the caliper smaller in cross section.

- The measuring technique may also be another source of random uncertainty. For example, the reading of the micrometer caliper may vary because one can't close it with the same force every time, and one's estimate of the fraction of the smallest division varies from trial to trial. Making multiple measurements also reduces the uncertainty from this source

Characterization of Uncertainties

The experimenter cannot immediately determine the cause of the variation of a set of measurements. A simpler task is to characterize this variation.

Consider the data below. Column 1 represents 10 readings of the diameter of a cylinder taken at one place, so that variations in the cylinder do not come into consideration.

Measurements	Deviation from Mean	
9.943 mm	0.0003	mm
9.942	- 0.0007	
9.944	0.0013	
9.941	- 0.0017	
9.943	0.0003	
9.943	0.0003	
9.945	0.0023	
9.943	0.0003	
9.941	- 0.0017	
9.942	- 0.0007	

How should one state the results of these measurements in a scientific fashion?

Expressed algebraically, the **mean** $\bar{x}$ of a set of n measurements $\{x_i\}$ is $\bar{x} = \sum x_i / n$. The mean of the 10 readings above turns out to be 9.9427 mm.

Column 2 gives each reading's deviation from the mean. The **standard deviation** σ (also known as the "root mean square deviation") is defined as

$$\sigma = \text{standard deviation} = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

The standard deviation of the above 10 measurements is 1.225×10^{-3}.

Note that if you make one measurement of some quantity x, then $n = 1$ and $\bar{x} = x_1$ in the above equation: the standard deviation of your measurement is $\sqrt{0/0}$, which is undefined. You don't know how reliable your measurement is.

Assuming you make more than one measurement, σ tells you the typical deviation from the mean you will find for an individual measurement. It depends on your experimental method. If you make more measurements, σ will not change much.
However, the more measurements you make, the more accurately you can expect to know the value of the mean. The uncertainty of the value of the mean is called **the standard deviation of the mean** σ_μ, and in general it is less than σ:

$$\sigma_\mu = \text{standard deviation of the mean} = \frac{\sigma}{\sqrt{n}} = \frac{1}{\sqrt{n}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

The standard deviation of the mean of the above 10 measurements is 3.96×10^{-4}.

When you take more measurements in order to minimize σ_μ, you are "gathering statistics".

One states one's results as **mean ± standard deviation of the mean**. From the data above, the diameter of the cylinder was measured to be 9.9427 ± 0.0004 mm.

Error Distribution and Error Bars

For many types of measurement one may assume that the error distribution is "normal": the probability of a given error ϵ is proportional to $e^{-\epsilon^2}$. If the error distribution is normal and the number of measurements is large, 68% of the measurements will lie closer than σ to the true value.
The purpose of the error bars shown on a graph in a technical report is as follows: if the reader attempts to reproduce the results in the graph using the procedure described in the report, the reader should expect a 50% chance the results will fall within the range indicated by the error bars.

If the error distribution is normal, the error bars should be of length $\pm 0.6745\sigma$.

Propagation of Uncertainties

Let $R = f(x, y, z)$ depend on measurements of three different quantities x, y, and z. The uncertainty ΔR in R which results from an uncertainty Δx in the measurement of x is

$$\Delta R = \frac{\partial f}{\partial x}\Delta x \ ,$$

and the fractional uncertainty in R is

$$\frac{\Delta R}{R} = \frac{\frac{\partial f}{\partial x}}{f}\Delta x \ .$$

In many experimental situations, the errors are uncorrelated and normally distributed. In this case the uncertainties add in quadrature (the square root of the sum of the squares):

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\frac{\partial f}{\partial x}}{f}\Delta x\right)^2 + \left(\frac{\frac{\partial f}{\partial y}}{f}\Delta y\right)^2 + \left(\frac{\frac{\partial f}{\partial z}}{f}\Delta z\right)^2} \ .$$

Δ denotes the uncertainty in a quantity, and σ refers to the standard deviation.
Some examples:

A) $R = x + y$. If the uncertainties in x and y each have a normal distribution and are independent, they combine in quadrature:

$$\Delta R = \sqrt{\Delta x^2 + \Delta y^2} \ .$$

Note that if $R = x - y$, then $\Delta R/R$ can become very large if x is nearly equal to y. Hence avoid, if possible, designing an experiment where one measures two large quantities and takes their difference to obtain the desired quantity.
   B) $R = xy$. The fractional uncertainties combine in quadrature:

$$\frac{\Delta R}{R} = \sqrt{(\frac{\Delta x}{x})^2 + (\frac{\Delta y}{y})^2} \ .$$

Note the same result occurs for $R = x/y$.
   C) Consider the density ρ of a solid cylinder (Exp. M-201b):

$$\rho = \frac{m}{\pi r^2 L}$$

where m = mass, r = radius, L = length, are the three measured quantities. Then

$$\frac{\partial \rho}{\partial m} = \frac{1}{\pi r^2 L} \qquad \frac{\partial \rho}{\partial r} = \frac{-2m}{\pi r^3 L} \qquad \frac{\partial \rho}{\partial L} = \frac{-m}{\pi r^2 L^2} \ .$$

If the errors have normal distribution and are uncorrelated, then

$$\frac{\Delta \rho}{\rho} = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(2\frac{\Delta r}{r}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

   D) Area of a circle: $A = \pi d^2/4$: $\Delta A/A = 2\Delta d/d$.

Significant Figures

Suppose you measure the diameter of a circular disk to be 24.326 ± 0.003 mm and want to compute its area $A = \pi d^2/4$. Evidently $A = 464.7627...$ mm^2, but how many digits are significant?

The fractional uncertainty in d is $\Delta d/d = \frac{0.003}{24.326} = 1.2 \times 10^{-4}$. From example D) on the last page, this gives $\Delta A/A = 2.4 \times 10^{-4}$, so the uncertainty in A is $\Delta A = .11$ mm^2.

This tells us that only the first five digits are significant, so A should be reported as

$$A = \pi d^2/4 = 464.77 \pm 0.11 \text{ mm}^2$$

A good rule is to use one more digit in constants than is available in your measurements, and to save one more digit in computations than the number of significant figures in the data. When you use a calculator you usually get many more digits than you need. Therefore **at the end**, be sure to **round off** the final answer to display the correct number of **significant figures.**

SAMPLE QUESTIONS

1. You measure $d = 1.0 \pm 0.1$ cm and $s = 1.0 \pm 0.1$ cm. What is the uncertainty in $r = d + s$?

   (a) 0.1 cm
   (b) 0.14 cm
   (c) 0.2 cm

2. You measure r with a percentage uncertainty of 1%. What is the percentage uncertainty in $A = \pi r^2$?

   (a) 1%
   (b) 1.4%
   (c) 2%

3. What happens to σ, the standard deviation, as you make more and more measurements? What happens to σ_μ, the standard deviation of the mean?

   (a) They both remain same
   (b) They both decrease
   (c) σ increases and σ_μ decreases
   (d) σ approaches a constant and σ_μ decreases

4. You measure $m_1 = 115.34 \pm 0.01$ g and $m_2 = 1.0 \pm 0.1$ kg, in order to find $m_3 = m_1 + m_2$. How should you report m_3?

   (a) 1.11534 ± 0.00001 kg
   (b) 1.11534 ± 0.1 kg
   (c) 1.1 ± 0.1 kg

Part I
Electricity and Magnetism

E-201 Electrostatics

Objectives:

To investigate charging by rubbing (triboelectricity); charging by conduction; and charging by induction.

Preliminary Questions:

1. What is the difference between a "conductor" and an "insulator"?

2. Write down the equation for the electric field caused by a point charge:

3. Indicate whether the following statements are true or false:
   opposite charges attract, like charges repel
   opposite charges repel, like charges attract

4. More precisely, the equation for the force between two point charges is:

5. A conductor is brought into contact with ground. Indicate which of the following situations are possible:
   negative charge flows from ground to conductor
   negative charge flows from conductor to ground
   no charge flows

6. Write down two occasions on which you have encountered static electricity.

7. You are in a car with the windows rolled up. The frame of the car is made of metal. The car has rubber tires. A thunderstorm develops. Because you are inside the car, you are to some degree protected against injury due to lightning strike. Which of the following is the best explanation for your protection?
   –the fact that you are inside the metal frame, which is a hollow conductor;
   –the fact that you are isolated from ground by the insulating rubber tires.

8. Record the temperature (in °C) and relative humidity (in %) of the lab room.

   If the air is dry, it is comparatively easy to generate static electricity (you may have already noticed this). If the air is damp, it is comparatively difficult.

Experiment I: Charging by Rubbing (Triboelectricity)

Apparatus:

Electrometer; Faraday Cup; Pasco Interface (to provide electrical ground); brass test sphere; silk cloth; ebonite rod (black); rabbit fur; acrylic rod (clear).

When any two objects rub together, electrons move from one to the other. One object ends up with "too many" electrons, the other with "not enough". Depending on the nature of the objects, the number of electrons that move may be very small or very large.
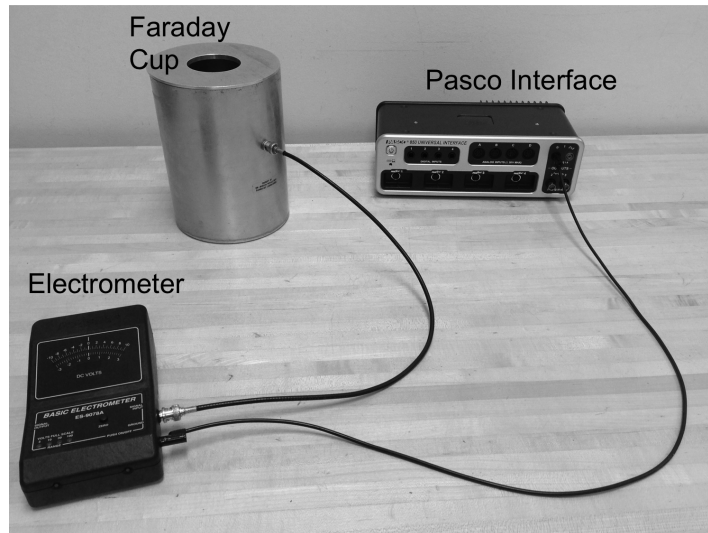
Figure 1: Setup for Experiment 1.

See the "Troubleshooting" section on page 16 if you run into any difficulties.

1. As shown in the picture, connect the SIGNAL INPUT of the electrometer to the Faraday Cup, and connect the GROUND port of the electrometer to the ground input of the Pasco interface. Make sure the Pasco interface is plugged in. If you insert an object with too many/too few electrons into the Faraday Cup WITHOUT TOUCHING THE SIDES OR TOP, the electrometer will read negative/positive.

2. Turn ON the electrometer. Set the electrometer to VOLTS FULL SCALE RANGE of 100. Push the ZERO button to remove any charge on the electrometer. The digits display and meter display should both indicate "0". Call over your TA if they don't. Press the ZERO button any time the electrometer reads something other than zero when nothing is inserted in the Faraday Cup.

3. Rub the silk cloth vigorously against the test sphere, as if you are trying to polish the test sphere. Also try holding the silk up in the air and forcefully hitting the test sphere against it. Insert the test sphere into the Faraday Cup (without touching it). Indicate whether the electrometer becomes positive, becomes negative, or doesn't change (If the electrometer reading doesn't change, call over your TA).

4. Is the reading in accordance with the Triboelectric Series (next page)?

5. Touch the test sphere against the outside of the Faraday Cup.

6. Again insert the test sphere into the Faraday Cup (without touching it), and indicate whether the electrometer becomes positive, becomes negative, or doesn't change.
If the electrometer reading changes, it may be because there is charge on the handle of the test sphere. Clean the handle with soap and water (be careful not to run the handle with a paper towel after cleaning, otherwise it may acquire a charge again) and repeat the previous step. If the electrometer still doesn't read zero, call over your TA.

7. If all went well, the test sphere should have been charged in step 3, but neutral in step 6. What did you do that caused the test sphere to become neutral, and what happened to the extra charge?

Table I: The Triboelectric Series
Various substances ranked from greatest tendency to charge positive when rubbed (hair) to greatest tendency to charge negative when rubbed (teflon)
Hair (most positive)
Rabbit fur
Acrylic (clear plastic)
Hands, skin
Glass
Nylon
Wool
Quartz
Cat Fur
Lead
Silk
Aluminum
Paper
Cotton (neutral)
Steel
Wood
Amber
Ebonite (looks like black plastic)
Nickel, copper
Brass, silver
Gold, platinum
Sulfur
Rayon
Polyester
Styrofoam
Orlon
Saran
Polyurethane
Polyethylene
PVC
Teflon (most negative)

8. Insert the acrylic rod into the Faraday cage. If the electrometer shows charge is present, clean the acrylic rod with soap and water, and verify it is uncharged. If it is still charged, call over your TA.

9. Rub the acrylic rod with the silk.   Does the acrylic rod acquire a positive or negative charge?

10. Repeat step 8, using the ebonite rod.

11. Rub the ebonite rod with the rabbit fur. Does the ebonite rod acquire a positive or negative charge?

12. Are your results from steps 9 and 11 in accordance with the Triboelectric Series (see table at right)?

13. You should be able to find at least one item that you brought with you to lab on the Triboelectric Series. Touch the test sphere to the outside of the Faraday Cup, rub the item you brought against the test sphere (which is made of brass), and insert the test sphere into the Faraday Cup to see what type of charge it has acquired.

    Indicate what item you brought and whether the test sphere charged positive or negative.

    Is this in accordance with the Triboelectric Series?

Experiment II: Charging by Conduction

**Apparatus:** electroscope; acrylic rod; silk cloth; ebonite rod; rabbit fur; Pasco interface.

Figure 2: Electroscope

An electroscope detects the presence, but not the sign, of electric charge. The leaves rise when there is charge on the leaves, and fall when there is no charge (as in the picture above). The leaves and the knob of an electroscope are connected by a conductor.

1. Inspect the leaves on your electroscope; make sure there are two of them, and make sure they are not risen. If they are risen, touch the knob with your finger, and they should fall. If you can't get the leaves to fall, call over your TA.

2. Rub the ebonite rod with the rabbit fur, and touch the ebonite rod to the knob of the electroscope. The leaves should rise (if they don't, call over your TA). According to the Triboelectric Series table, the ebonite rod should be charged negative. Assuming this is true, reproduce the following pictures in your lab notebook, and draw little "−" signs on them to indicate where the electric charges are during this process.
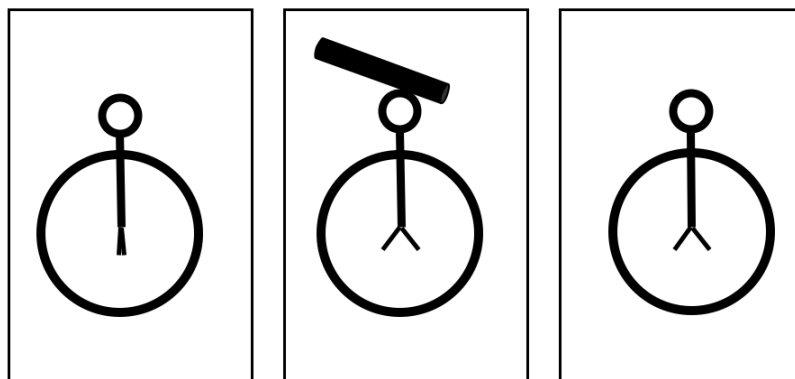
3. Plug a cable into the ground input of the Pasco interface, and touch the other end of the cable to the knob of the electroscope. What happens to the leaves?

4. Reproduce the following pictures in your lab notebook, and draw little "−" signs on them to indicate what happens to the charges on the electroscope during the previous step.
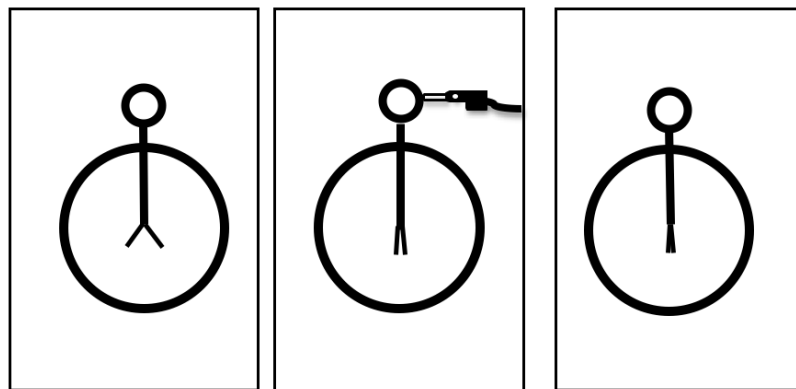
5. Rub the acrylic rod with the silk. According to the Triboelectric Series table, the acrylic rod should charge positive. Touch the acrylic rod to the knob of the electroscope. The leaves should rise. (Note: merely touching the acrylic rod to the knob may not be sufficient to cause charges to transfer. Acrylic seems to be less able to give up its excess charge than ebonite.) Assuming the leaves rise, reproduce the following pictures in your lab notebook, and draw little "+" signs on them to indicate where the charges are during this process.
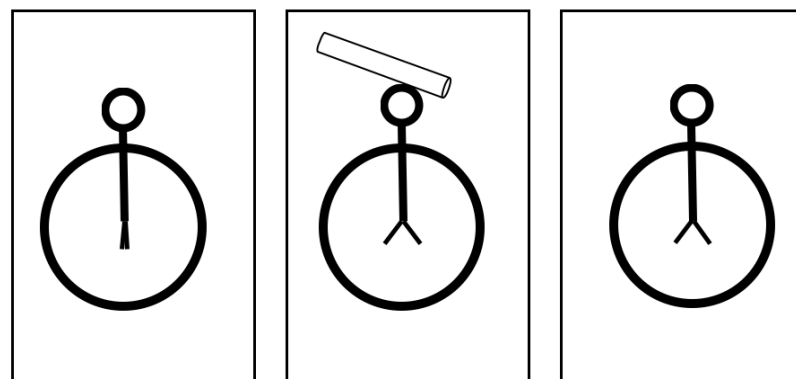
6. If the leaves of an electroscope are risen, is there any way to tell just by looking at the electroscope whether the charge on the leaves is positive or negative?

7. Touch the knob of the electroscope with your finger. What happens to the leaves?

Experiment III: Charging by Induction

Apparatus: electroscope; acrylic rod; silk cloth; ebonite rod; rabbit fur; electrometer; Faraday cup; Pasco interface (to provide electrical ground).

Below is the first of the three experiments we will do related to charging by induction.

1. Rub the ebonite rod with the rabbit fur, and touch the ebonite rod to the knob of the electroscope. This charges the electroscope by conduction, as in Expt. II step 2, and the leaves of the electroscope should now be risen.

2. Rub the acrylic rod on the lab table, which is coated in polyurethane varnish, and bring the acrylic rod near the knob of the electroscope without touching it. What happens to the leaves?

3. Reproduce the following pictures in your lab notebook and draw little "+" and "−" signs on them to show where the charges are.
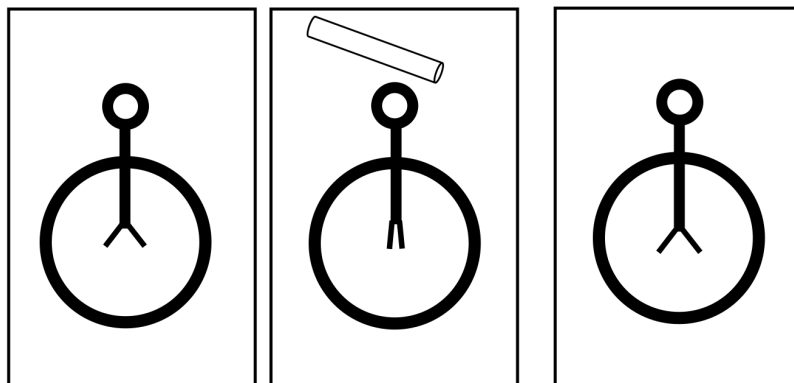

4. The results of steps 1 to 3 allow you to determine that the ebonite rod and the acrylic rod must have charges of opposite sign. Touch the knob of the electroscope with your finger. This should cause all excess charge to depart the electroscope, and the leaves to drop: you have "discharged" the object.

