Name_____   Section_____

Physics 208 Laboratory
Electric Fields and Electric Potentials

Your TA will use this sheet to score your lab. You must use complete sentences and clearly explain your reasoning to receive full credit.

What are we doing this time?

You will complete two related investigations.

PART A:
   Use a numerical simulation to plot on the screen equipotentials and electric field vectors for various charge distributions, and see how the presence of additional neutral conductors changes this.

PART B:
   Use the field plotting board to map the equipotentials of an electric dipole, and to determine how the potential difference 'across' a dipole depends on the angle with respect to the dipole axis.

PART C:
   Use the field-plotting board and the torso cutout to understand how an electrocardiogram measures properties of the heart electric dipole.

Why are we doing this?

To understand the electric potential energy around charges and conducting objects, and how to apply this understanding to interpreting an electrocardiogram

What should I be thinking about before I start this lab?

You should be thinking about the relation between electric potential, work, and energy.

Any safety issues?

No

A. Numerical Simulation

Click on "EM Simulator" in the applets column on the course web site "Laboratories" page, or go to https://www.physics.wisc.edu/instructional/phys208/emstatic/

The electric field at each point is shown as a vector, but all the vectors have the same length: the magnitude of the electric field is indicated by color. White = large electric field
Light Green = medium electric field
Dark Green = small electric field
You should be able to click and drag the positive charge around on the screen.

A1. The white line contours are equipotentials, connecting points in space that have the same electric potential. Each contour is a different electric potential, and the electric potential difference between adjacent contours is a constant value ΔV.
Why do the equipotentials get farther apart as you move away from the charge? (Answer in terms of the relation between electric field and electric potential).
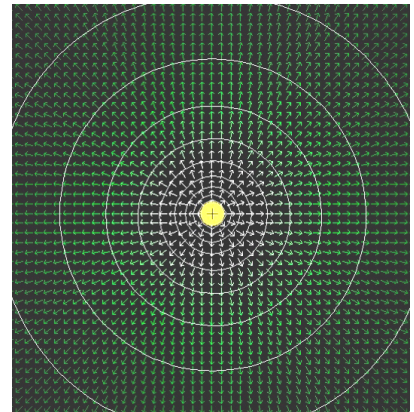
A2. *Conducting Planes* Under the setup menu choose 'Conducting Planes'. Two plates appear, with equal and opposite electric potential. Move the plates around with your mouse to see the effects on the field lines and equipotentials.
When the plates are aligned, the equipotential lines are approximately equally-spaced between them. Explain why this is so.
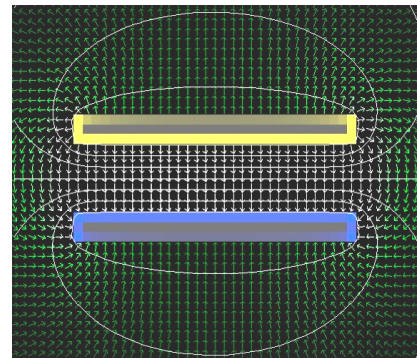
Note: you can "reset" any setup by loading a different setup, and then going back to the original setup.

Yellow indicates positive charge, and blue indicates negative charge. Explain how the charge arrangement is consistent with the direction of the electric field vectors between the plates.

Explain how the relative magnitude of the electric fields between the plates and outside of the plates is consistent with the charge distribution.

A3. Move the plates to the top and bottom of the screen.
Select "Mouse=Add Conductor (Gnd)" from the   Mouse dropdown menu.
Draw an empty box as indicated. If you mess up, click the mouse on a pixel you don't want, and it will go away.
Select "Mouse=Make Floater" and convert the grounded conductor to a floating conductor by putting your mouse over it and clicking. It is now an isolated conductor with zero net charge.
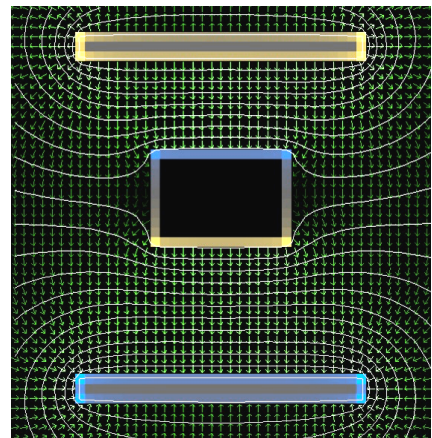
Explain why the charge is distributed as it is on the box that you drew.

Select "Mouse=Move Object" from the Mouse dropdown menu, and move your box around the screen. What is the electric field inside the box?

A4. *Dipole and induced charges:* Under the setup menu choose 'Dipole Charge'. You should see + and – point charges with the corresponding field lines and equipotentials.

Click and drag the charges so that the dipole is horizontal near the bottom of the screen, and takes up most of the screen.
Select 'Mouse=Add Conductor (Gnd)' and draw a filled rectangle near the top of the screen.
Select 'Mouse=Make Floater' and convert the grounded conductor to a floating conductor by putting your mouse over it and clicking. It is now an isolated conductor with zero net charge.
Select 'Mouse=Move Object' and drag the conductor around on the screen. The local charge density on the conductor is color coded, blue for negative and yellow for positive.

i) Drag the conductor down near or between the dipole charges. Describe what happens to the charge distribution on the conductor, and how the electric fields change. What value do you think the electric field has inside the conductor? Explain what is going on.
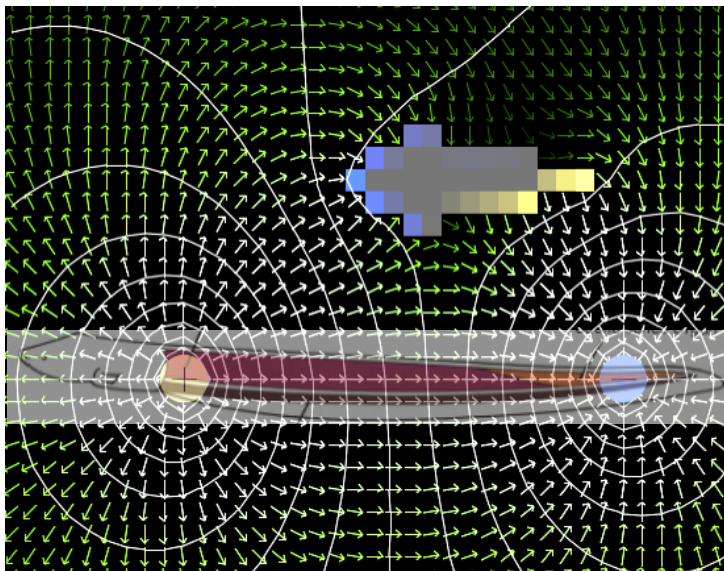
ii) How can the presence of the conducting object affect the fields near the dipole?
(Hint: how would you describe the induced charge distribution on the conducting object, and how would this effect the fields?)

iii) Suppose the dipole is an electrogenic fish, i.e. a fish that can cause a charge separation in its own body between its head and tail. Suppose that the conducting object is its (conducting) prey. The electrogenic fish senses its prey by detecting changes in electric fields on its own skin caused by the conducting prey. Move the prey around and watch the electric fields in the region of the dipole.

What do you think are some of the factors that affect how close the conductor must be to the fish before it noticeably affects the electric fields at the fish?

B: *Analog simulation*

Here you use a piece of conductive paper in which currents flow to simulate electric fields and equipotential surfaces in vacuum.

Field plotting board: Get a piece of conductive paper with two silver dots (representing conducting spheres), one on each end. On the field plotting board, first put down a sheet of white printer paper, then a sheet of carbon paper (carbon side down), and finally the graphite paper on top.

Power supply: Inspect the power supply to make sure there is a thin metal bar connecting the "—" and "GND" terminals; if there isn't, call over your TA. Use a red banana-plug cable to attach the output of the DC power supply to one magnet connector on the field plotting board, and a black cable to attach the ground output to the other (See Appendix A – Using a DC power supply). Put the magnet connectors on top of the silver dots on the conductive paper. This maintains a constant potential difference between the two painted conductors on the conductive paper.

Digital multimeter, DMM: Sit the points of the DMM probes in the electrical connections attached to the magnets. Set up the DMM to measure the potential difference between the magnets (see Appendix B – Using a digital multimeter).

Adjustments: Turn on the DC power supply and adjust the voltage until the multimeter reads about 18V (see Appendix A – Using a DC power supply). The display on the DMM is the electric potential difference across its inputs, $V_{Red} - V_{Black}$.
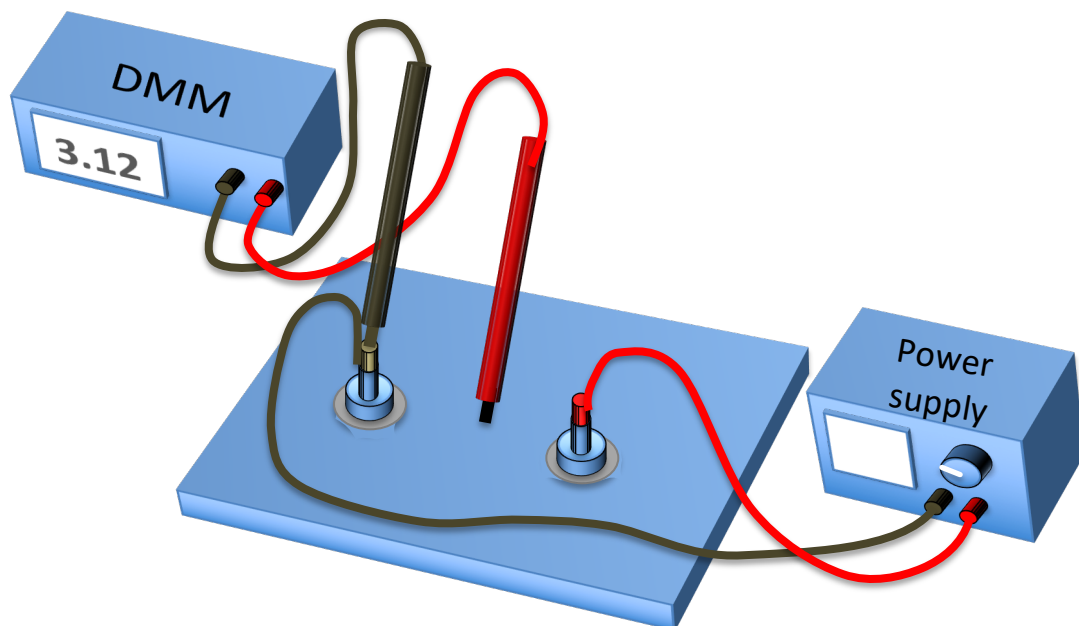
B1. *Electric equipotentials of a dipole*:

You should have a conductive paper with two silver dots representing different charges on a dipole. Rest the black probe from the DMM in the banana plug connected to the voltage supply black terminal. Map out equipotential lines using this procedure:

1) Trace the perimeters of each silver dot using a probe. This will cause some of the carbon on the carbon paper to transfer to the white paper underneath. You will then have maps of the 0 V and 18 V equipotential lines on the white paper.
2) Pick a number between 0 and 18, and **write it down** (you'll need it later).
3) Probe around with the red probe until you read that number on the DMM
4) Push down firmly with the red probe at that spot, making a dot on the white paper.
5) Probe around and find another spot with the same potential. Push down firmly to make another dot. Do this enough times so that later you will be able to connect the dots with a line that you can label with a numerical value for the potential.
6) This is an equipotential: a connected set of points with the same electric potential.
7) Repeat steps 2) to 5) until you have used four or five voltages.
8) Take off the graphite and carbon paper, and connect the dots. You should have at least six lines.

Draw your equipotential lines below, and label each with their potential:
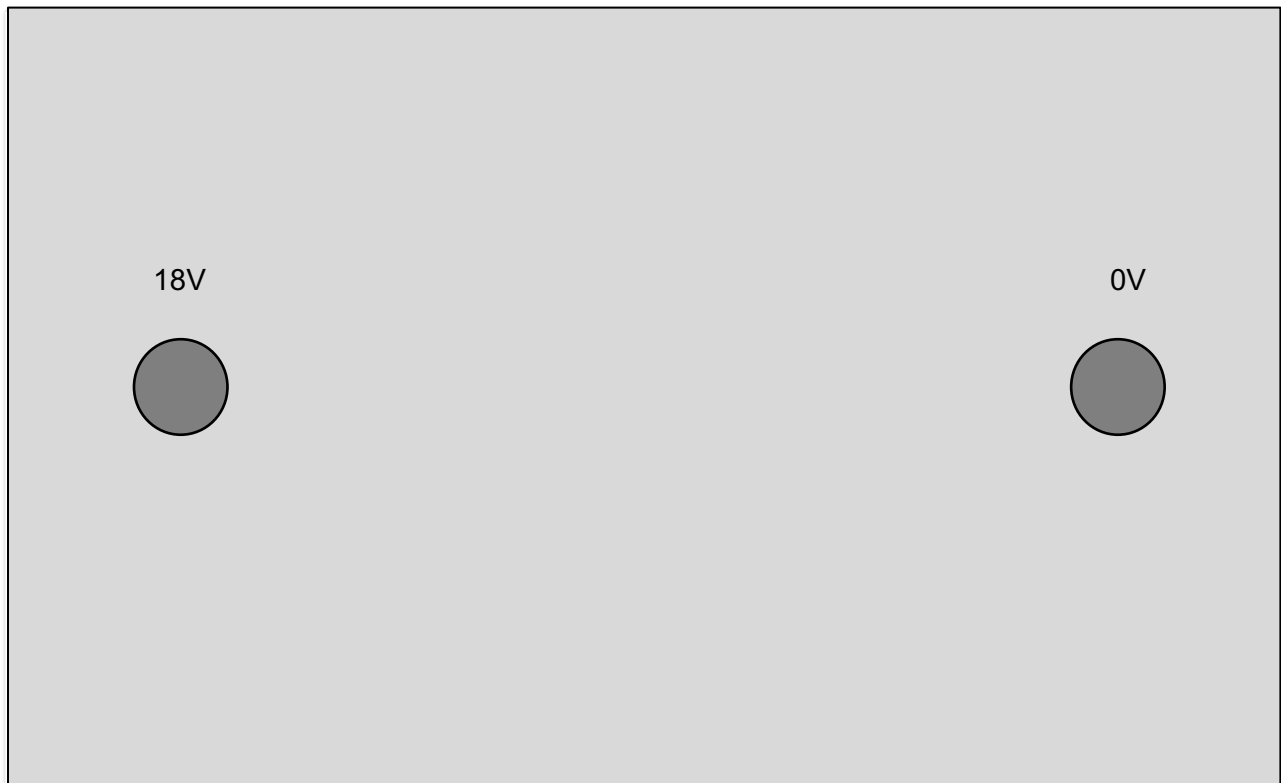
B2. *Electric potential differences around a dipole*

Now put the dipole back on the field plotting board (you won't need the carbon paper or the white printer paper). Connect the banana plugs from the + and − terminals of the power supply to the silver dots on the conductive paper. Now pick up the red and black voltage probes connected to the DMM, one in each hand. Put the probes a fixed distance apart on the conductive paper, centered on point C, at various angles with respect to the dipole axis as shown below, and read the voltage from the DMM.
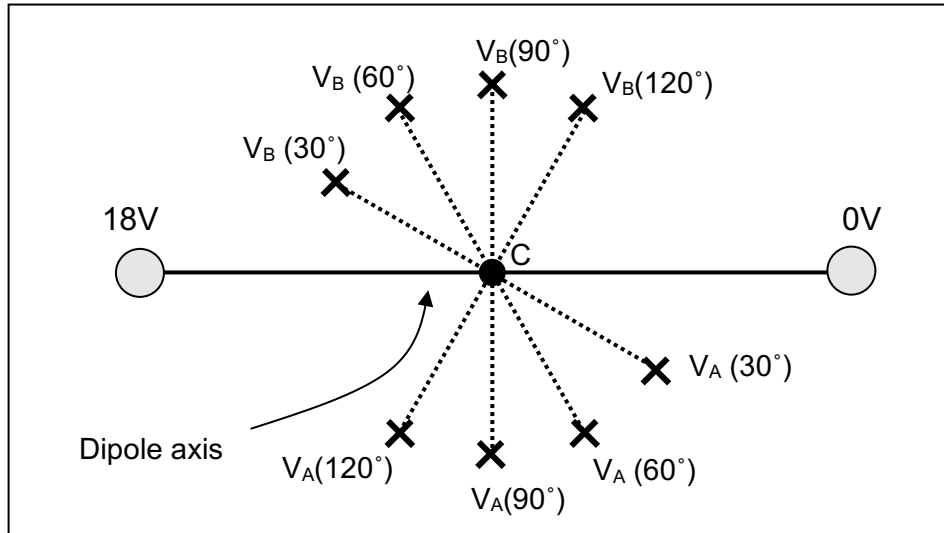
Record your data here for the following angles:

Angle	30	45	60	90	120	135	150
V_A - V_B							

Plot your results below. You will use this in interpreting the ECG in the next section.

POTENTIAL DIFFERENCE $V_A - V_B$ (V)
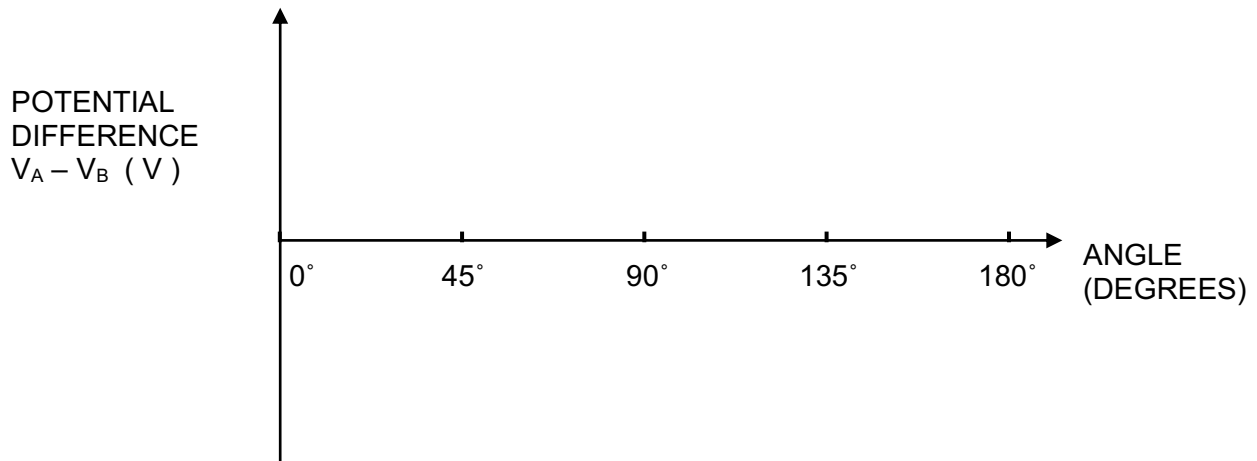
B3. Sketch the complete curve of V_A-V_B as a function of angle on the graph above (the curve should go through all of the points). If all you knew from B1 was the location and orientation of the dipole, would you be able to make an approximately correct rough sketch of this curve? (In the next section we'll investigate the inverse problem: given measurements of potential difference, deduce the orientation of the dipole.)