This concludes the first experiment on charging by induction; below is the second.

5. Rub the acrylic rod on the lab table, and bring the acrylic rod near, but not touching the knob on the electroscope. What happens to the leaves?

6. Assuming the acrylic rod is charged positive, reproduce the following pictures in your lab notebook, and draw little + and − signs on them to show where the charges are.
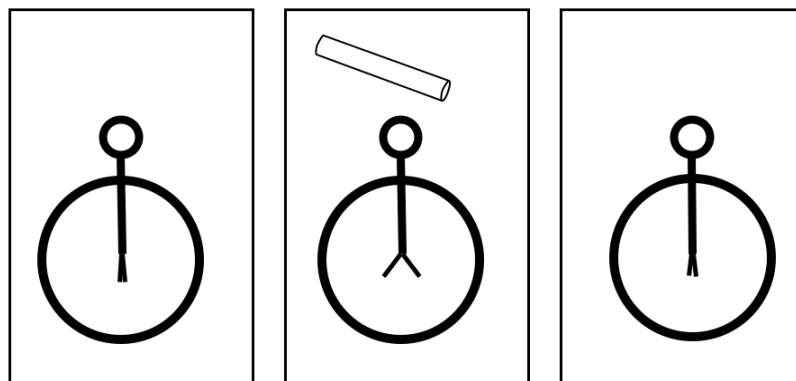
7. The charge on the electroscope is defined as the charge on the leaves plus the charge on the knob. Assuming you did not touch the acrylic rod to the knob, what was the charge on the electroscope in the middle cartoon above?

8. Plug a cable into the ground input of the Pasco interface, and repeat step 5, with one difference: while the acrylic rod is near the knob, touch the knob with your end of the cable, and then remove the cable. Only when the cable is gone should you remove the acrylic rod. Reproduce the following pictures in your lab notebook, and draw little + and − signs on them to show where the charges are.
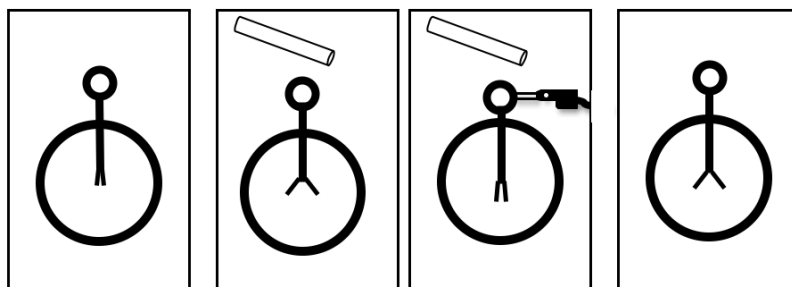
9. What is the sign of the charge that remains on the electroscope?

   This shows how an object can become charged by induction, and concludes the second experiment on charging by induction.

   For the third experiment on charging by induction we'll return to the apparatus shown in the picture associated with Expt. 1, step 1, and use the test sphere to sample, or "test", the charge at different points on a conductor. Make sure the rods, fur, silk, and any other objects which are likely to be charged are moved far away from the Faraday cup.

10. Turn ON the electrometer. Set the electrometer to VOLTS FULL SCALE RANGE of 100. Push the ZERO button to remove any charge on the electrometer. The digits display and meter display should both indicate "0". Call over your TA if they don't.

11. Take one of the big metal spheres, and touch it to the outside of the Faraday Cup. How much charge do you expect to remain on the big metal sphere after this?

12. Choose one person to manipulate the test sphere (we'll call this person TS in the instructions below) and one person to manipulate the ebonite rod and rabbit fur (we'll card this person ER).

13. ER rubs ebonite rod with rabbit fur, and inserts ebonite rod into Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

14. TS touches test sphere to outside of Faraday Cup, and then inserts test sphere into Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

15. ER brings ebonite rod near BUT NOT TOUCHING right side of the big metal sphere, and holds it there while TS completes the next step.

16. TS touches test sphere to the left side of the big metal sphere.

17. TS inserts the test sphere into the Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

18. TS touches the test sphere to the outside of the Faraday Cup, and then inserts the test sphere into the Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

19. ER brings the ebonite rod near BUT NOT TOUCHING the right side of the big metal sphere, and holds it there while TS completes the next step.

20. TS touches the test sphere to the right side of the big metal sphere, as close as possible to the ebonite rod WITHOUT TOUCHING THE EBONITE ROD.

21. TS inserts the test sphere into the Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

22. TS touches the test sphere to the outside of the Faraday Cup, and then inserts the test sphere into the Faraday Cup. Indicate whether the reading on the electrometer is positive, negative, or zero.

23. Based on the results of steps 10-22, indicate on the picture below the charge distributions on the ebonite rod and the big metal sphere.
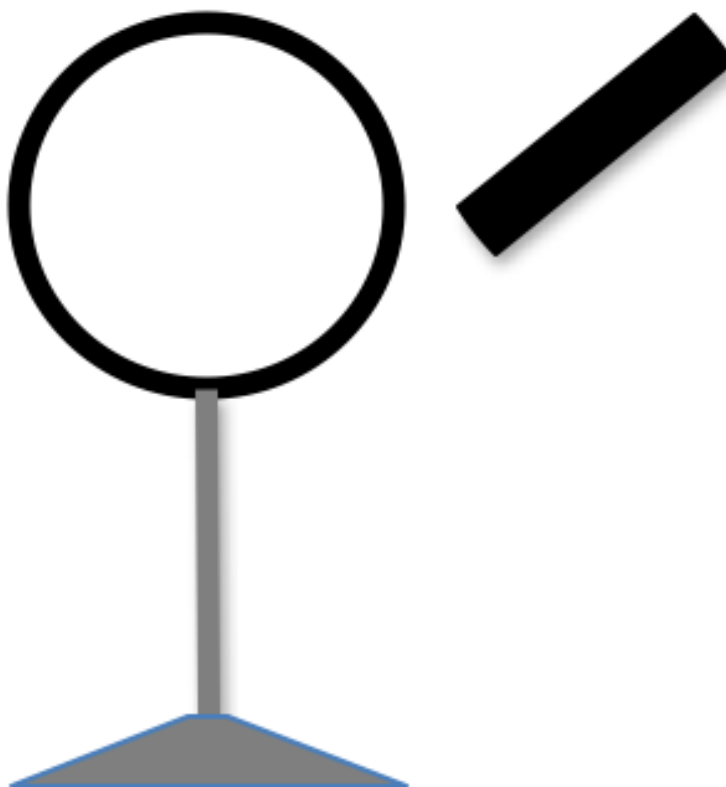
This experiment shows how the charge distribution on an object can be measured, one point at a time. It's important that the test sphere be much smaller than the object of which the charge distribution is measured, because every time the test sphere is touched to the object, some charge is taken away from the object. The smaller the test sphere, the less charge is taken away. A "measurement" that significantly changes what is to be measured is not a good measurement.

Conclusion Questions:

1. Why does touching the electroscope with your hand ground it? Do you end up with a net charge for a noticeable amount of time (longer than a few seconds)? If so, how can we see the effects of this?

2. Is it possible for a person to use an electroscope to differentiate between positive and negative charges? Explain based on your observations.

3. Do only insulators acquire charge by rubbing? Explain.

4. Electrostatics experiments often do not work well in humid weather. Explain why this might be so.

5. In very dry or cold weather, objects such as clothing, table tops, etc. that somehow acquire a charge tend to hold that charge for a long time, i.e. they are slow to discharge. How might this affect the observations in these experiments?

6. Where might you observe the effects of a net charge in your everyday life?

Troubleshooting

1. To remove all charge from the electrometer, press the "Zero" button while the electrometer is connected to earth ground. This connects the electrometer terminals to each other so that any charge flows from/to ground. If the meter does not read within a few percent of zero, notify your instructor.

2. If your clothing or hair has a net charge, the electrometer reading may change if you move around. Hence, during a given measurement, change position as little as possible and ground yourself.

3. In humid air insulators may adsorb enough moisture that charges leak off rapidly. If so, dry all insulators with a heat gun. Their large surface charges may influence nearby unshielded instruments. If so, ask your instructor for help; e.g. use grounded foil to shield against them. Also remove any clinging loose bits of fiber (e.g. silk or rabbit fur) that may disturb results.

4. The fragile leaves of the electroscope may tear if charged too heavily. **Do not disassemble the electroscope** to attempt repair: see your instructor.

5. To remove charges on the glass windows of the electroscope, lightly rub your hands over the windows while grounding your body.

6. When instructed to touch the metal sphere, which is made of aluminum, with the brass test sphere, avoid rubbing the two together. Rubbing may cause inaccurate results. You can see that brass and aluminum both have their specific locations on the triboelectric series. Here, we want to charge by conduction.

7. In humid weather or if there is excess charge on the handle, your test sphere may not hold charge. If this happens you can try cleaning or heating the handle (as described in the next item), or putting the lucite rod into the hollow conductor directly.

8. If you have grounded the test sphere, and yet it still causes the electrometer to deflect when inserted into the Faraday cup, it may be that the insulating handle is charged. Try inserting the handle into the Faraday cup.

9. There are two general methods to discharge an insulator: water and fire. Water: try breathing on the insulator. Perhaps the humidity in your breath will be sufficient to discharge the insulator. If this doesn't work, you could try washing the insulator in soap and water. Fire: A small alcohol lamp may be provided. An open flame is a simple source of both positive and negative ions. The heated air convects these ions upward such that the handle will attract the correct sign to make it neutral. **Hold the insulator at least 10 cm above open flame to avoid heat damage to the handle**. If a flame is not available, a heat gun may work, for the same reason.

10. Avoid unnecessary handling of insulators because handling may impair their insulating capability. (Perspiration is a salt solution which is a conductor.)

11. Always discharge paddles and cup before starting an experiment. To test if an object is charged, put it into the cup and see whether the electrometer deflects.

E-202 Electric Fields

Objectives:

> To develop understanding of the relationship between electric fields and equipotential contours; to physically map both in two dimensions.

Preliminary Questions:

1. Can electric field lines pass through a vacuum? (assume electrostatic equilibrium)

2. Can electric field lines pass through an insulator? (assume electrostatic equilibrium)

3. Can electric field lines pass through a conductor? (assume electrostatic equilibrium)

4. What is the relationship between electric field lines and equipotential surfaces?

5. What is the relationship between the electric field magnitude just outside a conductor, and the charge density on the surface of the conductor?

Apparatus:

> Power supply (18V, 3A Max); Fluke 115 Digital Multimeter (DMM) & test probes; conductive paper with various conducting electrode configurations; field plotting board; carbon paper; white paper; red and black banana cables

Fluke DMM: To use the DMM, choose the DC voltage indicator, $\overline{\overline{\mathbf{V}}}$, from the dial of measurements. Place one probe on the electrode that is grounded and place the other at a different location on the conductive paper. The DMM will now read the difference in electric potential between those two locations. Don't touch the conductive paper–it will compromise your measurement. Pressing harder will not improve your measurement. Note that although the DMM will measure the potential difference between arbitrary points, one probe should always be referenced to ground for the purposes of this lab.

Experiment:

1. Place white paper on the field plotting board, then a piece of carbon paper (black side down). On top of those, place the conductive paper with a dipole electrode configuration (shown in Fig .1).

2. Record the shape of the electrodes (the shiny silver pattern on the conducting paper) on the white paper by tracing them LIGHTLY using a probe tip.

3. Using the power supply, place 18 volts across the terminals of the plotting board (as in Fig. 1). Check the quality of the electrodes you are using with the DMM to make sure there are no appreciable potential differences between various locations within the electrodes. If you find any, ask your TA to find you a new one or fix the silver paint quality.
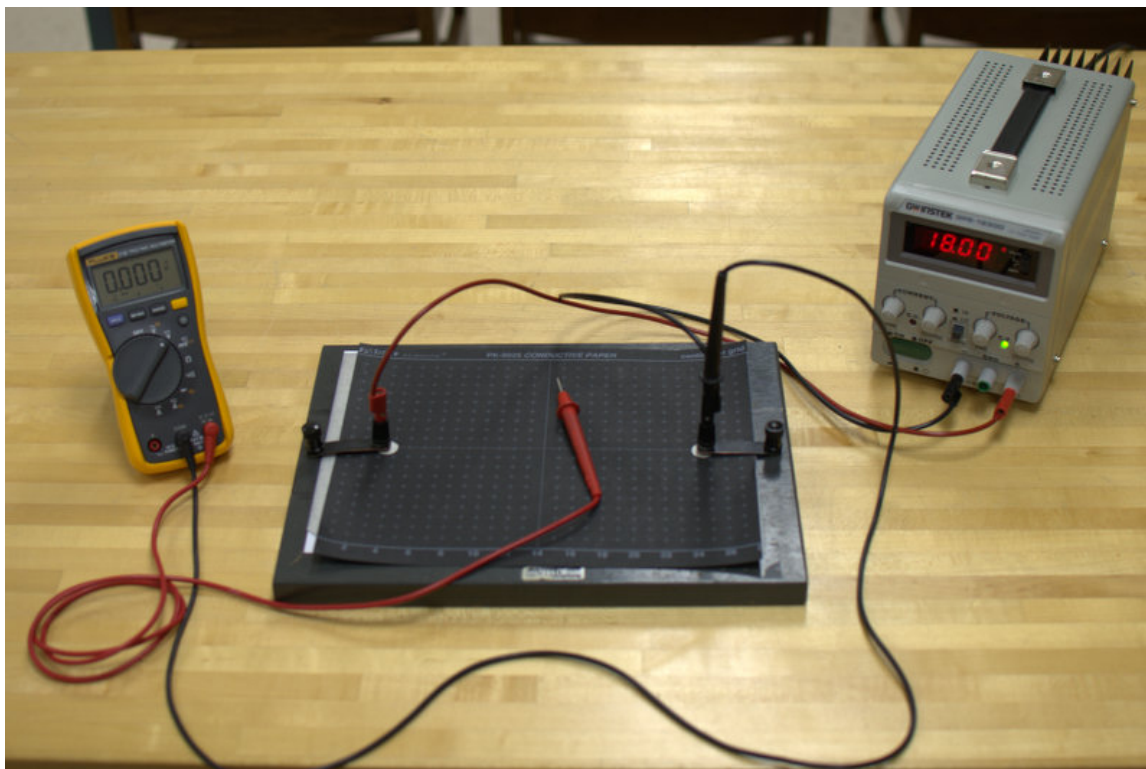
Figure 1: Experimental Setup

4. Map the equipotential line which corresponds to +3 volts by exploring the region of the grounded electrode with one probe while keeping the other probe on the grounded electrode. Make a mark wherever you find a potential of +3V; space the marks out so that you can later draw a smooth line through the marks. Note: the marks only need to be close together when the direction of the equipotential changes rapidly. (If you can't find +3 V, skip it and start with +6 volts instead).

5. Map the +6 V, +9 V, +12 V, +15 V equipotential lines (if you can't find the +15 V equipotential, stop with +12 V). Remove the white paper when completed.

6. In principle, where are the 0 V and 18 V equipotential lines?

7. On the white paper, connect the marks representing points that have the same potential with smooth lines. Now you have an equipotential "map".

8. Repeat steps 1-7 for the two configurations shown in Fig. 2.
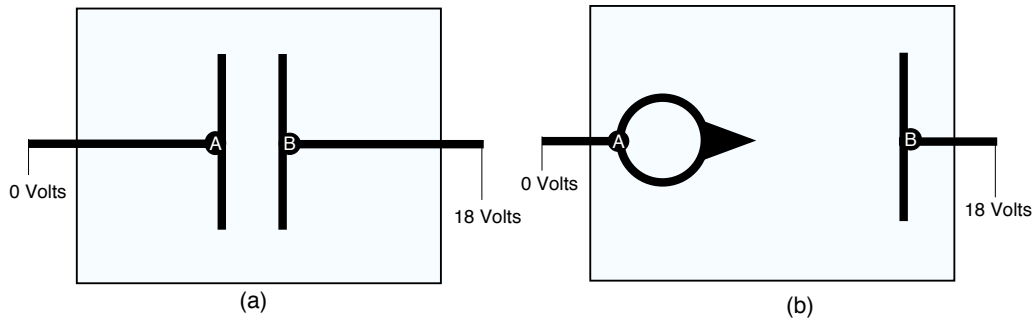
Figure 2: Electrode configurations for (a) parallel plates and (b) a lightning rod.

9. Place the three maps side by side and compare them.

10. In which map is the maximum electric field the largest?

11. We cannot be sure the electrode outlines correspond to 0 V and 18 V equipotentials, because the conductive ink might not be perfect. Thus consider only the 3 V, 6 V, 9 V, 12 V, and 15 V equipotentials. Take the lightning rod map, and, using a ruler, estimate the maximum electric field magnitude, in units of Volts/m. Write this magnitude, and its location on the map, in your lab notebook.

12. Assuming the conductive ink was perfect, what would you expect the potential to be in the interior region of the left-hand electrode of the lightning rod map?

13. Consider the parallel-plate map. Again considering only the 3 V, 6 V, 9 V, 12 V, and 15 V equipotentials, use a ruler to estimate the average electric field E between the plates, in units of Volts/m. Write this in your lab notebook.

14. Imagine an actual set of parallel plates which has the same cross-section as the map, and has the same electric field E between the plates as you estimated in the last step. Using this value of E, estimate the charge density σ on each plate, in units of Coulombs/m^2.

15. Consider the dipole map. Using a ruler, estimate the electric field at the point midway between the two poles, and write this in your notebook.

16. Assume there is a charge $+q$ at the center of the 15 V equipotential, and a charge $-q$ at the center of the 3 V equipotential. Use a ruler to measure the distance d between these two charges. Write d in your lab notebook.

17. Derive an expression for the electric field E_{mid} that occurs midway between two point charges $+q$, $-q$ separated by a distance d. Write this in your notebook.

18. Use your estimate of E_{mid} from three steps ago to infer q, and write this in your notebook (this is the charge that would be on an actual set of spherical conductors, hanging somehow in midair, that had the same cross-section as the map).

19. What is the angle between electric potential lines and electric field lines? Hint: Consider the relationship between electric potential and electric field:

$$V_b \; - \; V_a \;\; = \;\; - \int_a^b \vec{E} \cdot d\vec{l}$$

and note that $V_b = V_a$ for any points b and a on the same equipotential.

20. Use your answer to the previous question to draw 5 electric field lines on each of the equipotential maps. Include the direction of the field.

21. Considering just the electric field lines: how can you tell where the electric field is the largest?

22. Considering just the equipotential lines: how can you tell where the electric field is the largest? (The answers to this question and the last question, taken together, allow a way to double-check whether the field lines are drawn correctly).

23. True or false: electric fields tend to have larger magnitudes around sharp points than around blunt surfaces.

24. True or false: if a conducting object becomes charged, the charges tend to congregate on the pointy parts of the object.

25. It is clear that lightning rods protect buildings against damage from lightning strikes. Two theories have been advanced why this might be the case:

   a. The lightning rod is a pointy object; charges congregate on the point, and readily leak off, thus preventing the building from becoming charged, and attracting lightning;
   b. The lightning rod, which must be connected to ground by a thick metal wire, does little to prevent lightning strikes, but ensures that when lightning does strike, the current passes harmlessly through the thick wire to the ground, rather than through the building.

   One of these theories has a wealth of evidence to back it up, and one does not. Which is which?

E-203 Capacitance

Objectives:

To examine very carefully the movement of charges in a capacitor; to observe and account for the effects of stray capacitance.

Preliminary Questions:

1. What is the relation between the charge Q on and the voltage V across a capacitor?

2. Can a grounded object (i.e. an object with potential 0 V) have nonzero charge?

3. Can a neutral object (i.e. an object with zero charge) have a potential of 0 V?

4. Must a neutral object (i.e. an object with zero charge) have a potential of 0 V?

Experiment I: Discharging a Capacitor
Apparatus:

Power supply; electrometer; plug-board; capacitors; cables with banana-plug connectors; cable with BNC connectors; BNC female to dual banana-plug adapter (Fig. 1).