Your heart is embedded in a conducting medium (your body), and is electrically active. This causes currents to flow in your body, and electric potentials develop throughout your body. An electrocardiogram measures potential differences at various points on your skin. From this, a cardiologist deduces what is happening at your heart.

In this section you set up an electrical signal inside the conducting sheet, and investigate the dipole magnitude and direction by looking at potential differences on the outside. This is similar to the way an electrocardiogram obtains information about your heart.

In a common approximation, the electrical activity of your heart can be characterized as an electric dipole, with a potential difference between the two poles. The electrocardiogram is trying to determine the orientation of a dipole in your heart by making measurements on the surface of your body.

How can a heart be a "dipole"?
When your heart beats, it establishes a very complicated charge and potential distribution that changes in time as different parts of the heart are stimulated. Your heart accomplishes this by moving around positive and negative charge.

The total charge is always zero, just rearranged, so a dipole is a good approximation. The 'fine-tuning' charge distribution that differentiates the actual distribution from a dipole is not very important. It generates a potential that dies away rapidly as you move away from the heart. So from far enough away, the potentials in the body due to the heart are indistinguishable from those produced by a dipole.

Here is a picture of the heart dipole at an instant 240 ms into a heartbeat, and a plot showing the tip of the dipole vector as a function of time (dotted path). The heart dipole changes both direction and magnitude during the heartbeat.
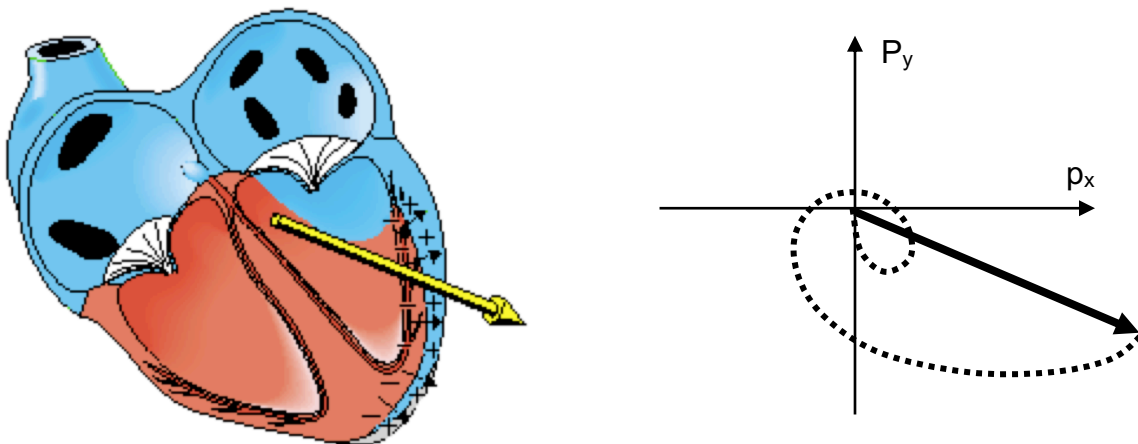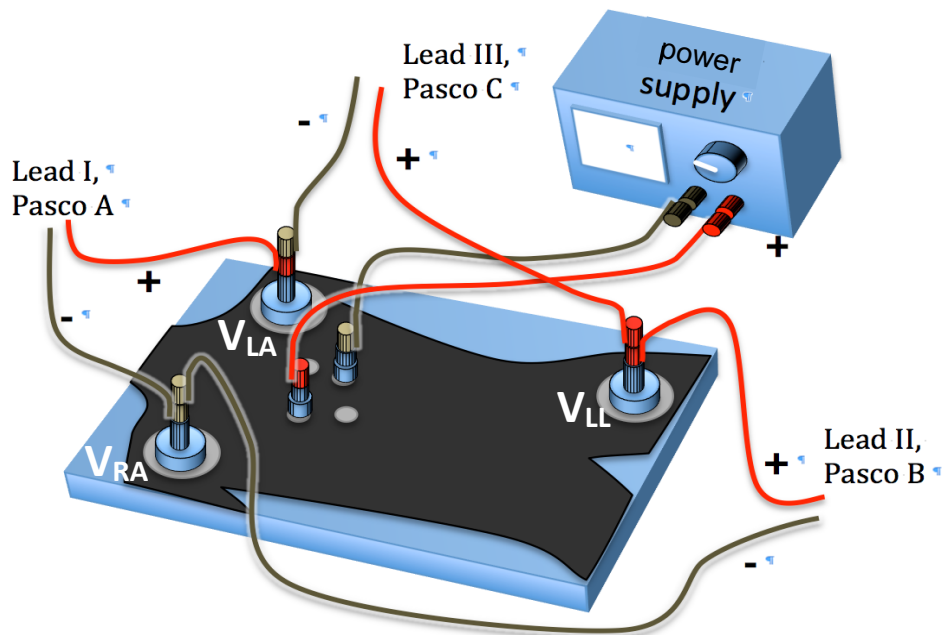
Turn on the Pasco interface.

Remove the dipole graphite sheet and carbon paper, and substitute the torso cutout (no carbon paper) as shown. The three main leads of an electrocardiogram are usually called Lead I, Lead II, and Lead III. These all give different views of the heart dipole.

In terms of the electric potentials $V_{RightArm}$ (V_{RA}), $V_{LeftArm}$ (V_{LA}), and $V_{LeftLeg}$ (V_{LL}), the voltages measured by the three leads are:

Lead I measures _____

Lead II measures _____

Lead III measures _____

Double-click the Lab3_Settings.cap file in the Lab Software/208 folder on the Desktop. This opens the data acquisition program with the correct settings.

You will use the large magnet electrodes to connect the leads to the arm and leg as follows: analog input A of the Pasco interface for Lead I, analog input B for Lead II and analog input C for Lead III.

You will use the small magnet electrodes to connect the output of the DC power supply to two of the heart dipole connections. Connect a banana plug cable from the red and black connections to the heart dipole magnet electrodes to power your heart model.

Set the voltage supply to 10V. The heart now has an electric dipole moment, and each of the three leads will measure some electric potential difference. We will refer to these voltage signals as "resting voltage".

You will change the heart electric dipole moment, to simulate the heartbeat, by increasing and decreasing the voltage applied by the power supply (see Appendix A – Using a DC power supply).

Click record on the data acquisition program, and increase the voltage to 15 or 18 volts, down below 10V, then back up to 10V, to simulate a heartbeat (ba-bump!). If you do this quickly, then wait a second, and then repeat, etc, it will look more like a heartbeat on an electrocardiogram.

Then move the small magnet electrodes to the other (perpendicular) pair of dots, placing the + electrode on the dot further from the head, and take another set of ECGs.

C1) For your two different orientations of the heart dipole, measure the excursion (positive or negative; magnitude not needed) from the resting voltage for leads I, II, and III. The resting voltage is the value of the signal with the voltage set at 10V, in between heartbeats.

Orientation	Lead I	Lead II	Lead III
#1			
#2			

To generate this data, you used a fixed heart dipole direction, and varied the magnitude of the dipole by adjusting the power supply to simulate the heartbeat. You also used a different dipole direction (~ perpendicular to the first one) that gave a very different set of ECG traces.

This different dipole direction might indicate a heart problem. For instance, if part of the heart is enlarged, the extra tissue in that part leads to a bigger component of the dipole in that direction.

You obviously know the dipole directions you used for the two different data sets. But suppose you *didn't* know, and you needed to use the ECG traces to determine the dipole direction and magnitude (as cardiologists need to do). For each of your data sets from this part, use your work in part B2) to qualitatively determine the direction of the heart dipole. Print out your ECGs if it is easier for you to analyze them that way.

C2) Explain below how you used the ECG data to determine the dipole direction.

Suppose one of the ECG leads gives a very small signal. How can you tell if this is because the dipole has a small magnitude, or because it has a particular orientation?

Suppose two ECG leads give almost the same voltage signal. What does this mean about their orientation relative to the dipole?

Suppose two ECG leads have the opposite sign of signal. How must the dipole be oriented?

Physics 208 Laboratory
Capacitor circuits and resistor circuits

Your TA will use this sheet to score your lab. It is to be turned in at the end of lab. You must use complete sentences and clearly explain your reasoning to receive full credit.

What are we doing this time?

You will complete three related investigations.

PART A:
Build capacitor circuits, investigating charge distributions and voltages.

PART B:
Build a circuit with light bulbs, using the relative brightness of the bulbs to visualize the current flow.

PART C:
Build resistor circuits, and measure current and voltage.

Why are we doing this?

Capacitors are almost as ubiquitous as dipoles, showing up almost everywhere there is an insulator. Actually, capacitors have some similarities to dipoles, with equal and opposite charges on the electrodes. That charge has to flow through something to get to the capacitor. The same holds for resistors. The ideas of current flow, current splitting along different paths, and potential differences, are essential ideas in all circuits.

What should I be thinking about before I start this lab?

You should be thinking about the aspects of capacitors you looked at in lecture and discussion. In particular, how the voltage across the capacitor is related to the charge on it, and how the current in a circuit delivers charge to a capacitor. Also how charge moves in a circuit, and that charge must always be conserved – it can be neither created nor destroyed.

Any safety issues?
The resistors in this lab will get fairly hot. Touch only the clear plastic housing.

For the first part of the lab, you use the circuit board below.
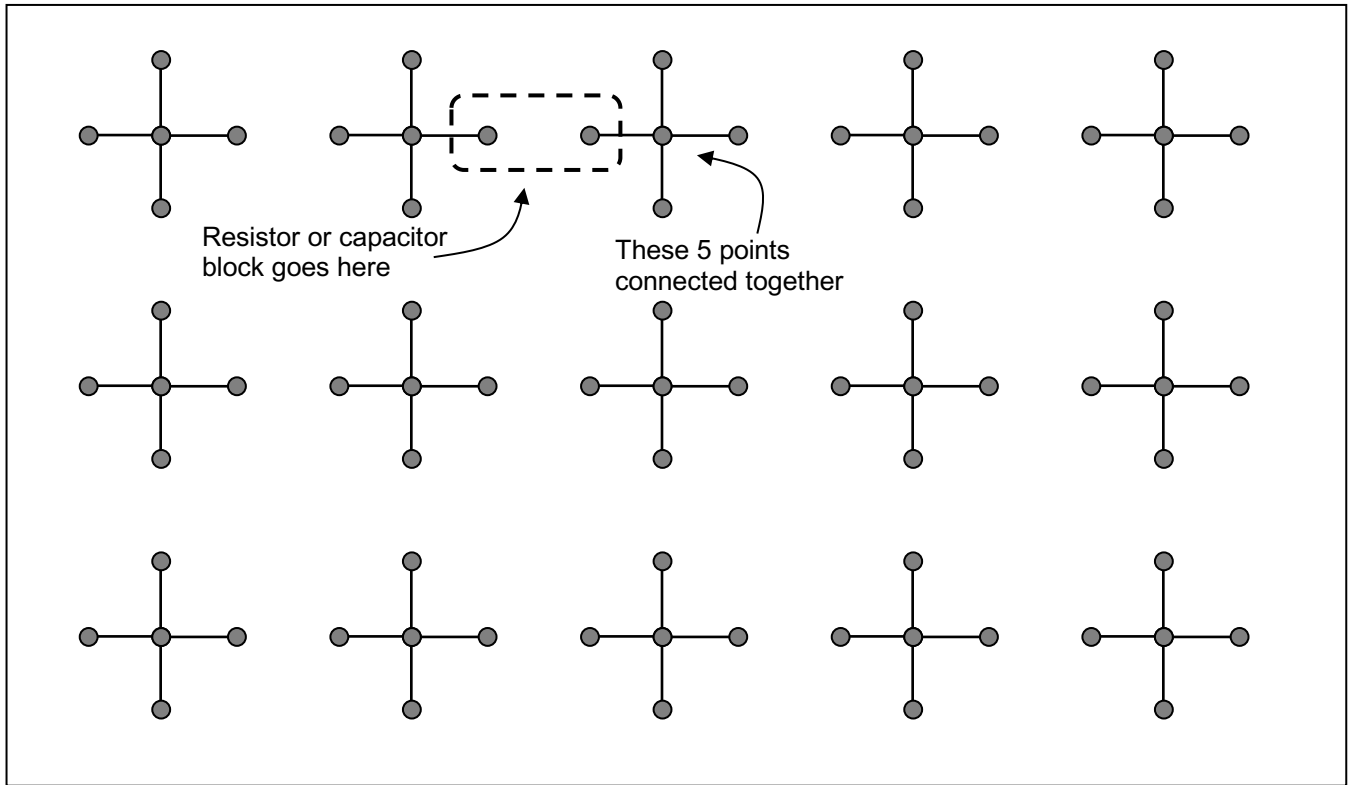
Resistor or capacitor block goes here

These 5 points connected together

Holes connected by black lines are electrically connected by conducting wires, so all points connected by black lines are at the same electric potential. You build a circuit by plugging in resistors and capacitors across the gap between crosses. The capacitors and resistors are built into plastic blocks with banana-plug connectors that exactly bridge the gaps. After you plug in a block, there will still be unused holes in each cross. You will use the remaining holes to connect the power supply to your circuit, and to connect the electrometer (capacitor circuits) or digital multimeter (resistor circuits) to measure potential differences and currents at various points in the circuit.

Inspect the power supply to make sure there is a thin metal bar connecting the "—" and "GND" terminals; if there isn't, call over your TA. Set the power supply voltage to 9 V (see Appendix A, *Using a DC Power Supply*).
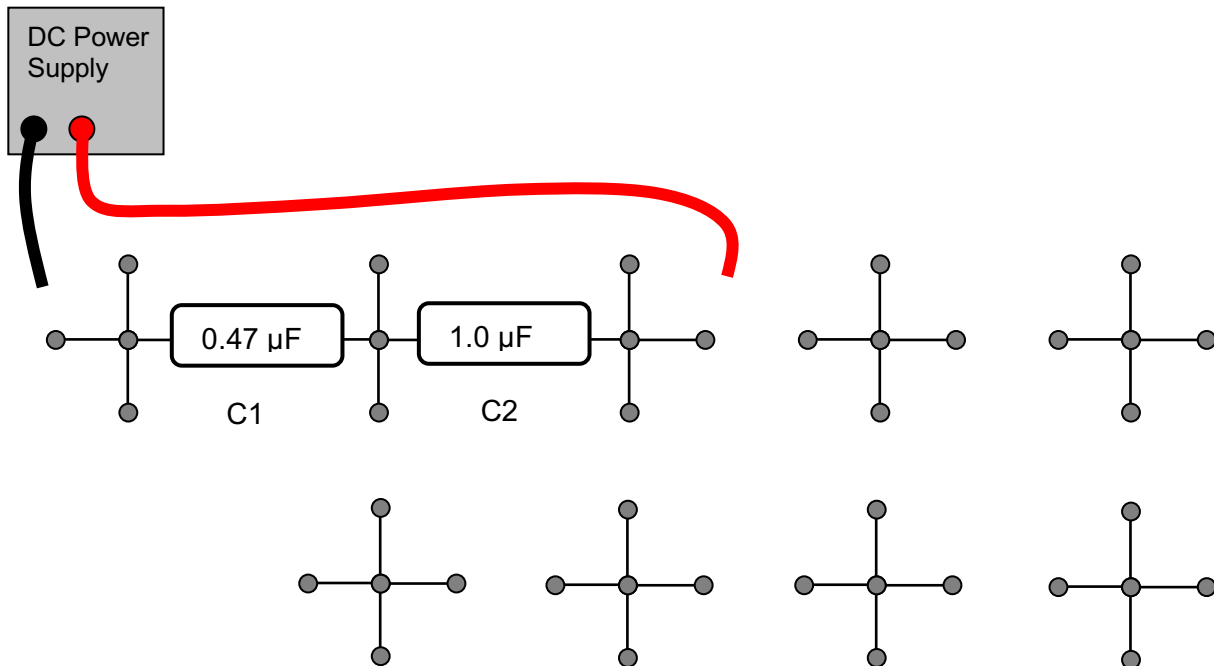
A. Capacitor circuits

You use the electrometer and the voltage probes to measure voltages (See Appendix C, *Using an electrometer*). Be sure to use the 10 V scale for this experiment.

1) <u>Capacitors in series</u>: you will build the circuit below and measure it, but first predict how the 9 V provided by the voltage source will split among the two series capacitors.

V across C1:   V across C2:

Build the circuit below (note that the voltage source is not connected).
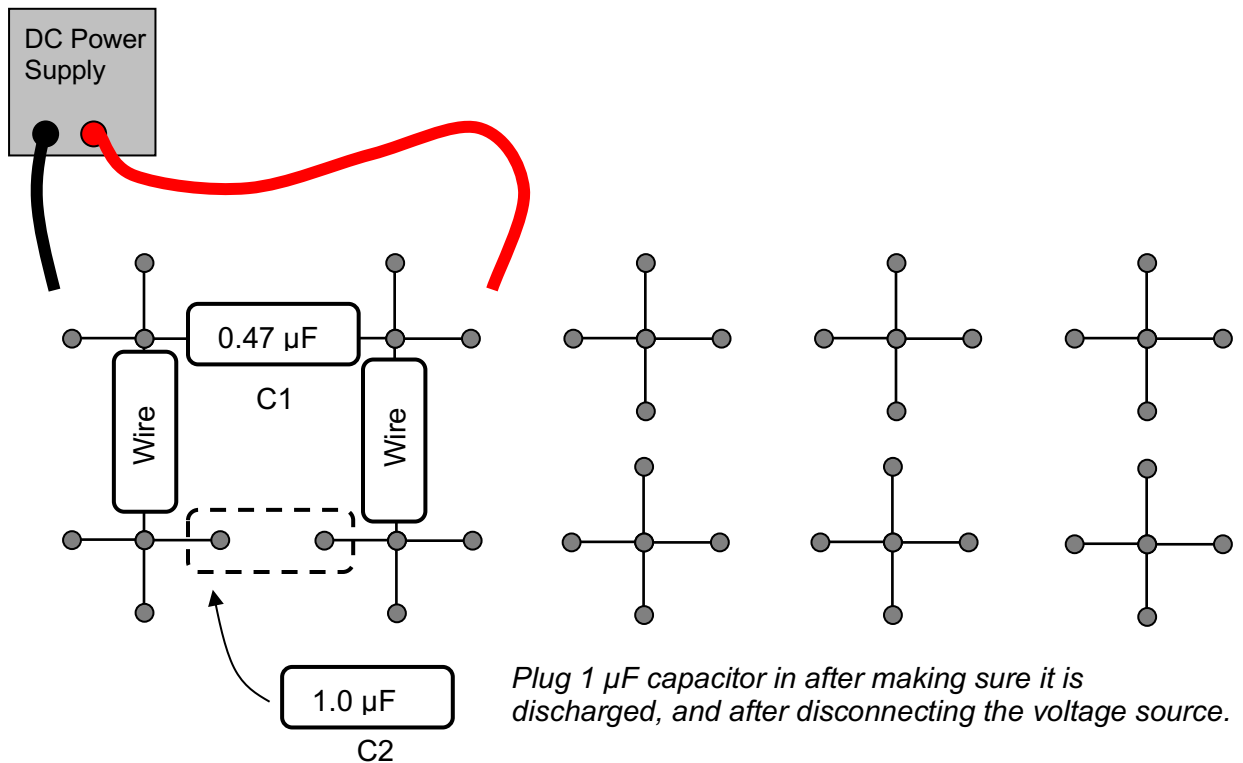