Figure 1: BNC female to dual banana-plug adapter. Note the tab on right labelled "GND". This indicates which side is electrically connected to the outer conductor of the BNC connector, which is often grounded.

1. Turn on the power supply, and set it to 9 V. Confirm that the power supply "−" and "GND" terminals are shorted together by a metal tab. A conducting path connects these terminals to a pipe driven into the dirt beneath Chamberlin Hall, via the internal circuitry of the power supply, and the wires in the walls of Chamberlin Hall. These terminals therefore establish a well-defined 0 V, or "ground", reference electric potential.

2. Turn on the electrometer, and set it to the 10 V scale. Do NOT connect the "ground" terminal of the electrometer to anything at this time.

3. Connect the circuit shown in Fig. 2. The lines on the plug-board denote electrical connection. Each square of nine holes is electrically connected, and electrically isolated from the other sets. The set of holes along each border of the plug-board is electrically connected (but isolated from the set on the opposite border, and from all the nine-hole squares).
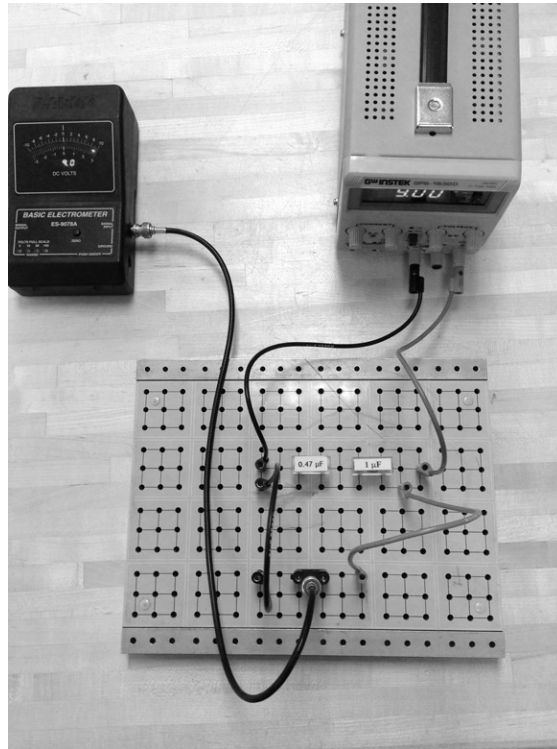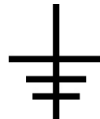

Figure 2: Initial configuration of circuit in Expt. I.

4. This symbol is used to indicate an object that is electrically connected to ground:

Thus this circuit can be represented schematically as in Fig. 3. Note that the electrometer (assumed to be a perfect measuring device) does not perturb the circuit it is measuring, and is therefore not shown in the schematic.
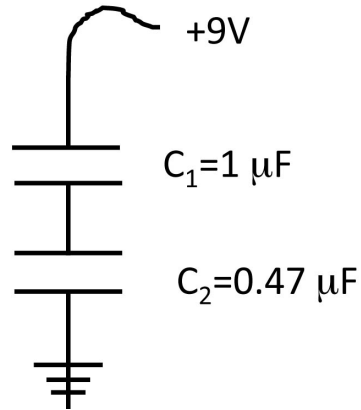
Figure 3: Schematic of initial configuration of circuit in Expt. I.

5. In the above diagram, note that the region in between the two capacitors (it looks like a sideways "H") is not connected to anything. If the total charge on this region was initially zero, it must therefore remain zero until some other object is connected to it.

6. The capacitors in this lab have equal and opposite charges on their plates. The distribution of charges on the configuration shown in Fig. 2 must therefore be as shown in Fig. 4 (we have not yet calculated the magnitude of Q_1).
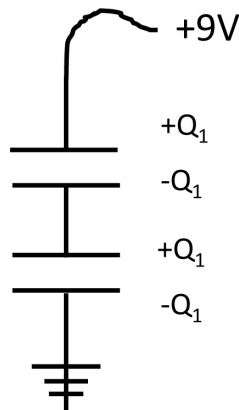
Figure 4: Distribution of charges of initial configuration of circuit in Expt. I.

7. As configured in Fig. 2, the electrometer is set up to measure the voltage drop across both capacitors, which is the same as the voltage supplied by the power supply. Note the electrometer reading in Fig. 2 agrees with the power supply reading.

8. What do you predict will be the voltage drop across each capacitor? Write down your prediction.

Next we will confirm the predictions by measuring the voltages across each capacitor using the electrometer. Do the following three steps every time you make a measurement with the electrometer:

- connect the GND plug of the BNC-to-banana plug adapter to the GND terminal of the power supply (or BNC cable connected thereto);

- press the zero button on the electrometer;

- connect the BNC-to-banana plug adapter across the object across which you want to measure the voltage.

The first two steps ensure the electrometer is fully discharged before making a measurement, and therefore not acting as a "charge ferry" to move charge from one part of the circuit to another.

9. Extract the BNC-to-banana-plug adapter from the plugboard, and measure the voltage across each capacitor (one at a time). Each voltage should be within a volt of your prediction.

   If your measurements seem wrong, disconnect the "+" terminal of the power supply from the circuit, and connect an aluminum "jumper" in parallel with each capacitor. This should discharge both capacitors. Then try again. Call over your TA if you can't get the predictions in step 8 to agree with the measurements in step 9.

In what follows, we will make three attempts to discharge (remove all charge from) the capacitors (step 10 is the first attempt, step 11 the second, and step 12 the third). Reproduce each of the following diagrams in your lab notebook.

For each diagram, set up the circuit on the plug-board. Use the electrometer to measure and record the voltage across each capacitor. Record the measured voltages on the diagram. Note that the voltage supply is connected in the first diagram of each step, but disconnected in the other diagrams.

Assume the charges on the capacitor plates are initially distributed as in the first diagram of each step, and use your voltage measurement to decide whether the charges on each of the capacitor plates in the other diagrams are $+Q_1$, $-Q_1$, or 0. Your answer should be based only on your measured voltages; you do not need to calculate Q_1.
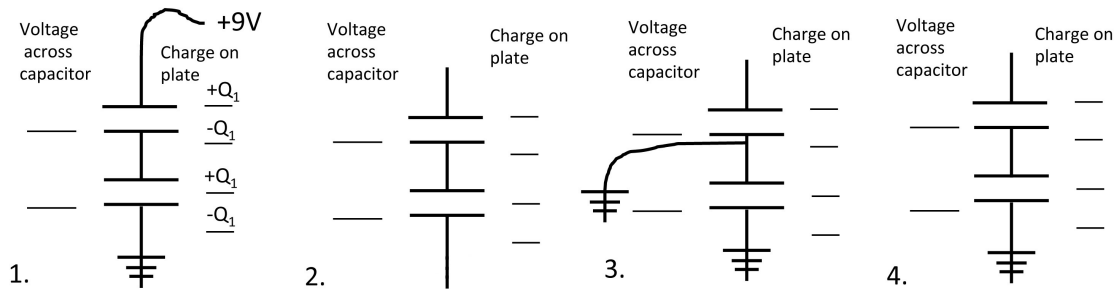
10. The three diagrams below represent our first attempt to discharge the capacitors. Is either capacitor discharged?
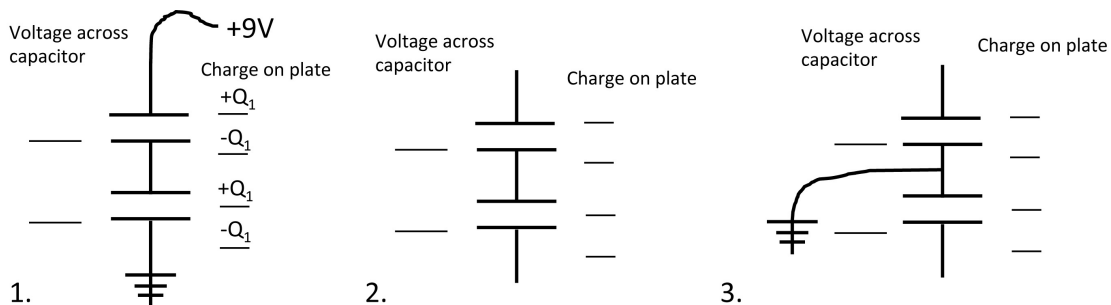
11. Repeat Step 10 with the three diagrams below. Is either capacitor discharged?
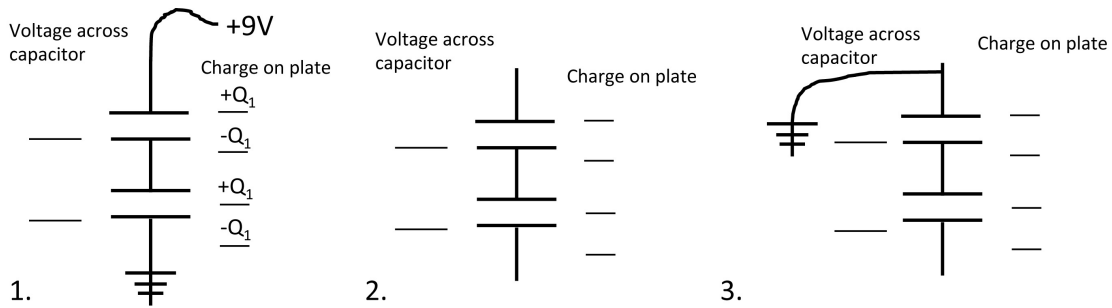
12. Repeat Step 10 with the diagrams below. Is either capacitor discharged?

13. Consider the following sequence of operations: 1) start with configuration as in first diagram in step 12; 2) disconnect the lower capacitor from ground; 3) connect the 9 V terminal of the power supply to the "H" shaped region between the two capacitors, without disconnecting it from the top of the upper capacitor. Would the upper capacitor be discharged?

14. State the necessary condition for discharging a capacitor.

Experiment II: Stray Capacitance
Apparatus:

Pasco Interface; power supply; electrometer; large parallel-plate capacitor with moveable plate; low-capacitance lead; motion sensor (Fig. 5).

Figure 5: Experimental Setup

The parallel-plate capacitor has plate diameter $D = 19.95 \pm 0.05$ cm; an indicated distance of 0 mm corresponds to an actual separation $d \sim 1$ mm. Insulating pads are mounted on one of the capacitor plates, so that this is the minimum possible plate separation.

The low-capacitance lead is shown below. The capacitance per unit length of a coaxial cable is $C = 2\pi\epsilon/ln(D/d)$, where d is the diameter of the center conductor, D is the outer diameter of the insulation, and ϵ is dielectric constant of the insulator. Our low-capacitance leads have four features that make them "low-capacitance": they are short; the center conductor is small; the insulation is thick; no outer conductor connector is used.
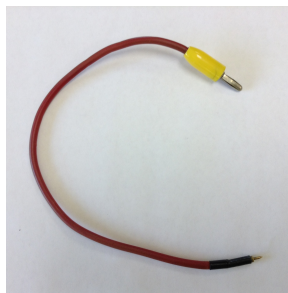

Figure 6: Low-capacitance Lead

Theory I: Consider a circuit composed of a voltage source and a parallel-plate capacitor, as shown in Fig. 7.
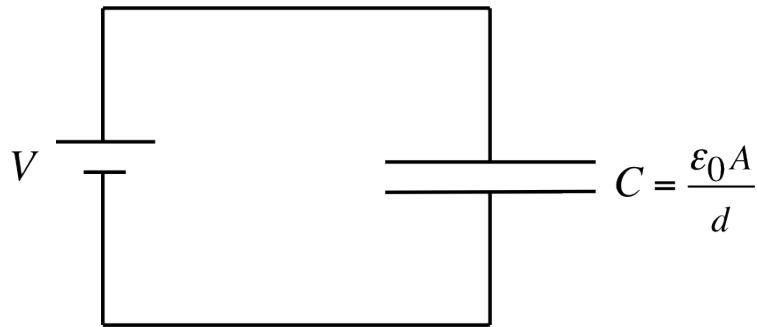

Figure 7: Ideal parallel-plate capacitor in circuit.

The capacitance of an ideal parallel-plate capacitor is $C = \epsilon_0 A/d$, where A is the plate area and d is the plate spacing. Suppose the plate spacing is set to d, the voltage across the capacitor is set to V, and then all external connections are removed. The capacitor charge Q will henceforth be constant, and therefore if d is changed, V must change: $V = Q/C = Qd/\epsilon_0 A$. The voltage should increase linearly with plate separation.

Procedure I: Test of Theory I

1. Set the power supply voltage to 9 V.

2. Set the electrometer range to 100 V.

3. Make sure equipment is connected as in Fig. 5. Setup checks:

   - "Signal Input" of electrometer connected to stationary plate of capacitor using low-capacitance lead (careful–delicate connection);
   - GND and "−" teminals of power supply connected by metal plate;
   - Electrometer ground connected to power supply GND terminal;
   - moveable place of capacitor connected to power supply GND terminal;
   - power supply "+" output connected to cable which is not connected to anything, but is long enough to be touched to the stationary plate of the parallel-plate capacitor;
   - motion sensor not used for this part of the lab.

4. Decrease the plate spacing to its minimum of about 1 mm.

5. Touch the "+" output cable to the stationary plate of the parallel-plate capacitor, and verify the electrometer now reads a steady 9 V.

6. Let the "+" output cable lie back on the table while you answer the next question.

7. According to "Theory I" above, the voltage should increase linearly with plate separation. The maximum plate separation is about 11 cm. If $V = 9$ V when $d = 1$ mm, what should the voltage be when $d = 11$ cm?

8. Test your prediction. What is the percentage discrepancy between prediction and measurement?

We expect you found a discrepancy of several thousand percent between prediction and measurement–the theory clearly needs to be revised.

Theory II:
Apparently our parallel-plate capacitor is not ideal. The problem is that the charge we put on the stationary plate affects the charges on all nearby objects, such as the table. This is an example of "stray capacitance", in which charge put on one object changes the potential of all nearby objects (not just the ones we intend). It can make circuits behave in unpredicted ways. Stray capacitance is modeled as a capacitance in parallel with the physical capacitor, as in Fig. 8. Call the stray capacitance C_S.
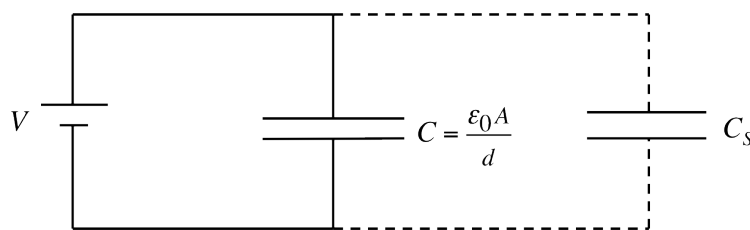

Figure 8: Model of real capacitor including the effect of stray capacitance C_s.

The relation between the charge Q on the parallel-plate capacitor and the voltage V applied to the parallel plate capacitor is then:

$$Q = (C + C_S)V, \tag{1}$$

where $C = \epsilon_0 A/d$, the parallel-plate capacitance, changes with plate spacing d, and C_S, the stray capacitance, does not.

This can be rearranged to solve explicitly for V:

$$V = \frac{(Q/C_S)\,d}{(\epsilon_0 A)/C_S + d}\ , \tag{2}$$

where d has been separated out because it is changing. This in turn can be rewritten

$$V = \frac{W\,d}{B + d}, \tag{3}$$

where $W = Q/C_S$ is the value taken by the voltage when the plate spacing goes to infinity, and $B = \epsilon_0 A/C_S$. We will now attempt to acquire data to test this model.
Procedure II: Test of Theory II

1. Set the plate spacing to maximum ($d \sim 11$ cm), touch the $+$ cable to the stationary plate, and verify the electrometer reads 9 V.

2. Let the $+$ cable drop. Shuffle your feet on the floor, shift your body in your chair, wave your arms—is there anything you can do that affects the electrometer reading?

3. If the answer to the above question was "no" call over your TA. Assuming the answer was "yes"—propose a one- or two- sentence explanation based on the concept of stray capacitance.

4. It's inconvenient that the low-capacitance lead is so short, and is so easy to accidentally disconnect from the electrometer. Why don't we use a longer lead, and put a connector on the end?

Now we are going to quantitatively test whether the theory in Theory II is correct. Our test is conceptually simple: we are going to charge the plates, and then vary the plate spacing with the charge fixed, while accurately measuring the plate spacing and the voltage across the plates. The measurement itself takes about two seconds. However, the setup must be done carefully if the measurement is to succeed (hence the length of the following set of instructions).

5. Connect the electrometer to analog input A of the Pasco interface. Zero the electrometer. Turn on the interface. The computer will record the voltage measured by the electrometer.

6. The motion sensor will be used to measure the position of the movable plate. Some notes about the motion sensor:
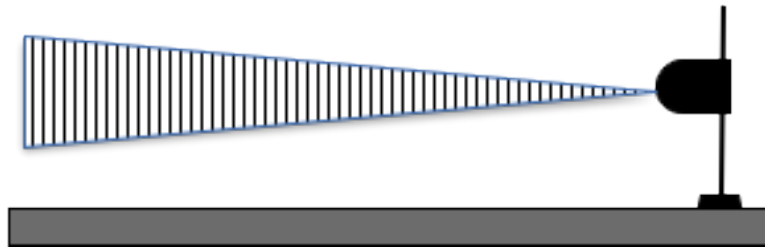

Figure 9: Motion sensor senses motion within a cone.

- The motion sensor sends out pulses of ultrasound, and listens for an echo. It calculates the distance to the object that caused the echo by dividing the time it waits before the echo by the twice the speed of sound (just like a bat does). Ultrasound is directional, so only objects within a cone in front of the motion sensor (see Fig. 9) cause echoes.

- If the motion sensor isn't oriented properly, it can return spurious measurements: for example, it might measure a distance you can see to be (say) 30 cm to be 6 m. This happens when it is not oriented properly. To orient the motion sensor to measure the position of the moveable plate of the parallel-plate capacitor, point it slightly upwards, about $5°$ above the horizontal. That way it won't "see" your hand, moving the plate. Always scrutinize motion sensor data for spurious data points, and reorient it if you find any.

- Keep in mind that the motion sensor measures the distance from itself to some object, in our case a moveable plate. We are interested in the distance between our two plates. We're going to have to do some math to get the measurement we want from the motion sensor measurement.

7. Connect the yellow plug of the motion sensor cable to digital input 1 of the interface, and the black plug to digital input 2.

8. Turn on the interface; turn on the computer, click "student" to login (no password required), go to Lab Software/202 on the desktop, and launch Physics202-E203.cap, the setup file for this experiment. If the motion sensor is connected properly, it should emit several sets of clicks as the setup file sets the software up.

Now that the hardware is set up, it is time to inspect the software. The screen should now look like Fig. 10 below.
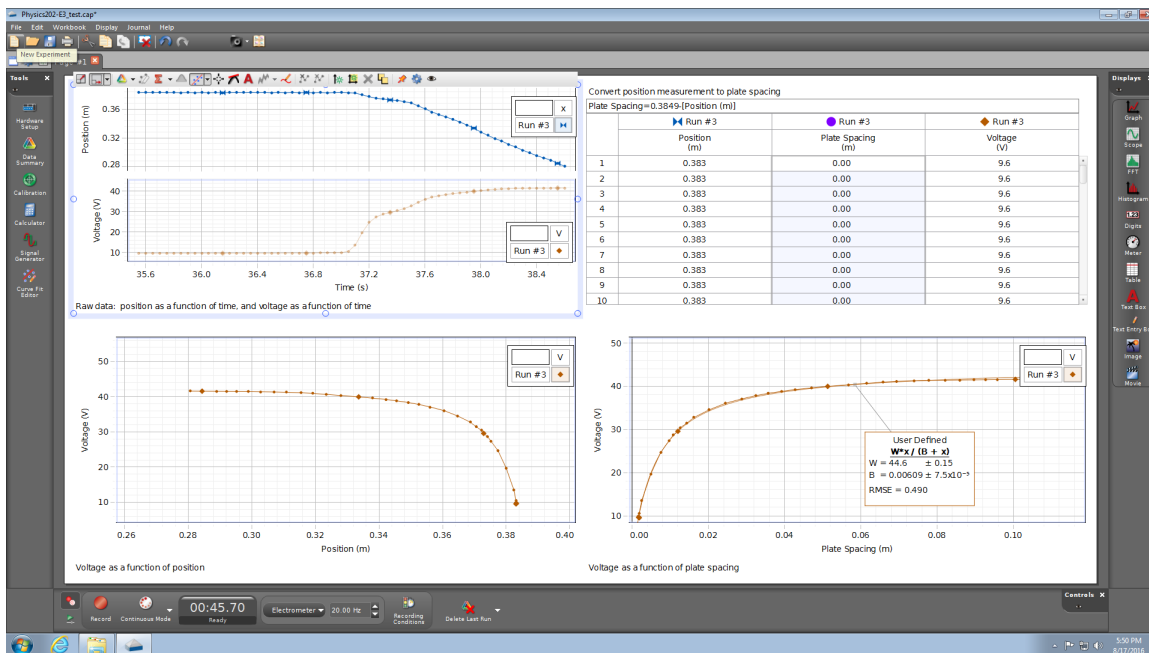
Figure 10: Screenshot of Capstone setup file.