a) First, discharge each capacitor, by touching both plugs simultaneously to the metal strip on the border of the plugboard, to make sure there is no charge on the plates.
b) Touch the black and red voltage source leads across the series circuit, then **<u>disconnect</u>** both the black and red leads from the circuit.
c) Measure the voltage drop across the 0.47 µF capacitor with the supply disconnected.
d) Compare to your prediction.
e) Repeat steps a-d for the 1.0 µF capacitor, and compare to your prediction.

2) <u>Parallel capacitors</u>.
Here you connect capacitors in parallel to see how they share charge. First, discharge
both capacitors. Next, charge up C1 (the 0.47 µF capacitor) to 9 V, then **<u>disconnect</u>**
the voltage source. Then connect the 1 µF capacitor (C2) in parallel with C1.

a) Do a calculation here to predict the final voltage across the capacitors.

Now do the experiment:

DC Power
Supply

0.47 µF

C1

Wire

Wire

1.0 µF

C2

*Plug 1 µF capacitor in after making sure it is
discharged, and after disconnecting the voltage source.*

b) Measure the voltage drop across the capacitors with the electrometer.
   Remember that the voltage source is disconnected here.
   How does this compare with your predicted value?

B. Light Bulbs

Compare the brightness of several combinations of light bulbs. The brightness of the bulb is a good qualitative indication of how much current is flowing through the circuit. A brighter bulb means a larger current. 1 Amp of current represents the movement of 6.242×10^{18} electrons through the bulb each second. There are three identical incandescent light bulbs at the table. Begin by comparing a single bulb to two in series. Starting with a single bulb, build the following circuit, setting the power supply to 9 V:
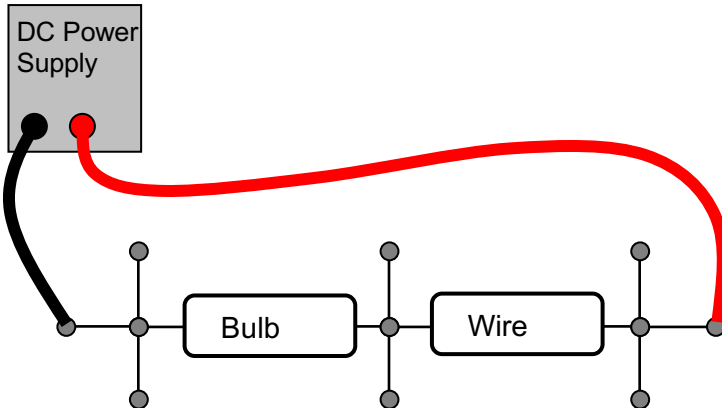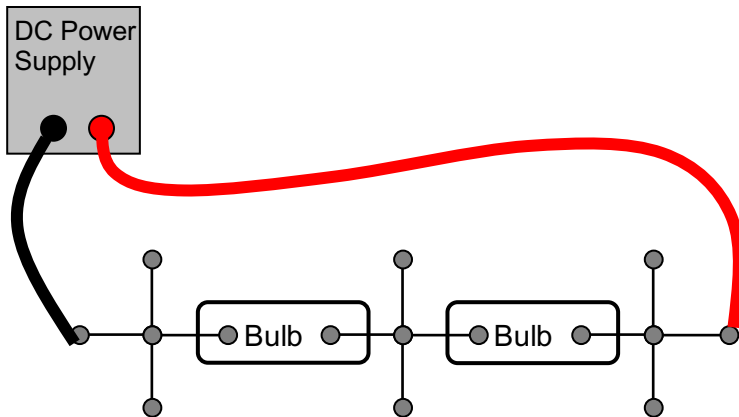

How does the brightness change when the voltage is increased?

Imagine that you replace the "wire" block with a second bulb, as shown below.

Which bulb do you predict will be the brighter of the two?

Now do the experiment.

Which bulb is brighter?

Explain the relative brightnesses of the three bulbs in the above circuits, in terms of the movement of electrons through each bulb.

Next, compare the brightness of a single bulb to two bulbs wired in parallel. You will
first connect one bulb to the voltage source. Then add a second bulb in parallel with
the first (see diagram below).

Predict how the brightness of the first bulb will change when the second is added:

Now do the experiment.
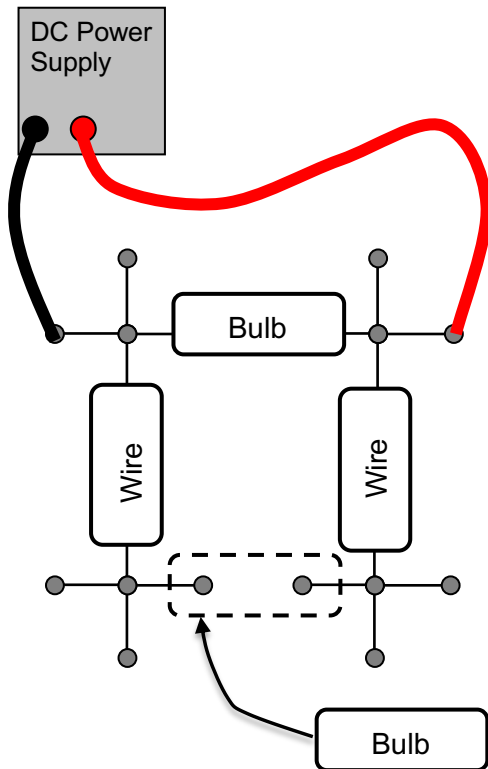
Use the relative brightnesses of the two bulbs to answer the following:

How did the brightness of the first bulb change when the second was added?
How do you think the voltage provided by the voltage source changed when the second bulb was added?
How do you think the current flowing out of the voltage source changed when the second bulb was added?
How do you think the current flowing through the two bulbs compare when they are both in the circuit?
How do you think the current flowing through either bulb compares to the current that flowed through the single bulb with no second bulb?

Lastly, compare the brightness of two bulbs combined in series to one bulb connected in series with a pair of bulbs wired in parallel (see diagram below).

Predict how the brightness of bulb A will change when the extra bulb is added:

Use the relative brightnesses of the bulbs to answer the following:

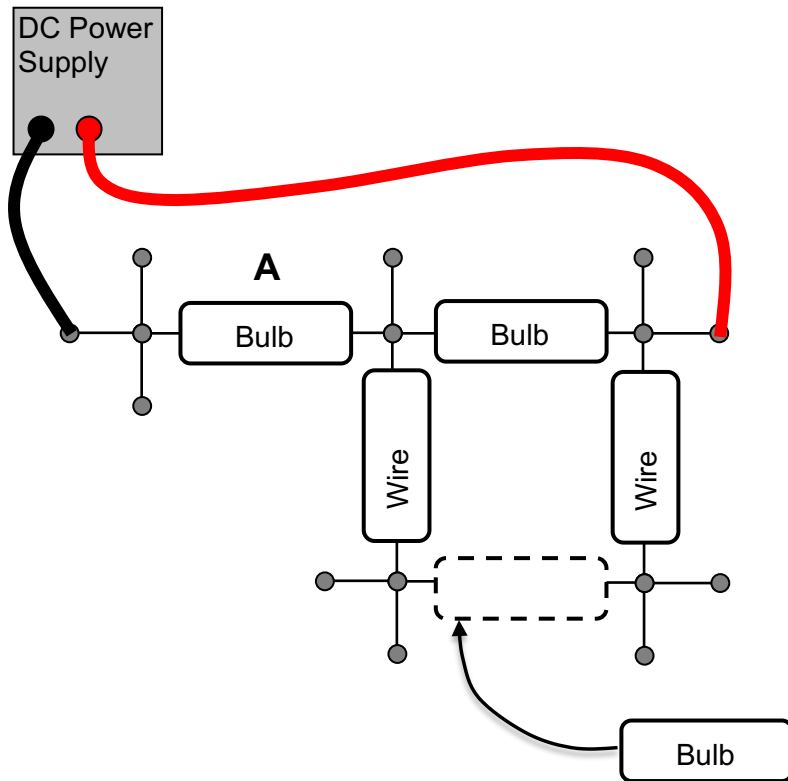| How did the brightness of bulb A change when the extra bulb was added? |
| --- |
| Using Ohm's law, compare the equivalent resistances of the two circuits, with and without the extra bulb. Which do you think has the larger equivalent resistance? |
| How do you think the voltage provided by the voltage source changed when the extra bulb was added? |
| How do you think the current flowing out of the voltage source changed when the extra bulb was added? |
| How do you think the current flowing through bulb A compares to the current flowing through the extra bulb when both are in the circuit? |