Real data has been saved, and is evident on each of the four panels on the screen. Those panels are:

- (upper left panel) Raw data: position as a function of time, and voltage as a function of time, as acquired by the motion sensor and the electrometer respectively.

- (lower left panel) Voltage as a function of position. The vertical coordinates of the two raw datasets, plotted against each other.

- (upper right panel) Convert position measurement to plate spacing. The conversion is given as "Plate Spacing = 0.3849 − [Position (m)]".

- (lower right panel) Voltage as a function of plate spacing. The third column of the upper right panel plotted as a function of the second. The data is represented by points, and can be compared directly to a fit, shown as a line, based on the theory in the Theory II section above. You should be able to see there is very good agreement between this set of data and Theory II.

Now we are ready to take data. The single purpose of our first dataset is to show the motion sensor has been oriented correctly, and is returning accurate measurements of the position of the moveable plate. Only the upper left panel of the screen will be needed.

9. Start with the plates at minimum spacing. Keep all parts of your body out of the cone of the motion sensor's sensitivity.

10. Click "Record" on the screen to start taking data.

11. Move the moveable plate all the way out, then all the way back.

12. Click "Stop" to stop taking data.

13. Verify that the data shown on the position-vs-time plot in the upper left window corresponds to reality. Look for "outliers"—-single data points that are grossly wrong—or other sudden jumps. If you find any, reorient the motion sensor and try again. Do not stop until you have no spurious data. Your data should look something like Fig. 11.

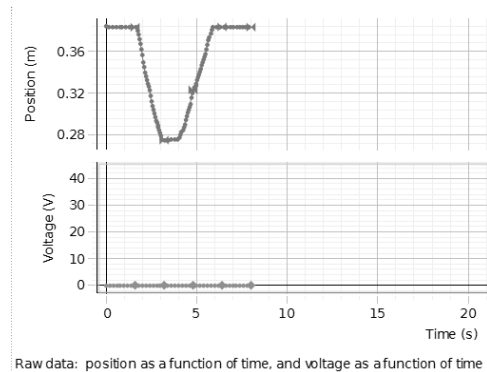Raw data: position as a function of time, and voltage as a function of time

Figure 11: Screenshot of motion sensor test data.

Next is the actual data that will be compared with the prediction of Theory II. You may find it helpful to coordinate your actions with your lab partner(s)—assign one person to operate the computer, another to handle the power supply + cable, and the third to actually move the capacitor plate.

14. Start with the plates at minimum spacing, and the power supply at 9 V.

15. Touch the + cable to the stationary plate of the capacitor, and hold it there.

16. Start taking data.

17. Remove the + cable from the stationary plate.

18. Smoothly and rapidly move the moveable plate to maximum separation (rapid movement minimizes charge leakage).

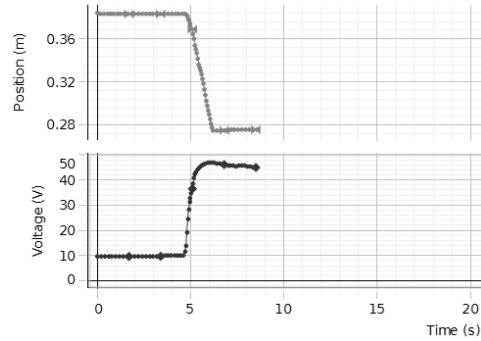19. Stop taking data. Raw data should look as in Fig. 12

Figure 12: Raw data: voltage and position, each as a function of time.

This concludes the taking of data. The purpose of the next few steps is to carefully reduce the amount of data being analyzed.

20. Check to make sure that the "Run #" on all four panels is the same as the one in the upper left panel.

21. Inspect the fit on the lower right panel. It may be good, it may be very poor–it should certainly not be perfect (what we are about to do should improve it).

22. Data taken while the moveable plate was motionless is extraneous and can be excluded. To exclude data taken prior to the movement of the plate:

    - Use left mouse button to highlight rows in table corresponding to data points you want to exclude.
    - Click right mouse button, and choose "Exclude Data". Excluded data points should now be replaced in upper left-hand plot by × symbols.
    - Repeat above steps to exclude data taken after plate stopped moving.

Look at the fit again–it may have gotten considerably better (or it may still be terrible). Our final step of analysis is to tweak the conversion between position and plate spacing.

23. Inspect the lower right window. The x-coordinate of the leftmost point should be the same as the first entry in the middle column.

24. Click on any entry in the upper right window: an equation will appear in the header. What are the units of the "0.3849", and what must it represent regarding the setup used to acquire this data? Click in the box in the upper right window where the plate spacing is calculated. Use the keyboard to modify the calculation, until the leftmost data point in the lower column is at a plate spacing of about 1 mm. The fit by now should be very good.

25. Inspect the box in the lower right window which specifies the fit parameters (these change as you change the calculation of the plate spacing). The quantity "RMSE" is the Root-Mean-Square-Error, analogous to Standard Deviation discussed in the "Characterization of Uncertainties" section on page 3. Modify the number used in the calculation of plate spacing in the upper right panel in order to minimize the RMSE. An RMSE of less than 0.5 indicates excellent experimental technique. Print one copy of your graph, and make sure the fit parameters are visible.

This completes the analysis. What have we learned?

26. For what range of values of plate spacing d does the ideal model used in Theory I accurately predict the voltage across the capacitor? (Refer the the graph in the lower right window).

27. What are the units of the fit parameter W?

28. Compare the value given for W to the shape of the graph. State in words the meaning of W. Hint: examine Eq. (3) in the limit $d \to \infty$.

29. What are the units of the fit parameter B?

30. The meaning of B could be stated as: "For plate separations much less than B, the parallel-plate theory presented in Theory I is accurate; for plate separations greater than B, it fails completely". Use the value of B to calculate the stray capacitance, in Farads, according to the theory in Theory II.

31. Describe in words how you could estimate the value of B from the graph, without doing any calcuations. Hint: what is the voltage when $d = B$?

32. A common challenge faced by electrical engineers is minimizing the stray capacitance. Suppose the stray capacitance in this circuit were cut in half. What would happen to W and B?

E-204 Electron Charge to Mass Ratio

Objectives:

To observe magnetic deflection of electrons, at fixed energy, in a uniform magnetic field; to measure e/m, the electron charge/mass ratio; to estimate the strength of the Earth's magnetic field.

Apparatus:

Vacuum tube; Helmholtz coil; power supply; compass; dip-needle compass.

Introduction:

Your vacuum tube contains a number of features for producing and visualizing a thin uniform electron beam. Refer to Fig. 1 and Fig. 2 for details.

Passing current through a wire filament (F) causes it to become hot. If the filament becomes hot enough, electrons spontaneously leave the surface (a process called thermionic emission).

The filament is in close proximity to a higher-potential electrical element (the cylindrical anode C), and so some of the electrons accelerate through the vacuum towards the anode. The current between the filament and anode is called the "anode current", and is shown on the "ANODE milliAmps" readout of the power supply.

To allow a narrow beam of electrons to leave the vicinity of the anode a thin slit, S, has been cut in the anode cylinder.
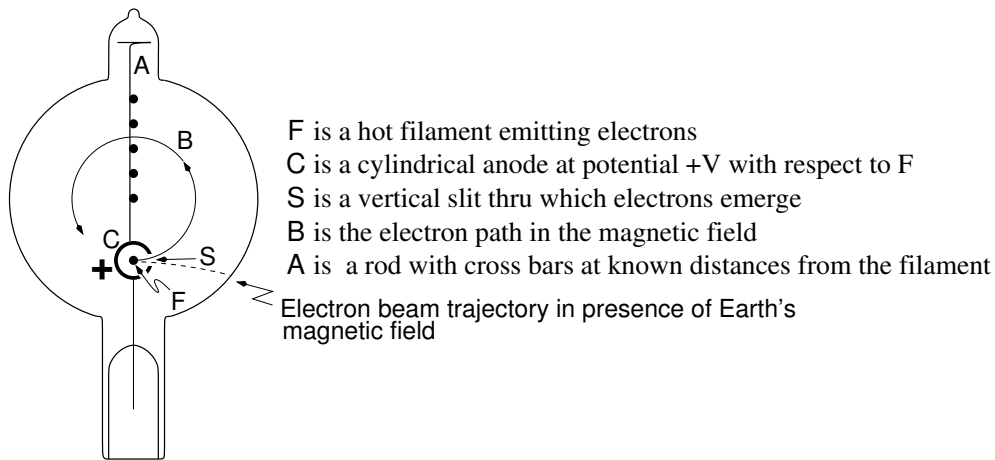

F is a hot filament emitting electrons
C is a cylindrical anode at potential +V with respect to F
S is a vertical slit thru which electrons emerge
B is the electron path in the magnetic field
A is a rod with cross bars at known distances from the filament

Electron beam trajectory in presence of Earth's magnetic field

Figure 1: Top view of vacuum tube (looking along field direction).

Normally the electron beam is invisible to your eye. However the e/m tube also contains Mercury (Hg) vapor. When electrons with energies in excess of 10.4 eV (1 eV = 1.602 $\times 10^{-19}$ J) collide with Hg atoms, some atoms become ionized or excited, and then quickly recombine and/or de-excite to emit a bluish light. Hence the bluish light marks the path taken by the electron beam. The electrons which collide with atoms are permanently lost from the beam.

The potential difference V between the anode and filament is shown on the "ANODE Volts" display of the power supply. Those electrons traveling toward the slit S emerge with a velocity v given by

$$Ve = \frac{1}{2}mv^2 , \tag{1}$$

provided that the thermal energy at emission is small compared to eV.

The purpose of the Helmholtz coil is to provide a spatially uniform magnetic field. This field is proportional to the current in the Helmholtz coils, which is displayed on the "FIELD Amps" readout of the power supply. If the vaccuum tube is properly oriented, the velocity of the electrons is perpendicular to the magnetic field. Hence the magnetic force vector $\vec{F}_B = e\,(\vec{v} \times \vec{B})$ supplies the centripetal force $\frac{mv^2}{r}$ for a circular path of radius r. Since $\vec{v}$ is perpendicular to $\vec{B}$,

$$evB = \frac{mv^2}{r} . \tag{2}$$

Eliminating v between (1) and (2) gives

$$e/m = \frac{2V}{B^2 r^2} . \tag{3}$$

A is a rod with cross bars at known distances
    from the filament

L , L$'$ are insulating plugs in the end of the anode cylinder

D is the distance from the filament to the first cross bar

G , G$'$ function as the filament leads and support

E is the anode lead. It supports the anode
    and the rod with cross bars
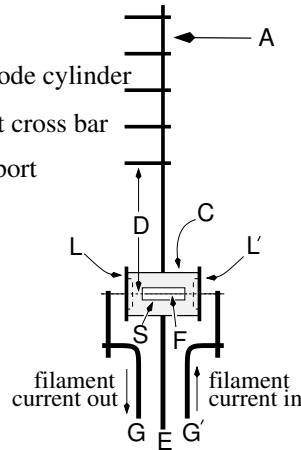
C is the anode cylinder

Figure 2: Side view of vacuum tube.

If the field in the Helmholtz coil is adjusted so that the beam of electrons strikes one of the cross bars in the vacuum tube, then the radius of curvature r must be half the distance D between the filament F and the cross bar (see Fig. 2). The cross bar positions are as follows:

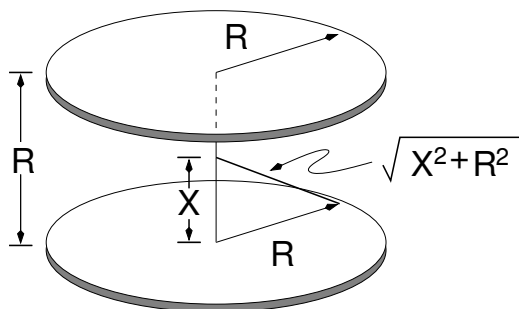| Cross bar No.	D=Distance to Filament	r=Radius of Beam Path
1	0.065 meter	0.0325 m
2	0.078 meter	0.039 m
3	0.090 meter	0.045 m
4	0.103 meter	0.0515 m
5	0.115 meter	0.0575 m

Figure 3: Helmholtz coil geometry. A Helmholtz coil consist of two identical coaxial coils which are separated by a distance R equal to the radius of either coil. Each coil carries a current I.

To find e/m we still need to relate the magnetic field strength B to the measured Helmholtz coil current, I.

The field created by a single coil at a point along its axis is in the axial direction, and is equal to

$$B(X) = \frac{N\mu_0 I R^2}{2\left[R^2 + X^2\right]^{3/2}},$$

where $B(X)$ is the field in Tesla, N is the number of turns in the coil, I is the current through the coil in amperes, R is the mean radius of the coil in meters, and $\mu_0 = 4\pi \times 10^{-7}$ Tesla meter/ampere.

Thus the field at the center of a Helmholtz coil (i.e. at $X = R/2$) is the sum of the fields from each of the single coils:

$$B = 2B(R/2) = \frac{N\mu_0 I R^2}{\left[R^2 + R^2/4\right]^{3/2}} = \frac{N\mu_0 I}{R\left[\frac{5}{4}\right]^{3/2}} = \frac{8}{\sqrt{125}}\left(\frac{N\mu_0 I}{R}\right). \qquad (4)$$

The Helmholtz coils used in this experiment have $N = 72$, and $R \sim 0.33$ m.

It can be shown that the field over a large volume near the center is approximately constant. The actual B at the maximum electron orbit is only $\sim 0.5\%$ less. [1]

Finally if we substitute (4) into (3) we obtain

$$\frac{e}{m} = \left(\frac{125}{64}\right)\left(\frac{2}{\mu_0^2}\right)\frac{R^2 V}{N^2 I^2 r^2} \qquad (5)$$

Preliminary Questions:

1. If you were to double the potential difference between the filament and the anode: A. the beam would get brighter; B. the radius of electron trajectory would get bigger.

2. If you were to double the current through the filament: A. the beam would get brighter; B. the radius of electron trajectory would get bigger.

---

[1]See Price, "Electron trajectory in an e/m experiment", *Am. J. Phys.* **55**, 18, (1987)

Experiment:

1. Connect the components as in Fig. 4 below. The current has the same direction in both coils of a Helmholtz coil.
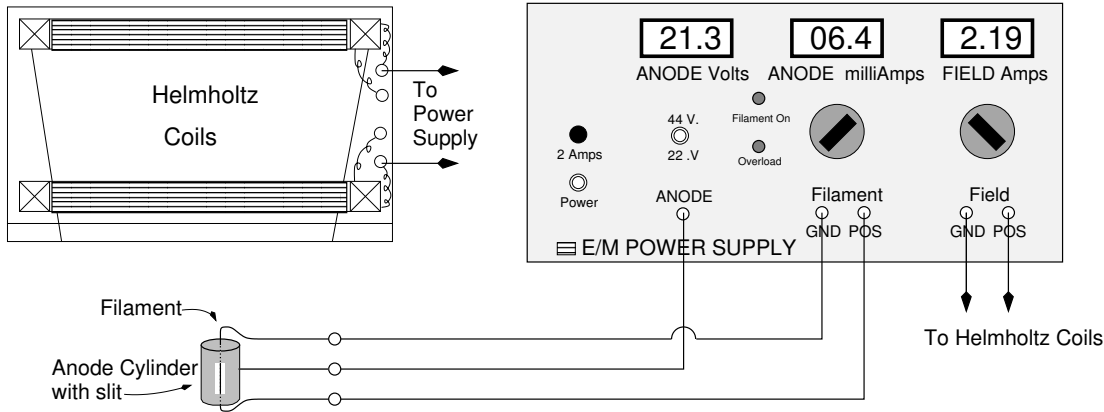

Figure 4: Basic wiring layout.

2. Determine the local direction of the Earth's magnetic field using the compass and dip-needle compass. You should find that it is in the same vertical plane as geographic north but at an angle about 70 degrees from the horizontal. Thus the dip-needle compass should point deep under Canada. Set the axis of the Helmholtz coils along this direction. Rotate the vacuum tube about its long axis until the cross bars are facing up.

> CAUTION: Nearby ferromagnetic material (e.g. steel in the power supply, the table and in the walls) can alter the local direction of B_e. As long as the field direction does not change during the experiment, there should be no problem.

3. Measure R, the mean Helmholtz coil radius.

4. Set the filament supply knob to zero before turning the power on.

5. Since e/m depends on V/I^2, one needs high quality meters for V and I. Our digital meters have an accuracy of $\pm$ one digit in the last displayed digit.

6. Start with ~ 22 V between filament and anode.

7. The anode current is displayed on the "ANODE milliamps" display. With the room dark, *gradually* turn up the filament control until the beam is visible. The anode current should remain zero until the filament is hot enough that you can see the glowing filament. The filament dial will often be well beyond the halfway position before the anode current departs from zero. You should not expect to see the beam until the anode current is at least a few milliamps. To make the beam more visible, use black cloth and black cardboard to block out stray light: place the black cardboard **inside** the Helmholtz coils and view from the top. When the beam appears, adjust the filament control to give 5-10 mA of anode current. **Do not exceed 15 mA!**

8. With no current through the Helmholtz coils, the earth's magnetic field should slightly curve the beam.

9. Turn up the Helmholtz coil current until the electron beam is steered into cross bar 1 (the cross bar closest to the filament).

10. Change the anode voltage to 44 V. Did the beam radius become larger or smaller?

11. Return the anode voltage to 22 V. Let I'_n denote the Helmholtz coil current necessary to steer the beam into cross bar n. Record I'_n for each of the five cross bars in the table below. Keep in mind that the electrons are responding to the sum of the Helmholtz coil field and the Earth's field.

n	r (m)	$I'_n(A)$	$I''_n(A)$	$I_n(A)$	$I_e(A)$	$e/m(C/kg)$	B_e (T)

12. Rotate the vacuum tube about its long axis by 180° and reverse the Helmholtz coil wires. Repeat step 11, using I''_n to denote the current needed to steer the electrons into the cross bars.

> CAUTION: Always rotate the tube in the sense to *REDUCE* the *TWIST* in the filament and anode leads. *Otherwise one can twist the leads off.*

13. Why is I'_n different from I'''_n?

14. Which direction does the Earth's field point, more or less towards the floor, or more or less towards the ceiling?

15. Let I_n denote the current that would be needed to steer the electrons into post n, if the Earth's field were not present. How is I_n calculated from your measurements I'_n and I'''_n?

16. Let I_e denote the current necessary to counteract the Earth's field. How is it calculated from I'_n and I'''_n?

17. Fill in the columns for I_n and I_e in the table.

18. Compute the electron's e/m from your data, estimate its uncertainty (the uncertainty is given by the standard deviation of the mean as described on page 4), and compare it to the accepted value of 1.76×10^{11} C/kg. Is the discrepancy between your value and the accepted value larger than or smaller than the uncertainty in your value?