C. Resistor circuits

1) Build the circuit below using first the resistor labeled 100 Ω resistor for R. Then use 200 Ω and 400 Ω. Set the power supply to 9 V and measure the current.
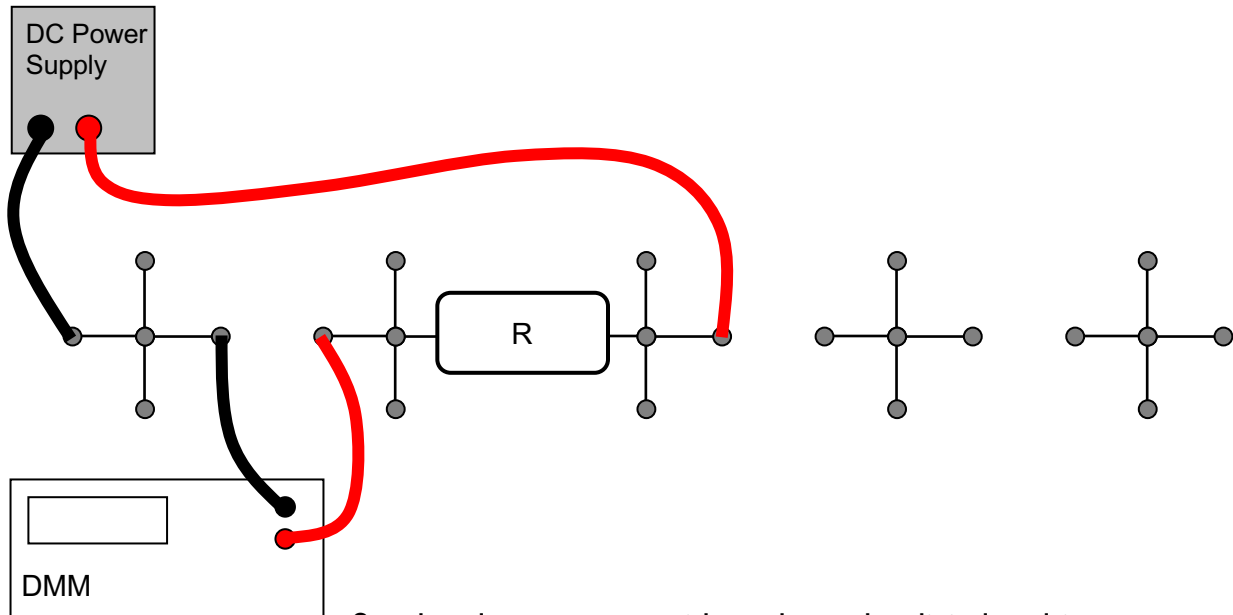
Set the electrometer aside and use the digital multimeter, DMM. Configure the DMM to measure the current through this circuit (see Appendix B, *Using a digital multimeter*).

Which way do the electrons move?

How much work is done by the power supply to move one electron around the circuit?

Complete the following table. The resistor labels are 'nominal' values — the actual resistance is likely to be a little different. These resistors are guaranteed to be within 10% of their labeled value.

Resistor	Voltage V	Current I	V / I = Calc. Resistance
100 Ω	9.0 V		
200 Ω	9.0 V		
400 Ω	9.0 V		

2) Now build the circuit below, and measure the current. Here the 'wire' is a plug-in block that is a metal conductor.

	Value	Units
Current =		
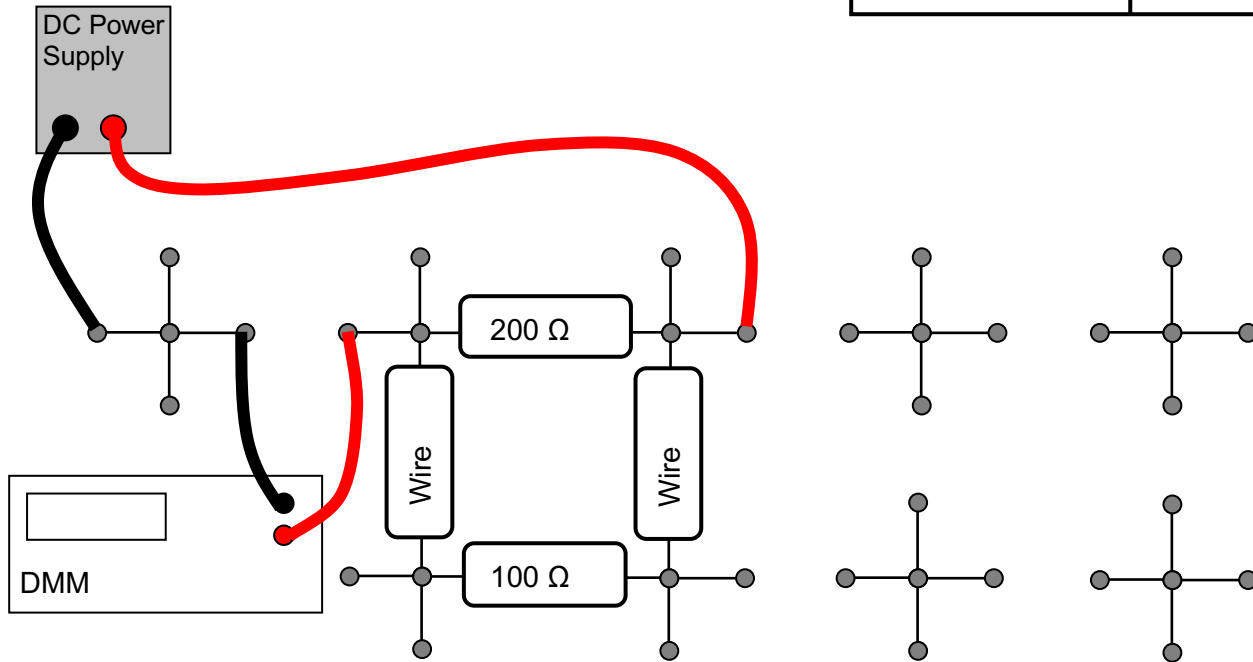
Explain in words whether the measured current will increase, decrease, or stay the same when you remove the 100 Ω resistor. Then pull it out and see if you were right.

Calculate the value of the current you measured at the top of the page.

3) *Voltage drops around the circuit, and measuring current with voltage drops.*

Now configure the DMM to measure a voltage difference instead of a current (See Appendix B, *Using a digital multimeter*).

Explain how the DMM can determine the current through a resistor by measuring electric potential difference (voltage drop) between the two ends of the resistor.

Now make the circuit below:
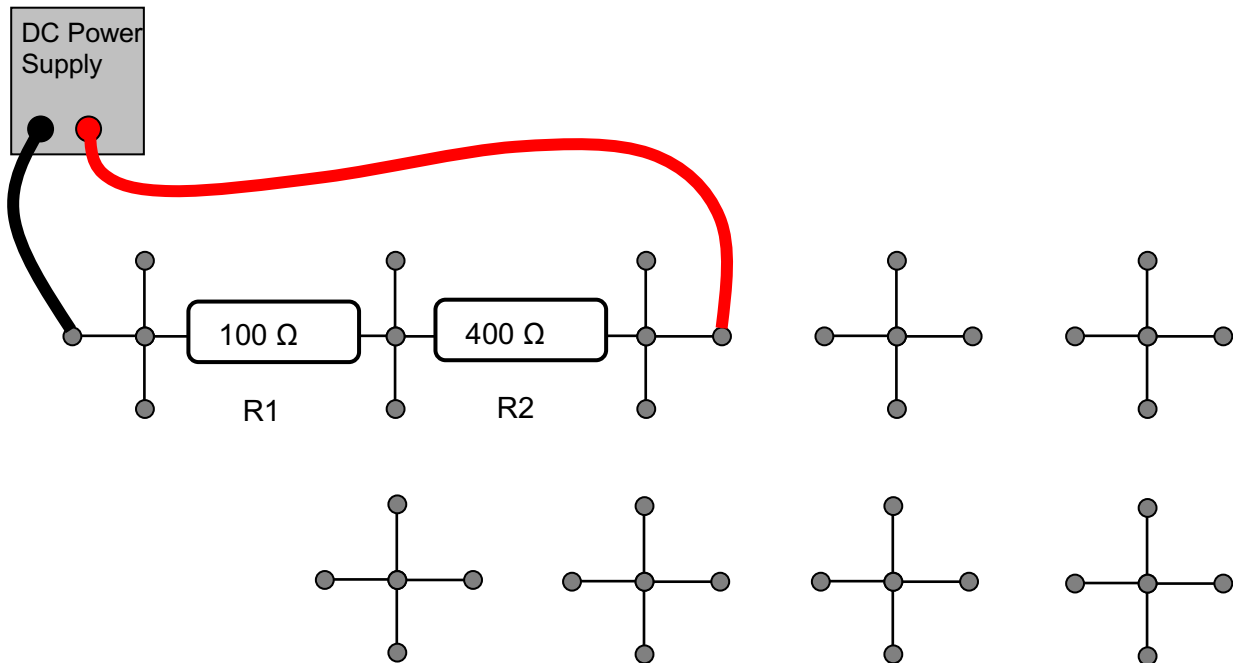
Use the DMM as voltmeter to determine the current through each of the resistors by measuring voltage drops. Write the current below.