19. Compute the local magnitude of the Earth's magnetic field, B_e, from your data, and estimate its uncertainty.

20. The local magnitude of the Earth's magnetic field varies from point to point, and at one point at different times. Go to the NOAA geomagnetic calculator https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm and deduce the current estimated value of the Earth's magnetic field in Madison. This calculator is based on an analytic model; local measurements are found to differ from it by an amount called the "local anomaly". Go to https://pubs.usgs.gov/of/2002/of02-493/HTML/WI_hi-res_mag_image.htm and deduce from it the value of the local anomaly in Madison. These data are also available on the bulletin board outside room 3320 Chamberlin. Record from these the accepted value of the Earth's magnetic field in the vicinity of Madison.

    Is the discrepancy between your value and this value larger or smaller than the uncertainty in your value?

21. One last thing to do: tilt the tube so that a helix is seen. Why do the electrons move in a helical path?

    One last observation: Note that the electron beam expands in a fan shape after leaving the slit. Interchange the filament leads and note how the fan shape flips to the other side of the beam.

Explanation: The fan shape deflection arises from the filament current's magnetic field acting on the beam. Our filament supply purposely uses unfiltered half wave rectification of 60 Hz AC so that for half of the cycle no current flows through the filament but it is still hot enough to emit sufficient electrons. The electrons emitted in this half cycle constitute the sharp beam edge which we use for measurement purposes. This trick not only avoids deflection effects for this part of the beam, but also avoids the uncertainty in electron energy arising from electrons being emitted from points of different potential along the filament. (During this half cycle of no filament current the filament is $\sim$ an equipotential.) The fan shape deflection relates to electrons emitted during the other half cycle when filament current flows. [See: F.C. Peterson, *Am. J. Phys.* **51**, 320, (1983)]

E-205 Magnetic Induction

E-205a Lenz's Law

Objectives:

To observe the eddy currents induced in a conductor moving through the field of a stationary magnet; to explore how the force due to eddy currents depends on the shape of the conductor.

> *YOU NEED TO KNOW:* the Lorentz force law; the right-hand rule that determines the direction of the force on a charge moving through a magnetic field.
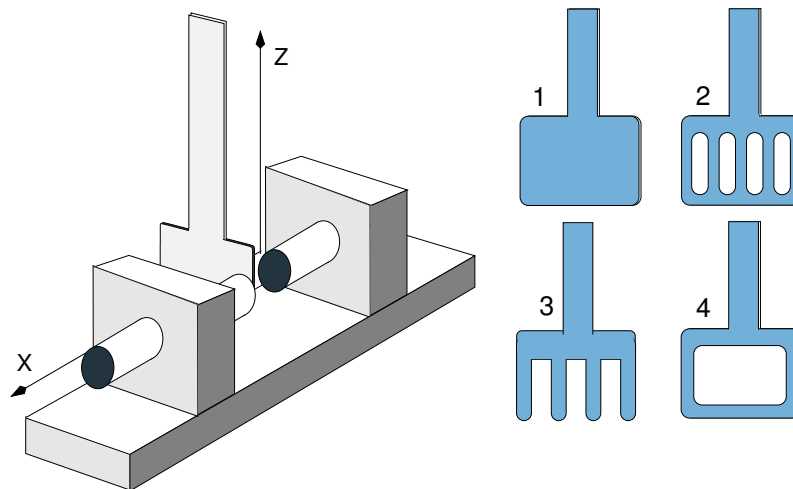
Apparatus:

A permanent magnet; four different pendulums; compass.

Figure 1: The magnet and the pendulums.

Experiment: (10 min)

1. Use the compass, the known direction of geographic north, the approximation that magnetic north is the same as geographic north in the vicinity of Madison, WI, and the knowledge that the Earth's northern-hemisphere magnetic pole (which until 2015 was located in Canada) is an S pole, to answer the following question: which end of the compass points towards magnetic N poles?

2. Use the compass to determine the direction of the magnetic field between the jaws of the permanent magnet. Define this to be the $+x$ direction. Make a note of this direction for later use (in step 7).

3. Set the jaws to be about 1 cm apart, and observe the behavior of each of the four pendulums when they swing through the jaws. Note that the pendulum axle has two slots, so you can run head-to-head competitions if you are careful. Which pendulum is affected most? Which least? Why?

4. Reverse the magnet. Does this change the swinging of any of the pendulums?

5. Take pendulum #1 in your hand and hold it between the jaws of the magnet. Move it rapidly back and forth *without touching* the jaws. What do you feel?
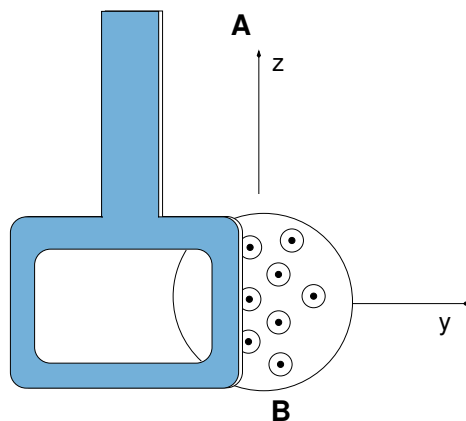
Figure 2: Pendulum moves in the $+y$ direction

6. As the leading edge of the pendulum in Fig. 2 enters the region of the magnetic field, predict the direction of the force on the electrons in the leading edge, using the right-hand rule: is it from A to B, or from B to A?

7. Enact the experiment shown in Fig. 2. In what direction do you observe the force on the pendulum to be?

8. The directions that you found in the previous two steps should be perpendicular. Write an equation and a sentence that describe how the force on the electrons in the direction predicted in step 6 gives rise to the force on the pendulum in the direction observed in step 7.

E-205b Induction - Dropping Magnet

Objective:

To show that a moving magnet induces an *emf* within a coil of wire.

Apparatus:

Pasco interface; voltage sensor; a stand holding a plastic tube and a coil; a long bar magnet.

Introduction:

In E-205a it was shown that a conductor moving through the magnetic field of a stationary magnet may experience a force. Here we show that a magnet moving in the vicinity of a stationary conductor (see Fig. 3) induces an *emf* in the conductor.

> *YOU NEED TO KNOW:* Faraday's Law; Lenz's Law; the right hand rule that determines the direction of the current induced in a conductor by a magnetic field that is changing with time.

Precautions:
- The bar magnet is very fragile. DO NOT DROP IT!
- The bar magnet is easily depolarized. KEEP OTHER MAGNETS AWAY!
- When dropping the magnet, HOLD THE TUBE AND STOPPER TOGETHER WITH YOUR HANDS!
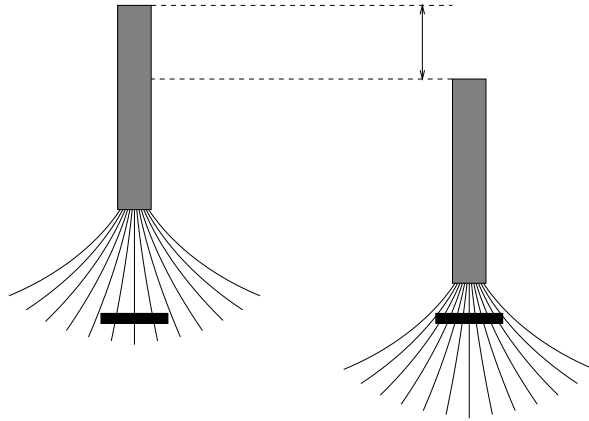
Figure 3: A moving magnet - magnetic field lines move across a wire

Experiment:

1. Connect the red wire of the voltage sensor to the top of the coil, and the black wire of the voltage sensor to the bottom of the coil. Then connect the other end of the voltage sensor to analog input A of the Pasco interface. Turn on interface.

2. Double click on the "Physics202-E205b" file in the Lab Software/202 folder on the desktop.

3. Set the distance $d_1 \sim 15$ cm between the top of the plastic tube and the top of the coil. Record this in your lab notebook.

4. The long bar magnet has a notch cut at one end: this is the N pole of the magnet.

5. Hold the magnet at the top of the tube; the end with the cut should be down, and just 1 cm or so inside the tube.

6. Click on the [Record] icon, then drop the magnet, then click "Stop".

7. Remove points at the beginning and end (when the magnet was stationary). Measure the heights V_1 and V_2 of the two peaks using the ✛ coordinates tool.

8. Slide the tube upwards, remove the rubber stopper and the magnet, replace the rubber stopper, and slide the tube down again.

9. Print one copy of your graph.
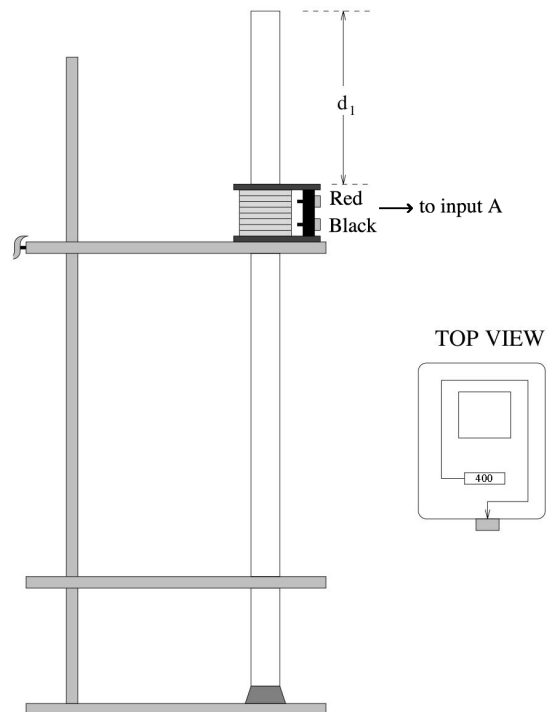
Figure 4: The setup

10. The graph you obtained should have a fall, a rise, a diminished slope, then a rise and finally a fall (the "diminished slope" occurs when the magnet is centered in the coil). Explain what is happening at these various times.

11. Explain why the two voltage peaks you measured in step 7 are not the same size. Recall that the velocity v of an object dropped from a height h is given by $v = \sqrt{2gh}$ where g is the acceleration due to gravity. Use this to calculate an approximation for V_1/V_2.

12. In the "TOP VIEW" diagram in Fig. 4, the box labelled "400" is the red input, and the small dark rectangle is the black input. When the North pole of the magnet is falling, and is inside the coil, is the induced current in the coil moving from red to black, or from black to red? Does this give a positive or negative voltage? Does this agree with the direction of your first peak?

    Occasionally a long bar magnet is found to have regions of reversed polarity, likely due to repeated mechanical shocks (it's amazing to think that banging a magnet on a table can cause all the atoms in a region to flip their spins). If you think your magnet has regions of reversed polarity, call over your TA.

13. Sketch how the graph of voltage vs time ought to look if the magnet were dropped upside-down relative to step 5 (nominal North pole at top).

14. Repeat steps 6-7 with the end with the cut at the top. Did you correctly predict how the graph would look?

15. Move the coil further down on the tube making the new distance d_2 at least about one-and-a-half times larger than d_1. Record this new distance d_2.

16. Repeat steps 6-7. Measure and record the heights V_1' and V_2' of the new peaks.

17. Is the ratio V_1'/V_2' larger or smaller than the ratio V_1/V_2?

18. Why has this ratio changed?

E-205c Induction - Fields in Space

Objectives:

To observe the *emf* induced in one conductor by a changing current in a nearby conductor; to investigate how the induced *emf* depends on the amplitude and frequency of the inducing current; to observe how the induced *emf* depends on the proximity and relative orientation of the two conductors.

Apparatus:

PC and PASCO interface; large back-to-back coil (N=200 turns; radius $\rho = 0.105$ m, series resistance $R \sim 9\,\Omega$) and stand; a small detecting coil (n=2000 turns).

Introduction:

A voltage *applied* to one conductor (by a power supply, for example) can *induce* an *emf* in a nearby conductor. Here we apply a voltage with a triangular waveform to a large coil, and measure the *emf* induced in the small coil.

> *YOU NEED TO KNOW:* The *emf* induced in a (small) coil is $\mathcal{E} = -nA\,dB/dt$, where n is the number of turns in the coil, A its cross-sectional area, and B is the magnetic field created by other nearby objects.
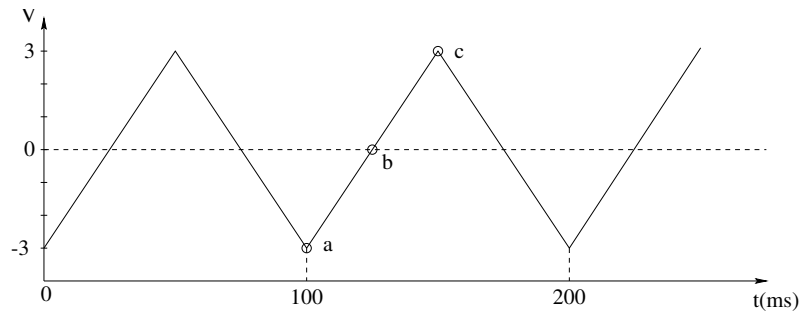
Figure 5: A triangular waveform

Experiment:

1. Double click on the "Physics202-E205c" file in the Lab Software/202 folder on the desktop. The monitor should now show a scope window and a window for the control of the signal generator.

2. If necessary, adjust the signal generator amplitude to 3 V and waveform to Triangle (Fig. 5).

3. Connect the signal generator to the large coil; then connect analog input A to the large coil and analog input B to the small coil, as in Fig. 6.
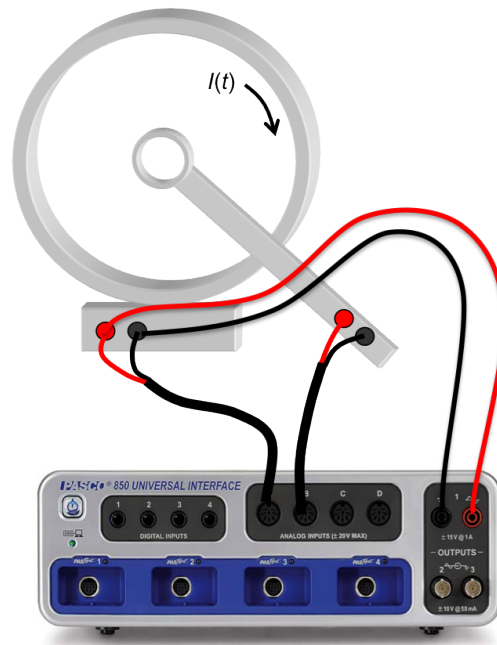

Figure 6: Connections between interface and coils.

4. Click the "On" button to turn on the signal generator and initiate data acquisition by clicking on the icon. You should now see the *emf* induced in the small coil together with the voltage applied to the large coil. Note that the triangle wave and the induced emf signal have different scales on the graph.

5. While recording data, move the small coil around and see how the amplitude of the induced *emf* changes.

6. Explain why the induced *emf* is a square wave.

7. Move and/or turn the small coil to achieve the maximum possible ratio $|V_B|/|V_A|$. Record this maximum ratio, and make a sketch of the orientation that produced it.

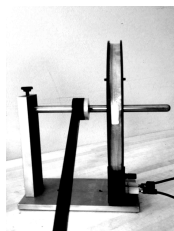In the next few steps we will measure the fall-off of B_z on axis, $B_z(z, r = 0)$.

Figure 7: Setup for measuring the fall-off of B_z on axis.

8. Put the small coil on the stand as in Fig. 7, and move it as close as you can to the large coil, so that the two coils are approximately co-planar. Define z as the distance between the planes of the coils; at the moment $z = 0$.

9. The magnitude of B_z along the axis of the coil can be shown to be

$$B_z(z) = \frac{N \mu_0 I \rho^2}{2(\rho^2 + z^2)^{3/2}} \ ,$$

where ρ is the coil radius, N is the number of turns in the coil, I is the current in the coil, and z is the distance along the axis from the plane of the coil (this formula was mentioned in lab E-204).

The only time-dependent quantity is I, and the only position-dependent quantity is z, so we can separate the time- and space-dependence by writing

$$B_z(z) = \frac{N \mu_0 I}{2\rho} \frac{\rho^3}{(\rho^2 + z^2)^{3/2}} \equiv B_0 \frac{\rho^3}{(\rho^2 + z^2)^{3/2}} \ ,$$

where B_0 is the (time-dependent) magnitude of the field at $z = 0$. The z-dependence is contained in the second factor, which is dimensionless and equals 1 when $z = 0$.

As we are studying now, if B_z is time-dependent, an *emf* will be induced in a second coil placed near the first. If the second coil is small, the *emf* will be:

$$\mathcal{E} = -nA \, dB_z(z)/dt = -nA \frac{\rho^3}{(\rho^2 + z^2)^{3/2}} \frac{dB_0}{dt} \ ,$$

where n is the number of turns in the small coil, and A is the area of the small coil.

Since the voltage sensor tells us V it is useful to write

$$\frac{dB_0}{dt} = \frac{N \mu_0}{2\rho} \frac{dI}{dt} = \frac{N \mu_0}{2R\rho} \frac{dV}{dt} \equiv k \frac{dV}{dt}$$

where R is the resistance of the large coil, k is a constant, and dV/dt is the slope of the voltage waveform shown in Fig. 5.

Putting the above three equations together gives:

$$\mathcal{E} = -nAk\frac{dV}{dt}\frac{\rho^3}{(\rho^2 + z^2)^{3/2}} \equiv \mathcal{E}_0\frac{\rho^3}{(\rho^2 + z^2)^{3/2}} \, , \tag{1}$$

where $\mathcal{E}_0$ is the *emf* induced in the small coil when it is located at z = 0.

10. Sketch by hand Eq. 1 as a function of z.

11. Make a table with four columns: z, measured *emf*, predicted *emf*, and discrepancy.

12. Measure the amplitude of the induced *emf* at $z = 0$. Since $z = 0$ for this measurement, equate it to $\mathcal{E}_0$, the predicted *emf* at $z = 0$. Fill in the first row of the table. By definition the discrepancy between measurement and prediction is zero for this measurement.

13. Repeat the above measurement at $z = 5$, 10 and 15 cm. Fill in the first two columns with your distances and measurements.

14. For our coil $\rho = 0.105$ m. Calculate the predicted *emf* for $z = 5$ cm, 10 cm, and 15 cm, using Eq. 1, and record it in your table.

15. Fill in the final column with the percentage discrepancy between the measured *emf* and the predicted *emf*. Indicate which point had the largest discrepancy.

We have now finished measuring how B_z falls off with increasing distance from the coil. In the next few steps we'll measure how the B-field at one point changes as the driving voltage is changed.

16. Replace the detecting coil to its original position at the center of the large coil. Decrease the amplitude of the triangular wave to 2 V.

17. Measure the amplitude of the square wave and record this value.

18. Did the slope of the triangular wave change? By how much?

19. Is the change in amplitude of the square wave what you would expect? Why?

20. Change the frequency to 15 Hz and re-measure the amplitude of the square wave.

21. Compare the amplitudes of the induced *emf* measured in steps 12, 17, and 20.

22. Return the frequency to 10 Hz. Rotate the detecting coil 90° so that it is in the horizontal plane. Observe the resulting induced *emf*.

23. Rotate the coil another 90° so that it is in the vertical plane again, and return the voltage to 3 V. Observe the resulting induced *emf*. Compare with the measurement from step 20.

24. In the "You Need to Know" box that started this section, why was it necessary to specify that the coil be "small"?

We hope the preceding exercise helps you visualize an invisible time-dependent magnetic field, which permeates empty space, and its role in the phenomenon of magnetic induction.

E-205d Induction - Circuit Elements

Objective:

To observe the L/R time constant of an LR circuit.

Apparatus:

PC and PASCO interface; two voltage sensors; a pair of nested coils; an iron bar that fits inside the inner coil; a plug board; and a 100 Ω resistor.

Introduction:

In E-5c we showed that a changing current in one circuit can induce an *emf* in another circuit that is not physically connected to it. Here we will observe this same effect, but in addition will see that if the current in a circuit changes, an *emf* is induced in that same circuit, and will explore the effects of this.

Experiment:

1. Set up the circuit shown in Fig. 8. Analog input A measures the voltage across the resistor, and is therefore proportional to the current through the outer coil. Analog input B measures the *emf* induced in the inner coil.

2. Double click on the "Physics202-E205d" file in the Lab Software/202 folder on the desktop. Make sure the iron bar is inserted in the inner coil.