Current through R1:   Current through R2:

In the next step you will put a 200 Ω resistor (call it R3) in parallel with R2. But before making the circuit, predict whether currents through R1 and R2 will *increase* or *decrease*.

Current through R1:   Current through R2:

Explain:

Now build the circuit below, and determine the voltages and currents.
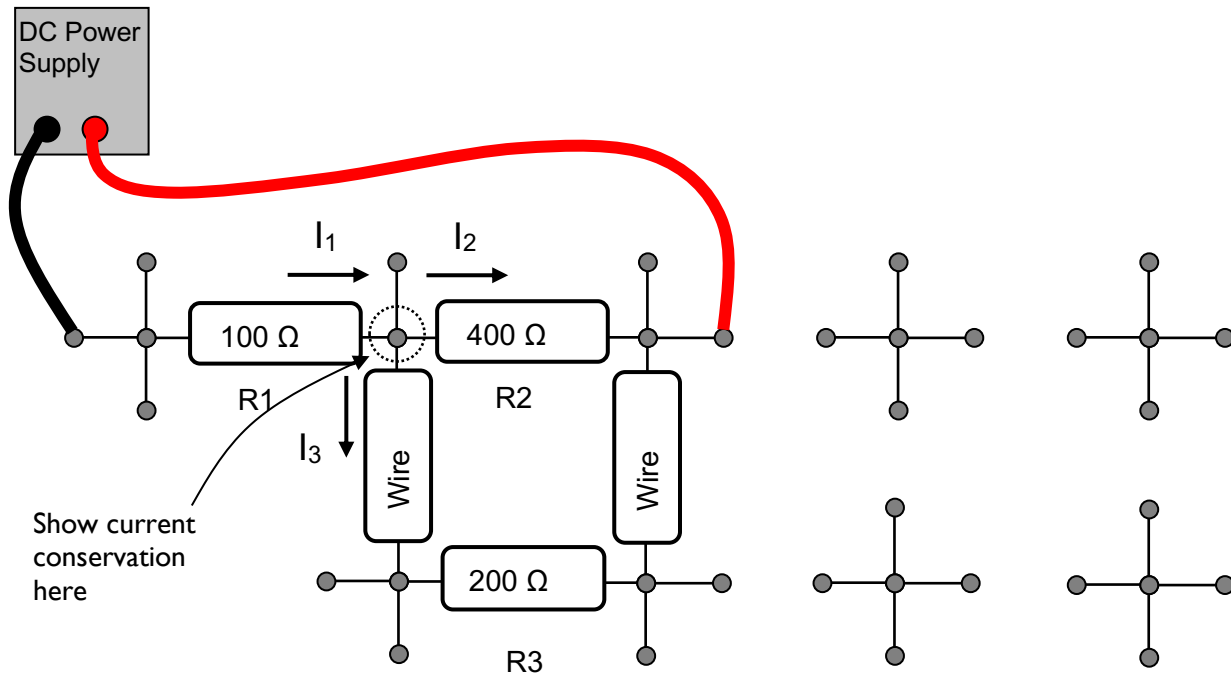
Voltage across R1:   Current through R1:
Voltage across R2:   Current through R2:
Voltage across R3:   Current through R3:
Voltage across wire block: Current through wire block

Explain how this agrees or disagrees with your prediction.

Explicitly verify that current is conserved at the node indicated above by showing that the current flowing into the node is the same as the current flowing out.

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Physics 208 Laboratory
Resistor-Capacitor (RC) Circuits

Your TA will use this sheet to score your lab. It is to be turned in at the end of lab. You must use complete sentences and clearly explain your reasoning to receive full credit.

What are we doing this time?

You will complete two related investigations.

PART A:
    Build resistor-capacitor circuits, and measure time-dependent currents and voltages.

PART B:
    Use these ideas to measure and investigate a cell membrane electrical model, investigating propagation of an action potential down the cell membrane.

Why are we doing this?

Capacitors are almost as ubiquitous as dipoles, showing up almost everywhere there is an insulator. Actually, capacitors have some similarities to dipoles, with equal and opposite charges on the electrodes. And they almost always show up in combination with some non-insulator — a resistor-capacitor circuit!

What should I be thinking about before I start this lab?

You should be thinking about the ideas of circuits you developed when looking at resistors and capacitors last week. In particular, how the voltage across the capacitor is related to the charge on it, and how the current in a circuit delivers charge to a capacitor.

For the first part of the lab, you use the same circuit board as you did last week. The board is shown below:
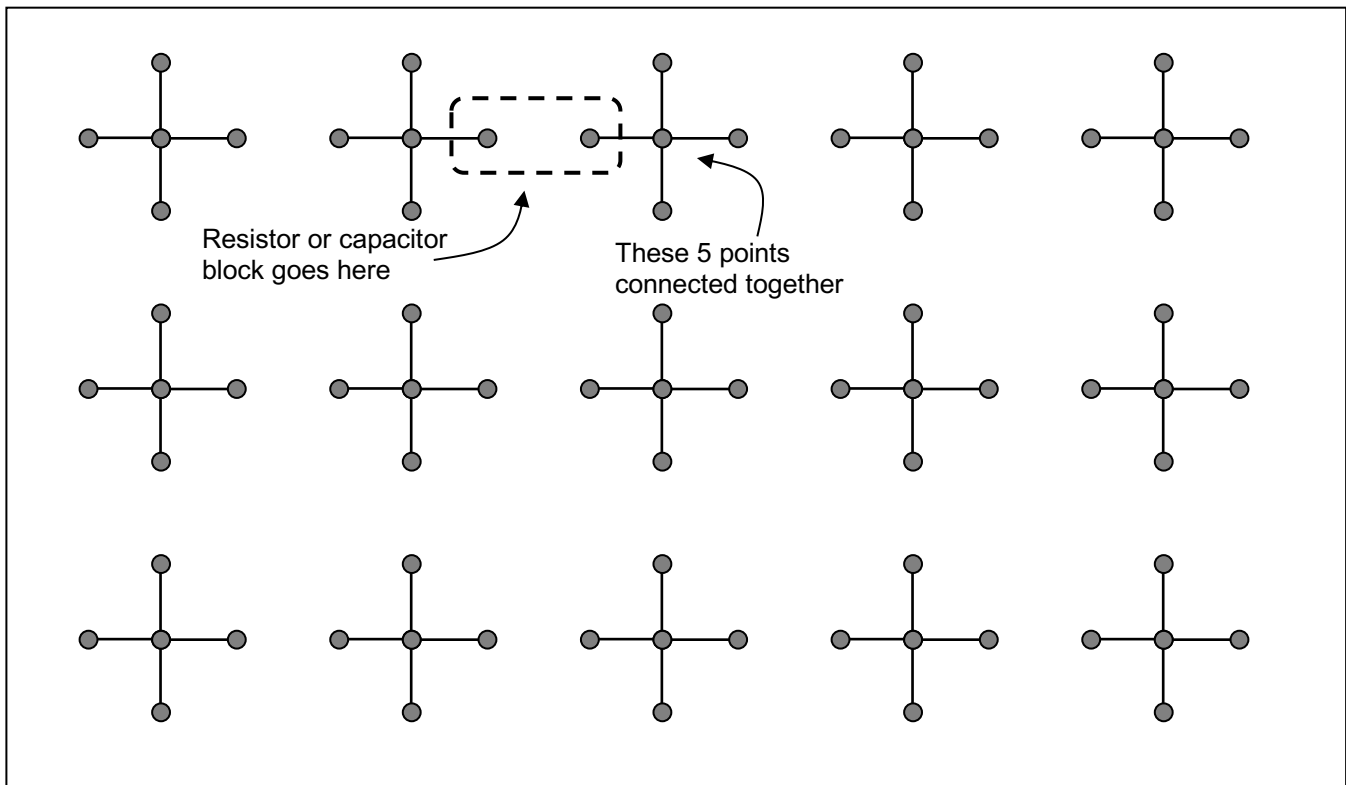
Resistor or capacitor block goes here

These 5 points connected together

Holes connected by black lines are electrically connected by conducting wires, so all points connected by black lines are at the same electric potential. You build a circuit by plugging in resistors and capacitors across the gap between crosses. The resistors are built into plastic blocks with banana-plug connectors that exactly bridge the gaps. After you plug in a resistor, there will still be unused holes in each cross. You will use the remaining holes to connect the variable voltage source to supply your circuit with charge, and to connect the DMM or Pasco interface to measure currents and potential differences at various points in the circuit.

Inspect the power supply to make sure there is a thin metal bar connecting the "—" and "GND" terminals; if there isn't, call over your TA.