(a) Schematic   (b) Physical Setup
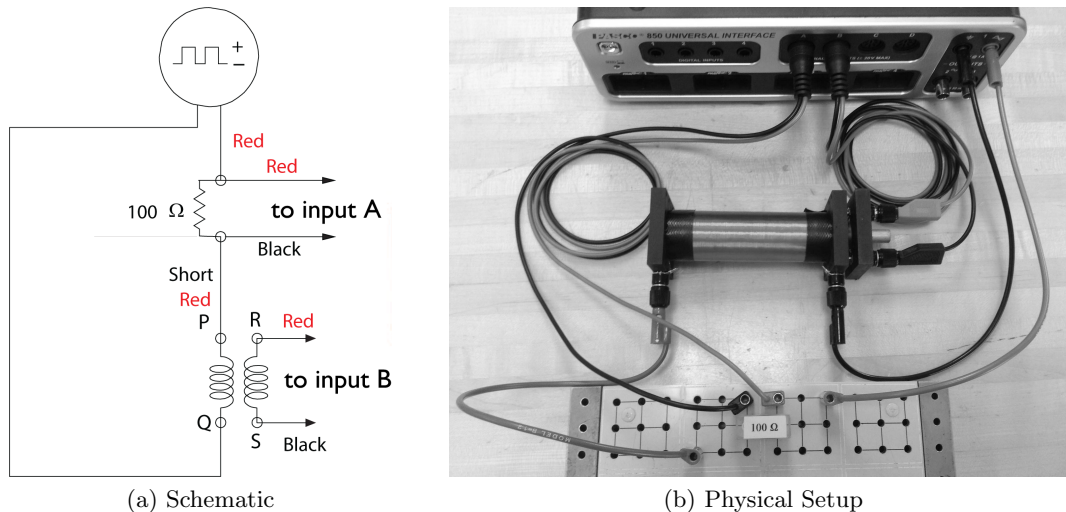
Figure 8: Schematic and physical setup

3. Check that the amplitude is $\sim$ 4 Volts, the frequency is $\sim$ 10 Hz, and the waveform is a square wave.

4. In E-5c, you applied a triangular-wave voltage to one coil, and observed a square wave in a nearby coil. What was the mathematical relationship between the square wave and the triangular wave?

5. Now we are applying a square wave to one coil. Sketch the waveform we expect to observe in the other coil. (Hint: what is the derivative of a square wave?)

6. Click on the [Record] icon.

7. The computer monitor should display three graphs:
   V A, which shows the voltage across the resistor as a function of time;
   V B, which shows the *emf* induced in the inner coil as a function of time; and
   (at the bottom) the voltage put out by the power supply.

8. Does the shape of V B look like your sketch from step 5? (It should.)

9. The shape of curve V A is not quite a square wave. Why not? HINT: this is an LR circuit with a time constant $\tau = L/R$

10. Estimate the time constant of curve V A by making measurements on the graph (see Appendix for a tutorial on how to do this).

11. Estimate the total R of the circuit from the "asymptotic" value of the current through the resistor. Why is this different from 100 Ω ?

12. Estimate the inductance L of the circuit.

13. The outer coil has $N = 2600$ turns of fine wire. Measure its radius r and length l, and calculate its inductance using $L = \mu_0 N^2 A/l$. Is this close to the value you got in the previous step? (It shouldn't be...)

14. Remove the iron bar. Take data. Estimate the time constant of curve A.

15. Assume the resistance of the circuit hasn't changed, and estimate the new inductance of the circuit. Is this closer to your calculation in step 13?

16. Explain in words why removing the iron bar changed the inductance of the circuit.

E-206 Oscilloscopes and RC Decay

Objective:

Learn the basic operation of an oscilloscope; use the oscilloscope to investigate the time constant associated with a series RC circuit.

Apparatus:

TDS 2001C or 2002B oscilloscope; 2 oscilloscope probes; plugboard and plugboard kit; multimeter; function generator; BNC-to-micrograbber adapter.

Introduction:

The oscilloscope is a high-speed graph-displaying device that displays graphs of electrical signals. In most applications the graph shows how signals change over time: the vertical (Y) axis represents *voltage* and the horizontal (X) axis represents *time*. This simple graph can tell you many things about a signal, including amplitude, frequency, waveform, and signal-to-noise ratio. Oscilloscope are widely used by electrical engineers and technicians.
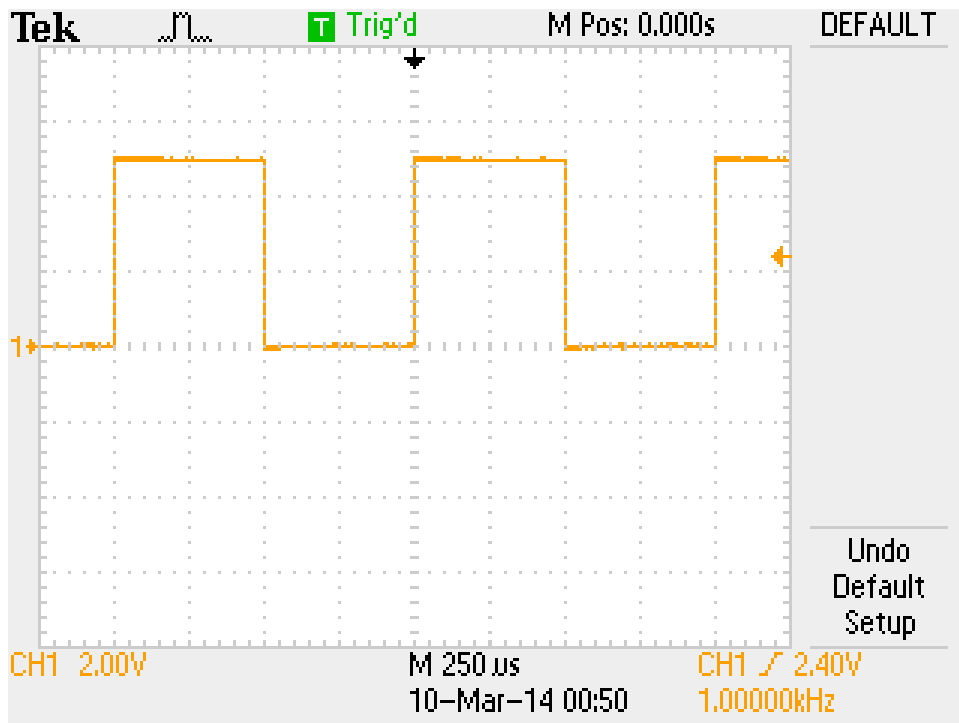
Figure 1: Initial Setup

Experiment I: Introducing the Oscilloscope

In this section, you'll set up the oscilloscope to display a waveform as shown in Fig. 1.

1. Power on the scope, and follow the directions that appear on the the screen; then press the "Default Setup" button on the second row of buttons at the top of the panel (if you ever get lost in this lab, you can press Default Setup and start from

scratch). You should see a display with a horizontal yellow line in the center, divided into eight vertical divisions and ten horizontal divisions.

2. Connect the Channel 1 probe to the "Probe Comp" contacts: the center conductor should be clipped to the top contact and the ground (alligator clip) should connect to the bottom contact. These contacts output a continuous 5V@1kHz square wave. At this point you should see a very unsteady display that is not scaled properly.

3. To stabilize the graph, adjust the "Trigger Level" knob. The trigger level is indicated graphically by an arrow on the right side of the display. Trigger level in Volts is also displayed numerically on the bottom right (we will be using a type of trigger called an "edge trigger"). You should now see a stable plot that is extends off the top.

4. Use the Channel 1 "Vertical" (or "Volts/Div") scale knob to display the entire waveform. The vertical scale (Volts per vertical division) is displayed on the bottom left corner of the display. You may have to readjust the trigger level after vertical scaling.

5. Use the "Horizontal" (or "Sec/Div") scale knob to scale the waveform horizontally to match the figure. The horizontal scale (Volts per horizontal division) is displayed in the bottom center of the display above the date.

6. Play around with all three knobs until you understand what they are doing.

7. What is the function of each knob, and how do the knobs relate to the numbers displayed?

8. What is the relationship between the scales and the grid that the waveform is plotted against?

9. How must the trigger level relate to the maximum and minimum voltages of the waveform to display a stable graph?

Experiment II: Basic Functions

The display grid allows crude measurements of amplitude and period. "Cursor" allows more accurate measurements.

1. Press the "Cursor" button on the second row of buttons on the top of the panel. Change the "Type" to "Amplitude". Using the knob to the upper right of the screen, adjust the cursor position to line up with the maximum voltage of the square wave. Note that the position of this cursor is displayed on the right side under Cursor 1. Record your measurement of this maximum voltage, and its attendant uncertainty.

2. Now highlight Cursor 2 and adjust the position to the minimum voltage of the square wave; record this voltage, and its attendant uncertainty. Based on your measurements, what is the peak-to-peak voltage, and its uncertainty?

3. Change the "Type" to "Time". Using the same mechanics as above, measure and record the period of the displayed waveform, and its uncertainty.

4. From the period measurement (and uncertainty), calculate the frequency (and uncertainty).

Another very useful device for electrical measurements is a *multimeter*. While an oscilloscope shows you the complete waveform, a multimeter collapses that waveform into a single number. Many multimeters can be set to measure either "AC" Volts or "DC" Volts. The steps below investigate one of the limitations of multimeters.
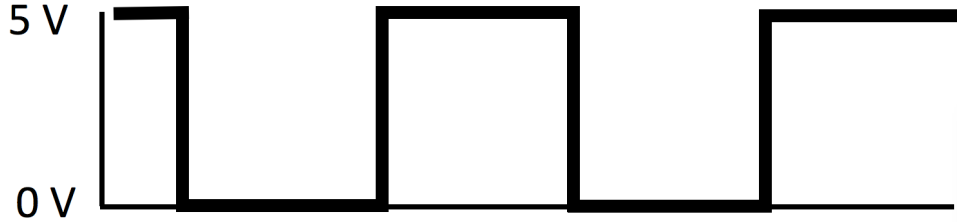

Figure 2: Oscilloscope Square Wave

5. Connect the multimeter to the Probe Comp contacts; set it to measure AC Volts; record the result as V_{AC}.

6. Set the multimeter to measure DC Volts; record the result as V_{DC}.

7. The mathematical definition of the RMS voltage is $V_{RMS} = \sqrt{\frac{1}{T} \int_0^T V^2(t)\ dt}$. Calculate V_{RMS} of the Probe Comp waveform (Fig. 2). Is it different from both of the previous two measurements?

8. Calculate the quantities $V_{mean} = \frac{1}{T} \int_0^T V(t)$ and $V_\sigma = \sqrt{\frac{1}{T} \int_0^T [V(t) - V_{mean}]^2\ dt}$ for the Probe Comp waveform.

9. Based on your answers to steps 5 through 8: what is actually measured by a multimeter set to measure AC volts? A multimeter set to measure DC volts?

Experiment III: External Signals

In this section a "function generator" will provide a signal for the oscilloscope to measure. The function generator output is referenced to ground, as is the oscilloscope probe, so be careful to connect the grounds to each other.

1. Turn off the scope cursor. Disconnect the probe from the Probe Comp terminals; connect it to the function generator output using the BNC-to-micrograbber adapter. **Always use a probe (not a random cable) to connect to a scope input.**

2. Turn the function generator and output signal on. Its default output 5V@1kHz sine wave should be displayed on your oscilloscope.

3. Use the scope "measure" function to measure the frequency and RMS voltage of the waveform; record these measurements. Use the formula for V_{RMS} given in the last section to calculate V_{RMS} in terms of amplitude for a sine wave. Use the measured RMS voltage to infer the amplitude of the sine wave. How does this compare with the "amplitude" shown on the function generator display?

4. Make a sine wave, triangle wave, and square wave with the same frequency and amplitude. Measure and record the RMS voltage of each. Compute V_{RMS} in terms

of amplitude for a triangle wave and a square wave. Use the measured RMS voltage to infer the amplitude of each wave, and record it in your notebook. How do the inferred amplitudes compare to what is shown on the function generator display?

5. What is the difference between the 5V@1kHz square wave generated by the oscilloscope and the 5V@1kHz square wave generated by the function generator? Does the scope measure V_{RMS} or V_σ?

We expect you found the amplitude inferrred from the scope measurement to be a few percent higher than shown on the function generator display. This is because the function generator is calibrated assuming it is connected to a load of 50 Ω, while the scope probe has in impedance of 10 MΩ.

Experiment IV: RC Decay

In this section the scope will be used to measure the time constant of the exponential drop-off of the voltage across a resistor in an RC circuit.
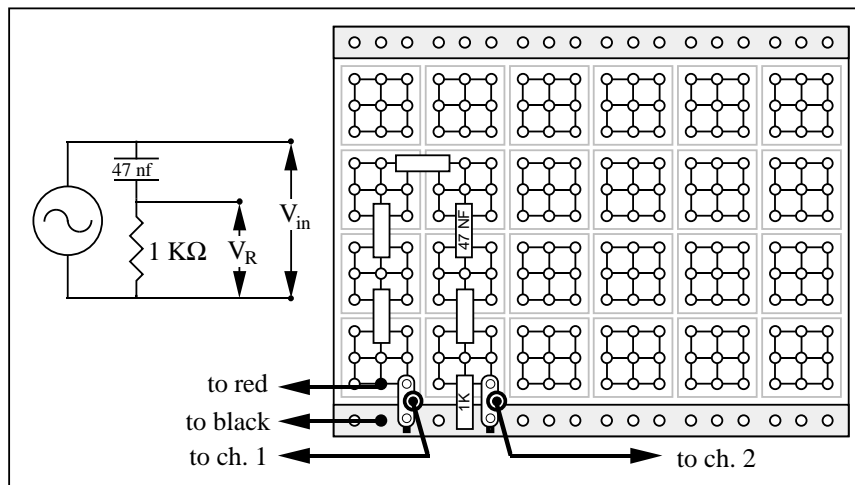
Figure 3: RC Circuit Schematic

1. Build the series RC circuit with the plug board kit as shown Fig. 3. The raised bump on one leg of the BNC-banana-plug adapter indicates which leg is ground; it corresponds to the little black square in the figure.

2. Drive the circuit with a 5V@1kHz square wave.

3. Use one probe to monitor the function generator output with the oscilloscope (as before), and connect the second probe into Channel 2 of the oscilloscope and use that probe to measure the voltage drop across the resistor. You'll need to press the blue "2" button. You should see something similar to Fig. 4.
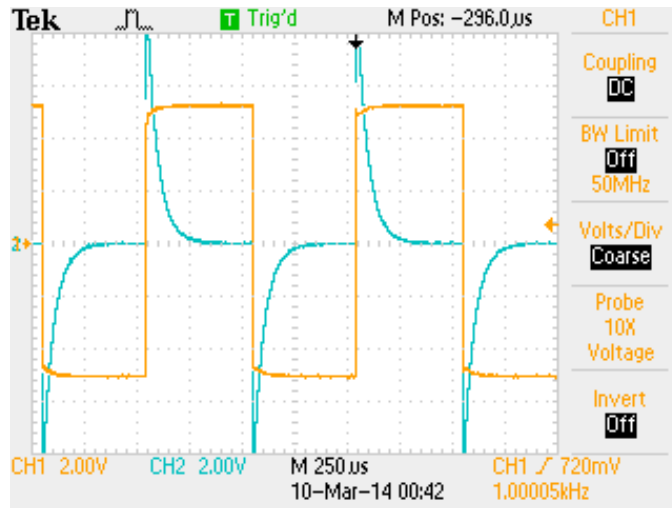
Figure 4: RC Circuit Trace

4. Using the cursor feature, measure the time constant for this circuit (see Appendix for a tutorial on how to do this). Does it agree with the theoretical value, $\tau = RC$, to within measurement precision? (Note our resistors have tolerance +/- 10%.)

5. For three additional different combinations of resistors and capacitors, measure the time constants and compare them to the nominal values $\tau = RC$. You will need to change the driving frequency of the function generator and the horizontal scale of the oscilloscope accordingly.

Experiment V: Differential Amplifiers

Amplifiers are devices which change the amplitude of the output signal compared to the input signal, without distorting the waveform of the input signal. Most amplifiers increase the amplitude. The customary symbol for an amplifier is a triangular shape:
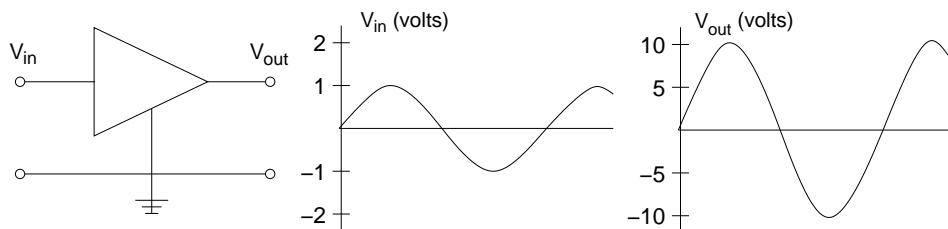
Figure 5: Amplifier Function

In the sine wave example above, the gain is 10 and the input signal is between an input terminal and ground. The internal oscilloscope amplifiers for channels 1 and 2 are of this type and have a common ground. Because of this common ground, one has problems in using a scope to examine **simultaneously** voltages across individual circuit elements that are in series.
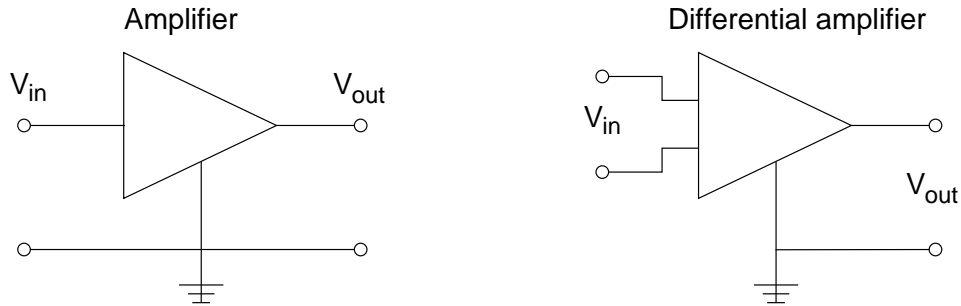
Figure 6: Amplifier vs. Differential Amplifier

We can avoid these problems by interposing "differential amplifiers" which have two inputs V' and V'', (neither at ground), and which amplify only the voltage difference $(V' - V'')$. See Fig. 6. Note now that the ground of the output signal is independent of any input ground.
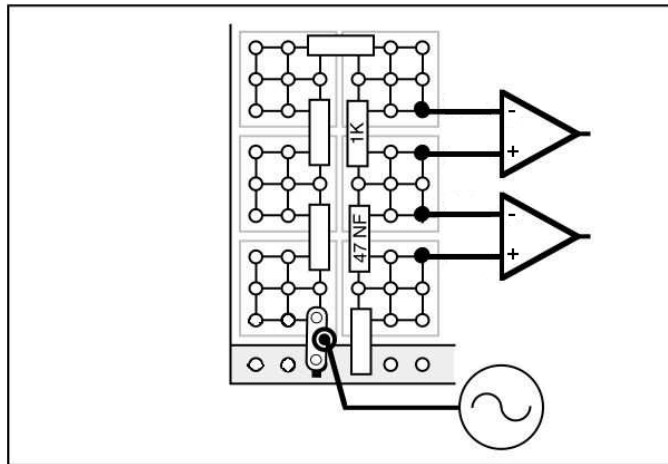

Figure 7: Inputs to differential amplifiers

1. Connect the resistor and capacitor signal to the differential amplifiers as shown in the figure above.

2. Connect the outputs of the differential amplifiers to the scope inputs, and set both gains to 1. You should see something similar to Fig. 8.
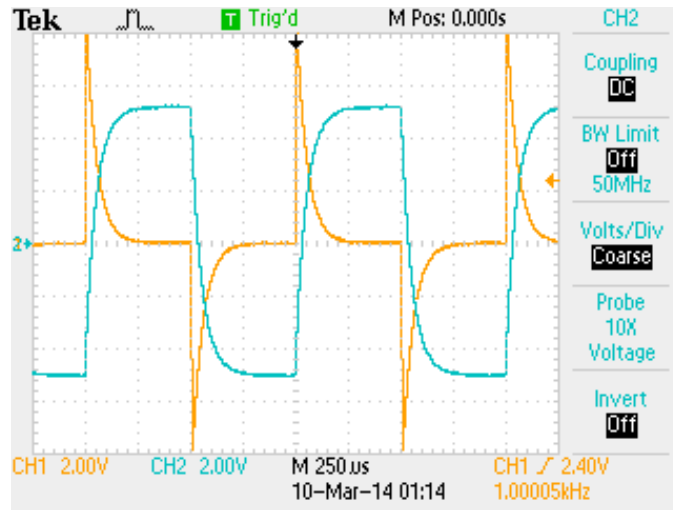
Figure 8: Differential Amplifier Outputs

3. Describe what is happening to the voltage drop across the resistor when the capacitor is charging and discharging.

4. Now press the pink "Math" button to bring up a selection of mathematical operators. Change the operation to "+". How is the display consistent with Kirchoff's laws?

E-207 Series LRC Circuits and Resonance

Objectives:
Study voltage and phase relationships in series LRC circuits; gain familiarity with impedance and reactance; observe resonance.

Apparatus:
Oscilloscope; plugboard kit; function generator; digital multimeter; differential amplifier.

Introduction:
The impedance Z of any part of a circuit as the ratio of the voltage across that part and the current though that part. Because impedance is defined as a ratio of voltage/current, impedance is measured in Ohms.

For AC circuits the ratio is a complex number: it has an magnitude and a phase. To avoid dealing with complex numbers, *resistance* and *reactance* are introduced. For ideal components:

- The resistance of a resistor is R (the reactance is zero);
- The reactance of an inductor L is $X_L = 2\pi f L$ (the resistance is zero);
- The reactance of a capacitor C is $X_C = \frac{1}{2\pi f C}$ (the resistance is zero).

The power dissipated by a resistor R is $P = V_{RMS}^2/R$, where V_{RMS} is the RMS voltage across the resistor. Inductors and capacitors do not dissipate power.

If a resistor, inductor, and capacitor are combined in series (as in Fig. 1), the magnitude of the impedance of the entire circuit is

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

Note that the impedance Z of a series RLC circuit is a *minimum* for $X_L = X_C$. The frequency for which this occurs is the *resonant frequency*. At resonance, the current through R is maximum, but the voltage V_{LC} across the LC series combination is zero. The *phase angle* ϕ of the series RLC circuit is

$$\phi = \tan^{-1}\left(\frac{X_L - X_c}{R}\right) \ ;$$

at resonance this is zero.

Experiment I: Dependence of Voltage on Frequency

1. Derive an expression for the resonant frequency of a series RLC circuit in terms of the inductance and capacitance of the circuit.

2. Create the circuit in Fig. 1 using the plug board kit. Use the function generator "output" (not "sync output") to supply V_{AC}. By default the function generator generates a sine wave at nominal frequency of 1 kHz and nominal amplitude of 5 V (10 V peak-to-peak). However it expects a 50 Ω load ($R = 50\,\Omega$), so the displayed amplitude will be different from the actual amplitude. Trust the oscilloscope's measurement to be the true amplitude.
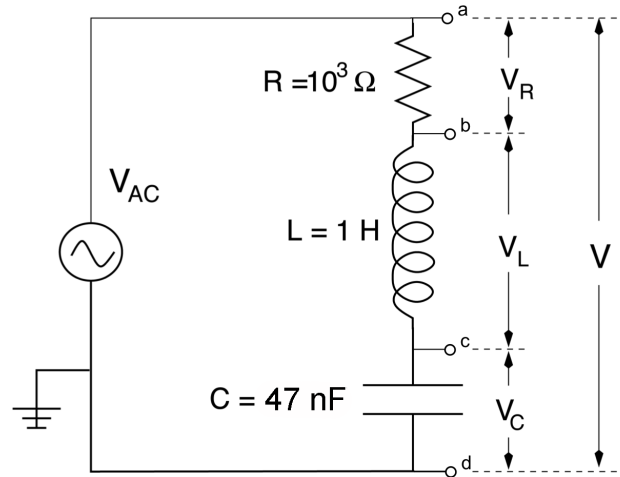
Figure 1: A Series LRC Circuit

3. Calculate the magnitude of the impedance Z of the above circuit (in Ohms).

4. Calculate the RMS current I_{RMS} through the circuit (in Amps).

5. Calculate the RMS voltage V_{RMS} across each component using $V_R = IR$, $V_L = IX_L$, and $V_C = IX_C$. Why is it the case that $V_R + V_L + V_C \neq V_{AC}$?

6. Use the digital multimeter (DMM) to measure the RMS voltage drop across the resistor (the voltage between points a and b indicated in the diagram). Check it against your calculation: your measurement should agree with your calculation. If it differs by a factor of $\sqrt{2}$, recheck your calculation.

7. Use the DMM to measure the RMS voltage drops across the inductor and capacitor. Are these consistent with your calculations?

8. Repeat steps 6 and 7 at 700 Hz and 400 Hz.

9. At 1000 Hz, which component has the largest voltage drop? At 700 Hz? At 400 Hz? Is this consistent with your expectations?

10. Measure the voltage drop across the resistor using channel 1 of the Oscilloscope, and the differential amplifier (as in lab E-6, Experiment V; use the x1 gain setting). Vary the frequency of the function generator until you find resonance.

11. How do you know when you have found resonance?

12. Measure the resonant frequency. Estimate the uncertainty by tuning the frequency as finely as possible, and estimating the upper and lower bounds of the resonant frequency.

13. Calculate the expected resonant frequency: is it consistent with your measurement?

14. While at resonance, use the DMM to verify that neither V_{bc} nor V_{cd} is zero.

15. Now measure V_{bd}. It should be close to zero. Is it?

16. Swap in the 0.47 μF capacitor, and measure the new resonant frequency.

17. Given that the capacitance has increased by a factor of 10, by what factor should the resonant frequency change?

18. Is this consistent with your measurement?

19. For four different frequencies on each side of resonance, including a few frequencies near the resonance frequency, measure the RMS voltage drop across the resistor. Make a table of V_R as a function of frequency.

20. Add a third column to the table and calculate the power dissipated in the resistor at each frequency. Use this table to create a plot of power vs frequency. Verify that it is sharply peaked at the resonance frequency. Do not delete your data yet.

21. Replace the 1 kΩ resistor with a 100 Ω resistor and repeat the previous 2 steps. Plot your data from the 1 kΩ resistor and the 100 Ω resistor on the same graph, and print a copy. How does the shape of the plot change?

22. Name one real-life application of an RLC circuit with a narrow peak in its power vs. frequency plot.

Experiment II: Dependence of Phase on Frequency

1. Switch back to the 1 kΩ resistor and use channel 2 of the scope to look at the voltage drop across the combination of the inductor and capacitor.

2. Use the Math feature to add the two waveforms (channel 1 and channel 2).

3. As you change the frequency, use the oscilloscope to measure how the relative phase between the voltage V and current I (see Fig. 2) changes.

4. At resonance, $\phi = 0$. Figure out how to measure ϕ using the oscilloscope. Find the resonant frequency. Estimate the uncertainty.

5. Which method of measuring resonant frequency appears to be more accurate: looking for maximum I, or looking for $\phi = 0$?
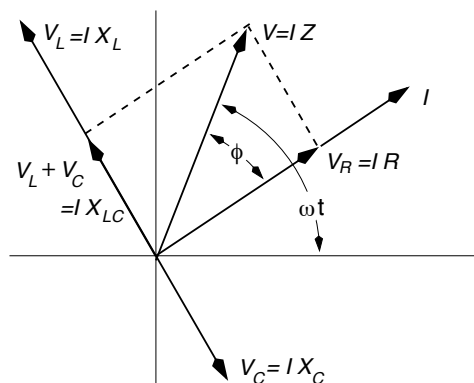

Figure 2: Phase Relations

Part II
Light

L-201: Diffraction and Interference

Objectives:

To observe diffraction; to observe interference; to measure the wavelength, λ, of laser light.

Apparatus:

Optical bench; diode laser assembly; single-slit wheel; multiple-slit wheel; screen; Pasco Interface; light sensor; rotary motion sensor; aperture bracket, on which is mounted aperture wheel.

Introduction:

The diode laser provides plane light waves of wavelength 650 (±10) nm. A plane wave passing through an opening will spread out (*diffract*). The spreading is rapid if the opening is narrow, e.g. after passing the narrow slit in Expt. I below. If two closely spaced narrow slits (narrow relative to the slit-to-slit spacing) are illuminated by the same laser beam, as in Expt. II, the two spreading beams will overlap and *interfere*.

> *CAUTION:*
> The laser is a very bright source. Do not allow the laser beam to enter the eye and do not point the beam at anyone!

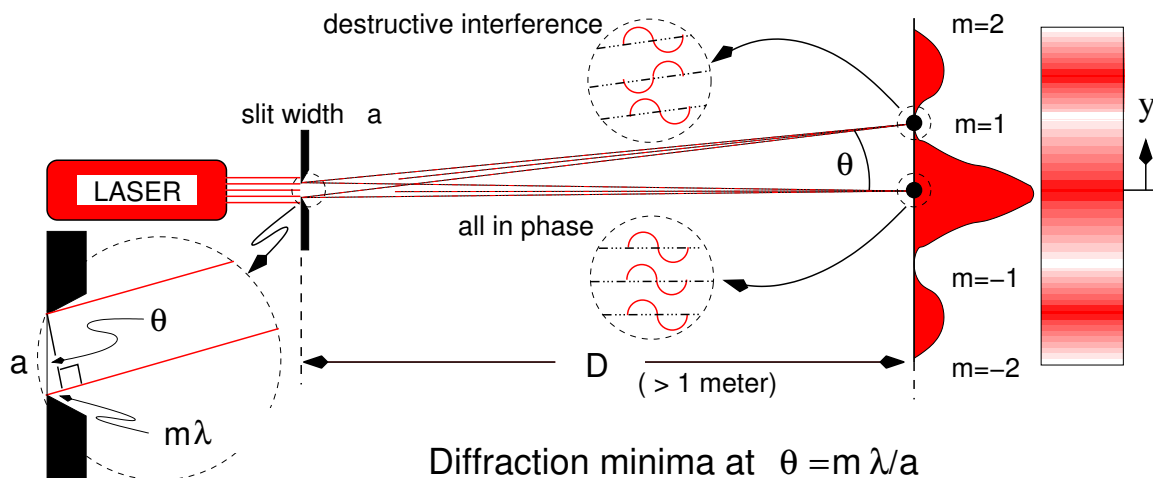**Experiment I: Single Slit Diffraction**

Figure 1: Schematic of single slit diffraction

The angular separation in *radians* of the first minimum from the center of the pattern is approximately

$$\theta = \lambda/a$$

where a is the width of the slit (use has been made of the small-angle approximation, $\sin \theta \cong \theta$).

1. Mount the laser, the single-slit wheel, and the screen on the optical bench as implied by Fig. 1. The wheel should be only a few cm from the laser, and the laser light should fully illuminate a given slit. Observe the pattern on the supplied white screen and qualitatively explain why in your lab book that the first *minimum* occurs as shown in Fig. 1 at $m = 1$.

2. Rotate the single-slit wheel and illuminate different slits. Qualitatively, how does the pattern vary as the slit width narrows?

3. Qualitatively, how do you expect the pattern would vary if the wavelength, λ, were decreased from red to blue-violet?

4. Remove the screen, and install the aperture bracket/light sensor/rotary motion sensor assembly.

5. Turn the single-slit wheel to a single slit width of $a = 0.08$ mm.

6. Rotate the aperture wheel so that aperture 2 is in front of the light sensor.

7. Double-click on the "Physics202-L201.cap" file in the Lab Software/202 folder on the desktop. Start the data acquisition by clicking the Record button. Move the combined light and rotary motion sensor in the lateral direction *gently and smoothly* by hand. Practice starting on one side of the diffraction pattern and moving smoothly towards the other.

8. Set the gain of the light sensor by setting the switch on the light sensor to 1, 10, or 100. A larger gain increases the sensor output but can more easily saturate the output. It may also increase the noise. Record the gain setting which gives you reasonably good results.

9. Let y be defined as the linear distance between the detector position and the location of the central maximum. Using the coordinates tool on the PASCO graph display, measure $\theta = y/D$ for $m = 1$ and -1. Calculate the percentage error between $\sin \theta$ and θ for your measured value of θ. Based on your answer, does it seem valid to approximate $\sin \theta$ with θ?

10. Use this information, and the known value of a, to calculate λ. Is your value of λ comparable with the stated value of the diode laser?

Experiment II: Two-Slit Interference

For two slit interference, shown in Fig. 2, the distance y to the nth bright fringe from the midpoint, $y = 0$, is

$$y = D \tan \theta \cong D\theta \qquad \text{and} \qquad \theta \cong n\lambda/d$$

Hence

$$\lambda \ = \ yd/nD,$$

(For more information refer to the text and recall that for small θ, $\theta \cong \sin \theta \cong \tan \theta$.)
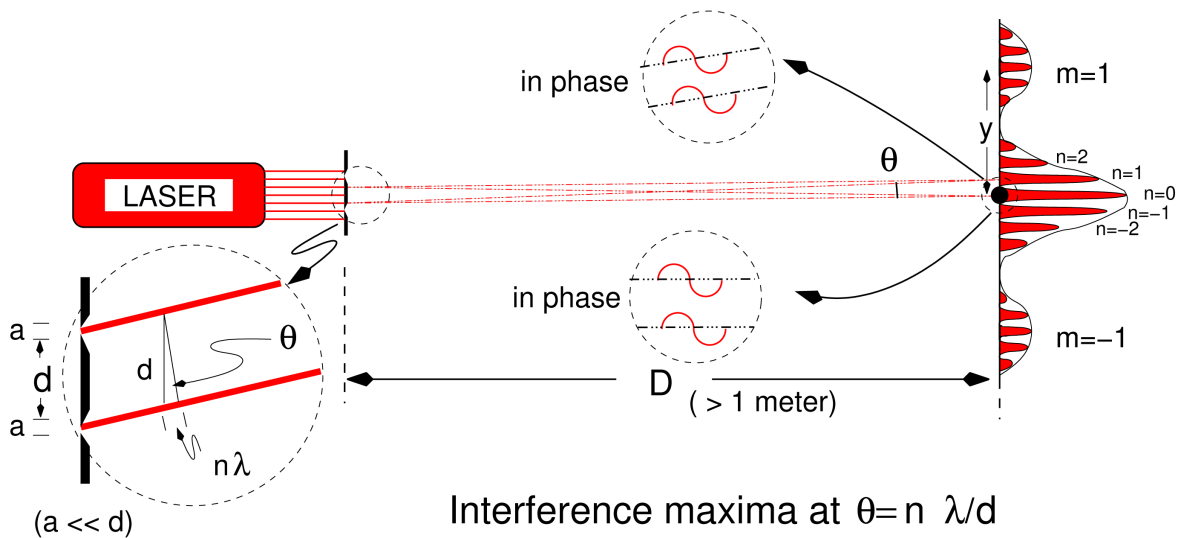

Figure 2: Schematic of double (or multiple) slit interference.

1. Install the multiple-slit wheel, rotate it to the section containing slit pairs, and illuminate one of the pairs with the diode laser.

2. Note the difference in pattern and spacing of the resulting interference fringes on the screen. From Experiment I you know that each individual slit causes diffraction. Thus you will observe a combination of single-slit diffraction and double-slit interference in all patterns. Observe the interference pattern for four slit pairs.

3. Choose one pattern for careful measurement and measure the separations between a number of adjacent maxima ($n = -1$, 0, 1, etc.) and calculate λ using the same general procedure as Experiment I.

4. Compare your calculated result with the stated value.

L-202: Mirrors and Lenses

Objective:

To study image formation and focal lengths of mirrors and lenses using the thin-lens approximation, leading to the thin-lens equation:

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} , \tag{1}$$

where p is the object distance, q is the image distance, and f is the focal length of the lens or mirror.

Apparatus:

PASCO optical rail; lenses and mirrors; telescope; illuminated arrow light source, and 12V power supply; sharply pointed rod; desk lamp; white screen.

Experiment I: Concave Mirror

1. Go to https://www.compadre.org/Physlets/optics/illustration35_1.cfm. Click "mirror"; then click on the middle of the horizontal line in order to place the mirror in the middle of the screen.
2. Click "object", then click near the left-hand side of the screen, about halfway between the horizontal line and the top, in order to place the object. You can move the object around, and make it bigger or smaller, by clicking on the object tip, and dragging the tip.
3. The x-coordinates of the object and image are shown. Use the cursor position (lower left of screen) to determine the location of the mirror. Find p and q, and then use the thin-lens equation to find f.
4. Adjust the object to get $p = q$, and obtain the focal length again.
5. Move the object so that $p = f$. Do you see an image?
6. Move the object so that $p < f$. Is there an image? Is it real or virtual? Is the image smaller or larger than the object?

A commonplace example of a concave mirror is an ordinary metal spoon. Look at your reflection in the concave surface of a metal spoon; note that it is upside down. If you keep moving the spoon closer, your reflection will flip to being right-side up (your eye may need to be within 1 to 2 cm of the spoon to see this). Extra credit question: your reflection appears to flip not when you are at a distance f from the spoon, but when you are a distance $R = 2f$ from the spoon–why is this?

Back to real life. Follow the steps below to measure the focal length f in three different ways.

> NOTE: The mirror holder contains a concave and a convex mirror on opposite sides. Be sure you use the *concave* mirror!

7. Obtain f by using object and image distances: Resolve the image of the illuminated arrow on the screen. For several different positions of the illuminated arrow, measure the object distance p and image distance q, and calculate the focal length f.
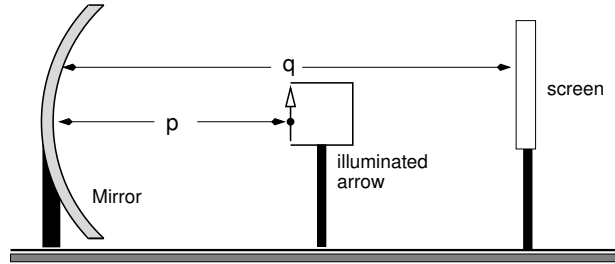
Figure 1: Layout of concave lens experiment.

8. Obtain $f = R/2$ by imaging at center of curvature ($q = p = R$): Replace the illuminated arrow and screen with the rod and place the rod at R. If the tip of the rod is at the center of curvature, a real inverted image will appear just above it with the tip and its image coinciding. An absence of parallax (see Appendix B) between the tip and image is the most sensitive test for coincidence. When the *parallax vanishes*, the distance between the tip and the mirror is the radius of curvature R. From several determinations of R (switching roles with your lab partners), estimate the uncertainty of your results.
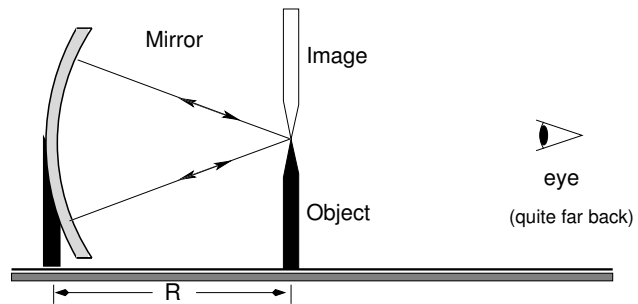
Figure 2: Object and image at center of curvature, R.

9. Obtain f by placing the object at the principal focus ($p = f$): Focus the telescope for parallel rays (e.g. focus on something out the window–see Appendix B). Keep the distance between tip and telescope small or the reflected light may *miss* the telescope. Find the focal length by looking for an *absence of parallax between the tip's image and the cross hairs* in the telescope. From several settings estimate the uncertainty of your f measurement.
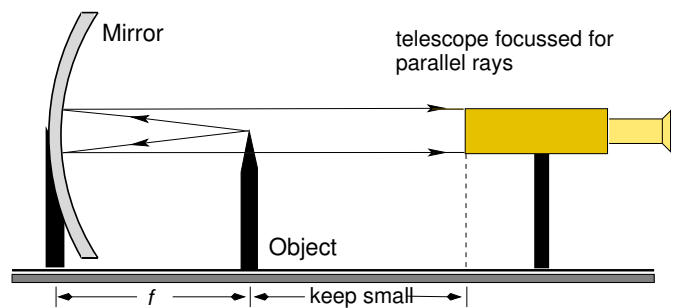
Figure 3: Object at f, image at infinity.

10. Which of the three ways of measuring f has the least uncertainty?

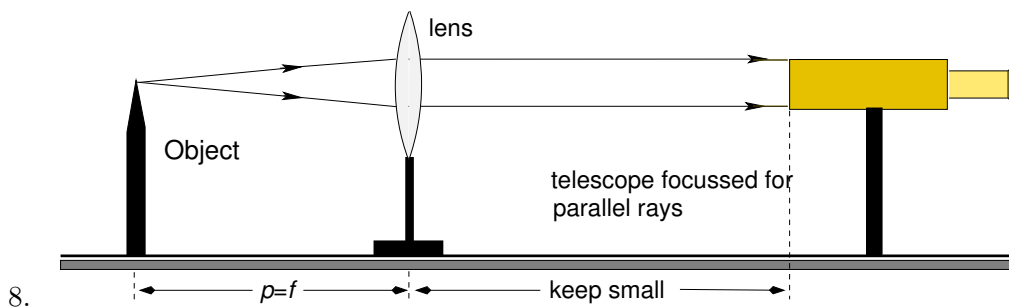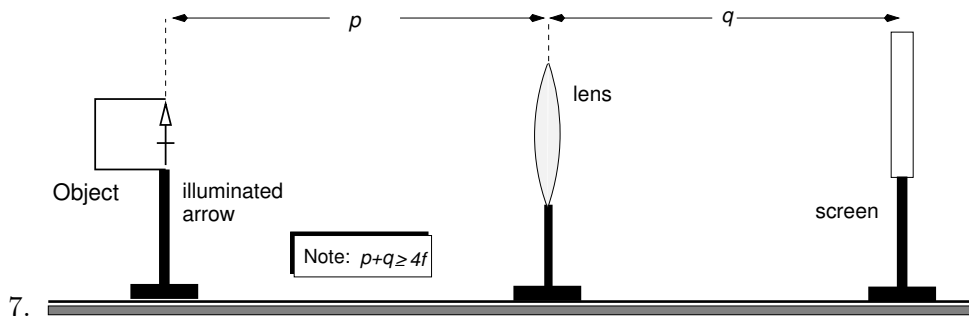**Experiment II: Converging Lens**

1. Return to https://www.compadre.org/Physlets/optics/illustration35_1.cfm.
2. Click "Clear All"; then click "Lens"; then click to place the lens in the middle of the screen. Click "Object"; then click to place the object somewhere near the left-hand side of the screen.
3. Find p and q, and use the thin-lens equation to find f.
4. Move the object so that its inverted image has the same height. Find f again.
5. Move the object so that $p = f$. Do you see an image?
6. Move the object so that $p < f$. Is there an image? Is it real or virtual? Is the image height smaller or larger than the object? What is the sign of q?

Back to real life: recall the thin lens formula

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{p} + \frac{1}{q} = \frac{1}{f}.$$

Measure f for each converging lens using the two methods diagrammed below (by adjustments in the object distance).

Start with the "red" lens, then do the "green" lens.

7.

8.

9. Which of these methods of measuring f has the least uncertainty?

Experiment III: Diverging Lens

Since the image of a diverging lens is always virtual, it is necessary to combine it with a converging lens and space the two lenses properly in order to make a real final image.

1. Return to https://www.compadre.org/Physlets/optics/illustration35_1.cfm.

2. Click "Lens"; place the lens in the center. A converging lens should appear. Click-and-hold on one of the focal points, and drag it sideways through the lens. The lens should now be a diverging lens. Click "Object", and place an object near the left-hand edge of the screen. Note that its image is virtual.

3. Measure p and q (make sure you get the sign of q right); use them to find f. Can you find an object distance for which the image height and object height are the same?

4. Click "Lens" again, and place the new lens in between the object and the diverging lens. The result should look like the picture below.

5. If necessary, move the object around so you see 2 images, labelled "1" and "2". Image 1 is the image produced by the converging lens, image 2 is the image produced by both lenses together. Move the object and alter its height, if necessary, so that the first image has the relationship $q_1 \approx 2|p_2|$. Note $p_2 < 0$ (i.e. image 1 is on the right of lens 2). Measure f_2, the focal length of the diverging lens. Compare it to your measurement in step 3 above.

6. Click and drag the lenses so that they change places. Is the ray diagram the same as before?

7. Back to real life. Use the set-up sketched below. First adjust Lens$_1$ so that with Lens$_2$ removed, $q_1 \sim 2p_1$. Measure q_1, insert the diverging Lens$_2$ reasonably close to Lens$_1$ and then locate the new image distance q_2. From $p_2 = d - q_1$ (a virtual object) and q_2 calculate f_2.

8. Is the sign of f_2 what you expect to get?
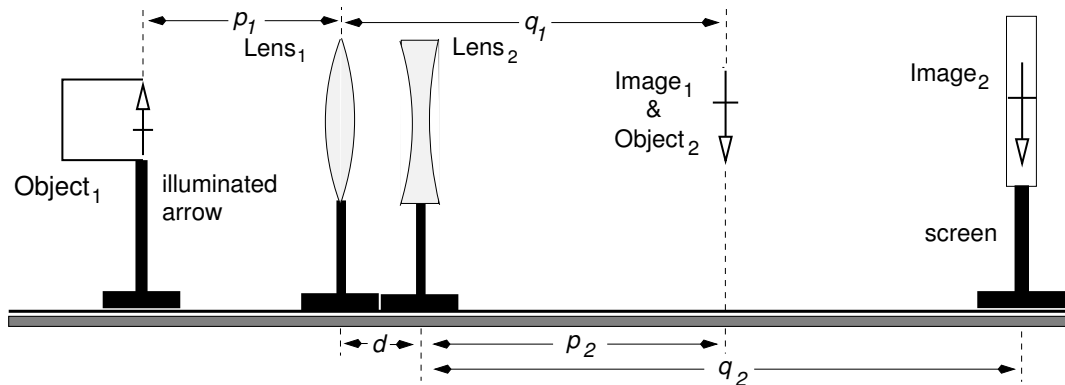
9. OPTIONAL: Find f_2 by this more sensitive method: with the pointed rod as object, detect the image by a telescope focused for parallel rays (as shown in the following figure.)

To align all the objects: tape a piece of paper with a lot of markings on it to the pointed rod. Look through the telescope and move the diverging lens forward and backward until you can see some markings clearly in the telescope. Then move the rod up or down, as necessary, and rotate the telescope from side to side, as necessary, until you can see the tip of the pointed rod. Then move the diverging lens a small amount until the tip is in focus.

As a last step you will move the pointed rod (i.e. vary p_1 and hence q_1) until a sharp image appears in the telescope with *no parallax* relative to the cross hairs. (This occurs only if parallel rays leave the diverging lens.) The image from the converging lens at q_1 serves as a virtual object for the diverging lens, Lens$_2$. After properly adjusting p_1 this virtual object will be at the focal point of Lens$_2$. Obtain q_1 by setting p_1 and using the known value of f_1. (Make sure that q_1 is large enough to accommodate $d + |f_2|$). Now look for the image in the telescope and adjust p_1. Note that since $q_2 = \infty$, $f_2 = p_2$ and $p_2 = d - q_1$.
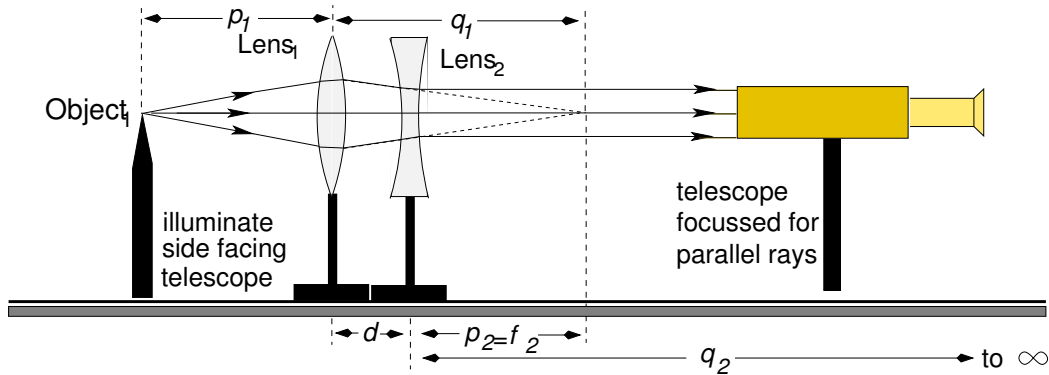

Experiment IV: Focal Length of a Convex Mirror (Optional)

Once again, since convex mirrors give virtual images it is necessary to study the mirror in combination with a converging lens.

Measure the focal length of the *convex* mirror by combining it with a converging lens. Set the pointed rod at twice the focal length of the lens ($p_1 = 2f_1$). Next adjust the mirror position until the inverted image position shows no parallax with the object. Then $R = d - 2f_1$ and

$$f_{\text{mirror}} \;=\; f_2 \;=\; R/2.$$

Of course the lens must have $f_1 > f_2$, so use a long focal length lens.
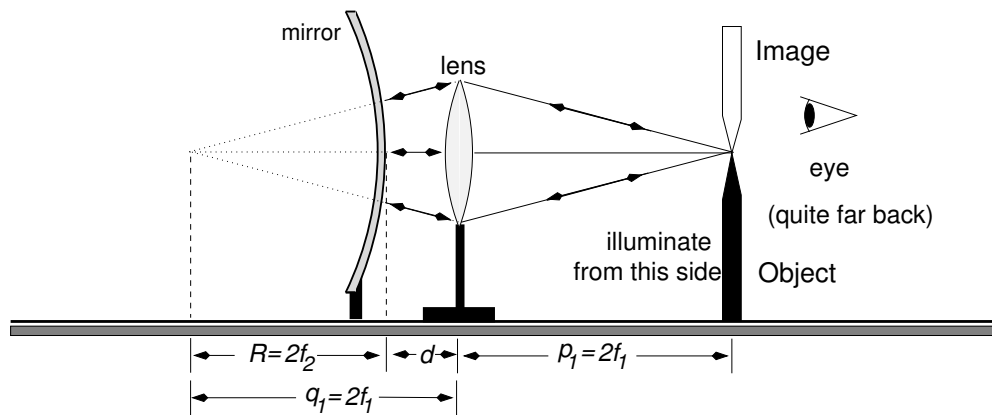
Appendices

How to Read the Time Constant of Exponential Decay from a Graph

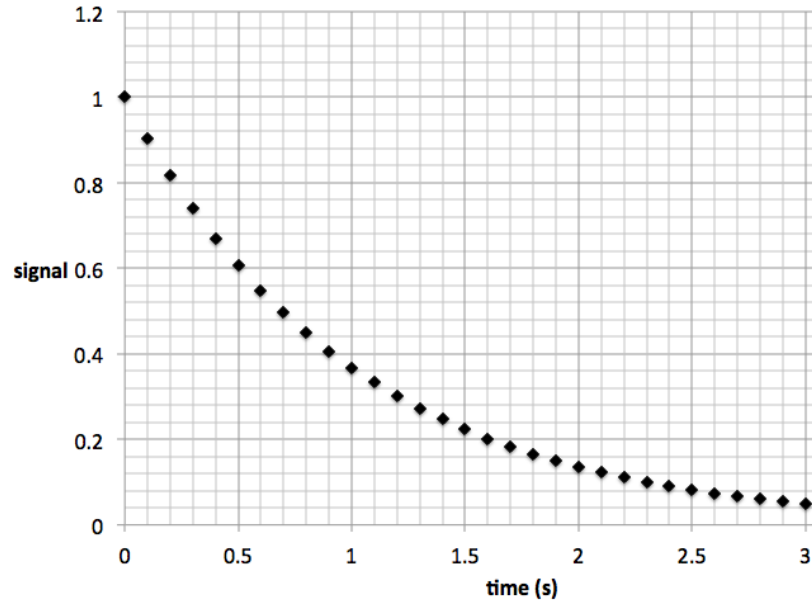
Figure 1: Exponential Decay with time constant $\tau = 1$ second.

The above graph was plotted using the formula **signal**$=1.0e^{-t/\tau}$, with $\tau = 1$ second. If you only had the graph, how could you deduce the time constant?

1. Specific numerical example using above graph:
   A. Pick two points with values you can read accurately from the graph. For above graph, try (0,1) and (1.6, 0.2).
   B. Take natural logarithm (to the base e) of ratio of signal values: $\ln \frac{0.2}{1.0} = -1.609$
   C. Time constant is difference between t values divided by this:
   $\tau = \frac{1.6 \text{ seconds} - 0 \text{ seconds}}{-1.609} = -0.994$ seconds

   Negative sign indicates decay (positive sign indicates growth). Time constant read from graph to within 0.6 % of the correct value!

2. Using mathematical language: to associate a time constant with some decaying signal, use the functional form **signal**$=Ae^{-t/\tau}$.
   A. Pick two points, first point with time t, second point with time $t + T$.
   B. Ratio of the signal at the two times will be $R \equiv \frac{Ae^{-(t+T)/\tau}}{Ae^{-t/\tau}} = e^{-T/\tau}$
   C. $\tau = \frac{T}{\ln R}$

   This works with any two points.

3. Some especially convenient choices:

—estimate the time it takes for the signal to decrease by a factor of $\frac{1}{e} = 0.3678$. This is the time constant. Confirm: on the graph above, the point with the signal value closest to 0.3678 is at t = 1 second.

–pick the first good data point and the last good data point. In graph above: (0,1) and (3, 0.05). Using above rule: T= 3 seconds, $R = 0.05$, so $\tau = -1.0014$ seconds. Time constant read from graph to within 0.1% accuracy!

Exercises:

1. How many time constants does it take for a signal to exponentially decay to a. half its value; b. one-tenth its value?
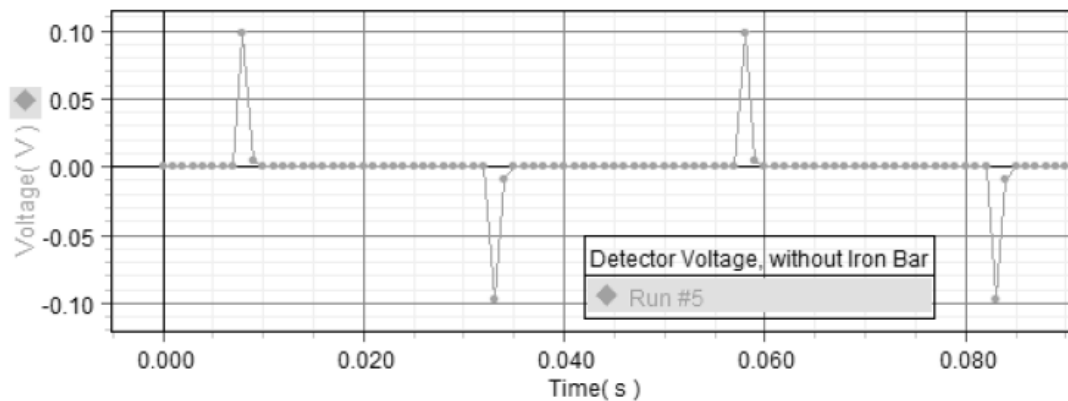
   answers: a. 0.69 (that is, 0.69 of a time constant); b. 2.3

2. Estimate the time constant associated with the signal below:
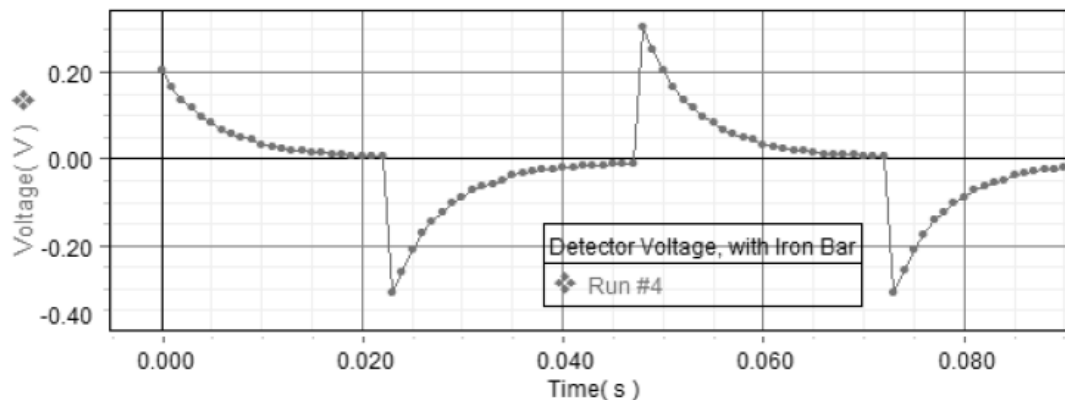
   answer: use two points (0.0,0.2) and (0.015,0.02) to get $\tau = -0.0065$ seconds.

3. Estimate the time constant associated with the signal below:

   answer: separation between adjacent points appears to be 0.001 seconds; take adjacent points at (0.008,0.1) and (0.009,0.005) to get $\tau = -3.3 \times 10^{-4}$ seconds.

Parallax and Notes on using a Telescope

1. **Parallax:**

   To do quantitative work in optics one must understand *parallax* and how it may be eliminated. PARALLAX is defined as *apparent motion of an object caused by actual motion of the observer.*

   As the observer moves left and right, object 1 appears to move to the left and right of object 2. The amount by which object 1 appears to move is proportional to the distance between object 1 and object 2. If object 1 comes in front of object 2, the direction of its apparent motion reverses.

   Try this with two fingers.

   Note that if object 1 is an image and object 2 a cross hair, the absence of parallax shows that the cross hairs are in the plane of the image.
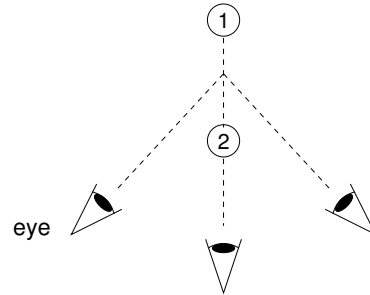
2. **Focusing a Telescope for Parallel Rays:**

   O = objective lens

   E= eye piece. It may be a single lens or several lens.
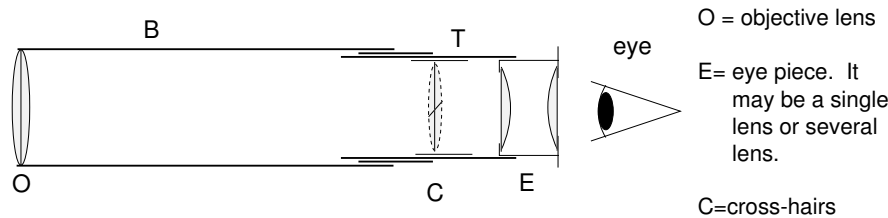
   C=cross-hairs

   The eyepiece E slides back and forth in the tube T and one should first adjust the eyepiece to give a clear image of the cross hairs. Then move the tube T back and forth in the barrel B until the image of a distant object, formed by the objective O, falls on the plane of the cross hairs. The test for this is the absence of parallax between the cross hairs and image.

   The rays from a distant object are nearly parallel. For viewing a distant object, use an open window if the window glass is not accurately plane. Otherwise poor image formation may result. You can check by trying it both ways. At night use a distant object in the hallway.

   The telescope, now focused for parallel rays, will stay so as long as the distance between O and C is unchanged. One may still adjust the eyepiece position to suit the observer.

3. **Finding an Image in a Telescope:**

   If you have trouble finding an image in a telescope, locate the image first with your unaided eye, and then pull the telescope in front of your eye, aligning it with your line of sight. With high magnification it is difficult to find the image in the telescope because the alignment must be nearly perfect before the image appears in the field of view. The eye has a rather large field of view so that the image will be visible over a range of positions.