A. Resistor-capacitor circuits

Here you connect a resistor and capacitor to investigate how a capacitor charges and discharges. Turn the DC voltage source on and set it for zero volts output (see Appendix A – *Using a DC power supply*). Connect the DC voltage source and multimeter to the 10 MΩ resistor and 1 µF capacitor as shown below. Configure the multimeter to measure voltage (see Appendix B – Using a digital multimeter).
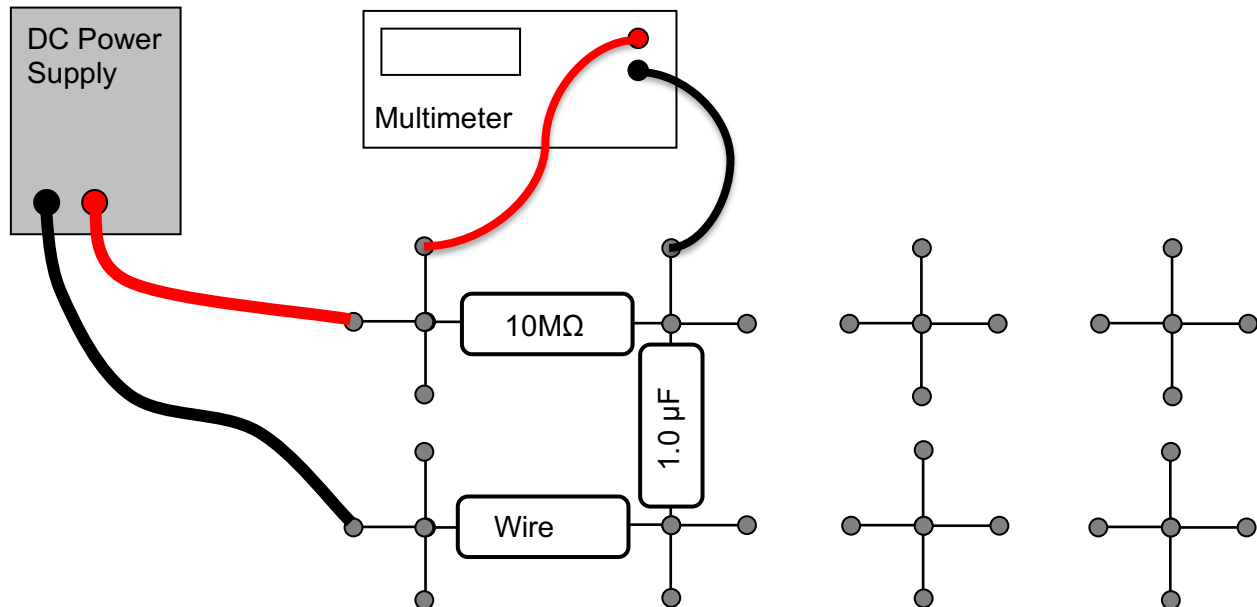
Starting with the power supply reading 0 V (the "fine" voltage control has to be set all the way counter-clockwise to achieve 0 V), quickly increase the voltage to about 17 V and watch the voltage readout of the DMM. Wait until it stabilizes (this could take a long time), then quickly turn the voltage supply to zero volts, and watch the voltage readout again.

1) What is the direction of the current after increasing the voltage from 0 V to 17 V?

2) This current represents a charge flow. What happens to this charge after it goes through the resistor?

3) What is the direction of the current after decreasing the voltage 17 V to 0 V? Remember that when the supply reads zero volts, there is no potential difference between the red and black terminals: it is as if a wire connects them.

4) How do think the voltage across the capacitor changed as a function of time when you changed the power supply 0-17 V? Why?

5) How does the capacitor voltage affect the current through the resistor? (Think about Kirchoff's loop law).

6) You saw that the voltage across the resistor changes smoothly with time, which means that the current through the resistor must be smoothly changing with time. But it can be easier to think about this in short time steps. Rapidly increase the voltage from 0 V to 17 V, and use the DMM measurement of the voltage across the resistor V_R to fill in the first column. Then use your calculator to fill in the other columns.
   V_R is the voltage drop across the resistor; I_R is the current through the resistor;
   V_C is the voltage drop across the capacitor;
   ΔQ_R is the charge that flowed through the resistor during the previous 2 seconds;
   I_R^{prev} is the current during the previous 2 seconds;
   Q_C is the charge on the capacitor.

Time	V_R	I_R	V_C	$\Delta Q_R = I_R^{prev} \Delta t$	Q_C
0	17.37 V			0 C	
2 sec					
4 sec					
6 sec					
8 sec					
10 sec					
12 sec					
14 sec					

Using your table above, sketch the charge on the capacitor as a function of time.

7) Now replace the 10 MΩ resistor with a 100 kΩ resistor and increase/decrease the supply voltage. How does the behavior compare with that of the 10 MΩ circuit?

Now use the computer to measure the time-dependent current through the resistor. Use the 1 µF capacitor, and the 100 kΩ resistor. To make an accurate measurement, the voltage needs to be switched very quickly from 0 V to 10 V (the Pasco can measure only up to 10 V), more quickly than you can do it by turning the knob. Set up the circuit below to quickly switch the voltage; set the power supply to 10 V. Turn on the Pasco interface.
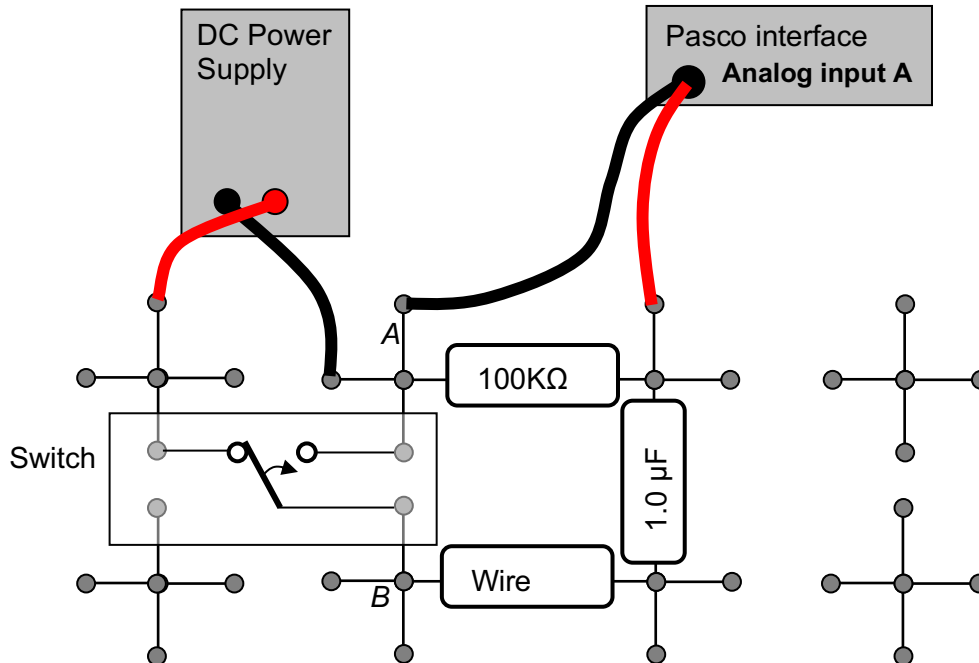
1) What will be the potential difference between points *A* and *B* when the switch is …
a) all the way to the right?

b) all the way to the left?

2) What voltage does analog input A measure in this circuit?

How can you use this voltage to determine the current flowing through the resistor?

Now move the switch all the way to the right.
Start the data acquisition program by double-clicking on the Lab5_Settings1.cap file in the Lab Software/208 folder on the Desktop. Click record and measure the time-dependence of the current through the resistor when you flip the switch all the way to the left, then all the way to the right, repeating several times. *Your switch may have a center position — we don't use it.*

3) What is your maximum measured *current*, and when does it occur?

4) Calculate the expected value of this maximum current, and compare to 3).

5) Directly from the data on the computer, determine the time constant τ of the circuit.

6) Calculate the time constant from the resistor and capacitor values and compare to your measurement in 5).

7) Your measured curve on the screen is 'Voltage Across the Resistor' *vs* time, which you showed in 2) could be converted to current vs time by using Ohm's Law. Find a similar method to convert the area under your measured curve to the final charge on the capacitor. (Hint: what you did the table of A6 was equivalent to doing the integral $\int_0^t I_R(t)dt$ to find $Q_c(t)$).

8) Click the Highlight button 🖉 and use the mouse to select the decay from maximum to zero current on your graph. Find the area under the curve by clicking the Area-Under-Curve button ⬆. Then use the method you found in 7) to calculate the final charge on the capacitor.

9) Without using any measured data, calculate the theoretical value of the final charge on the capacitor. (Hint: the charge on a capacitor is determined by the voltage across it and its capacitance).

10) How does your value compare to the measured one?

Now think about this circuit, but don't build it or measure it.
Why would you ever care about this circuit? Be patient — in the next section you use this as a basis for a model of a nerve signal (action potential) propagating down a cell membrane.
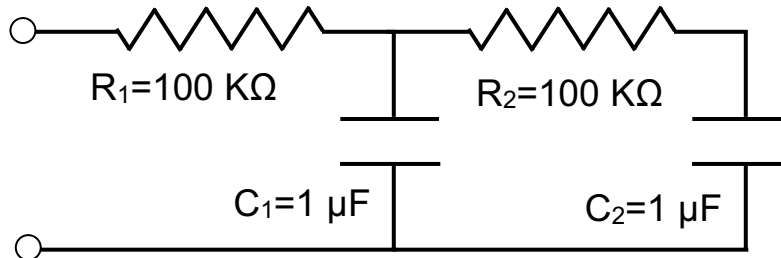
1) Suppose the capacitors start out discharged, and you apply 10 V across the circuit. At the instant you apply the voltage, what are the currents through R_1 and R_2?

2) Where does the charge flowing at this instant end up?

3) Think about later time intervals. Why does C_1 charge up sooner than C_2?

If the voltage rising above some threshold value across each capacitor triggered something to happen, then that event would occur sooner at C_1 and some time later at C_2. In this way you can think about this as a signal propagating down the circuit (e.g. an action potential). In the next section you watch a voltage pulse propagate down a similar circuit.

B. Electrical model of a cell membrane
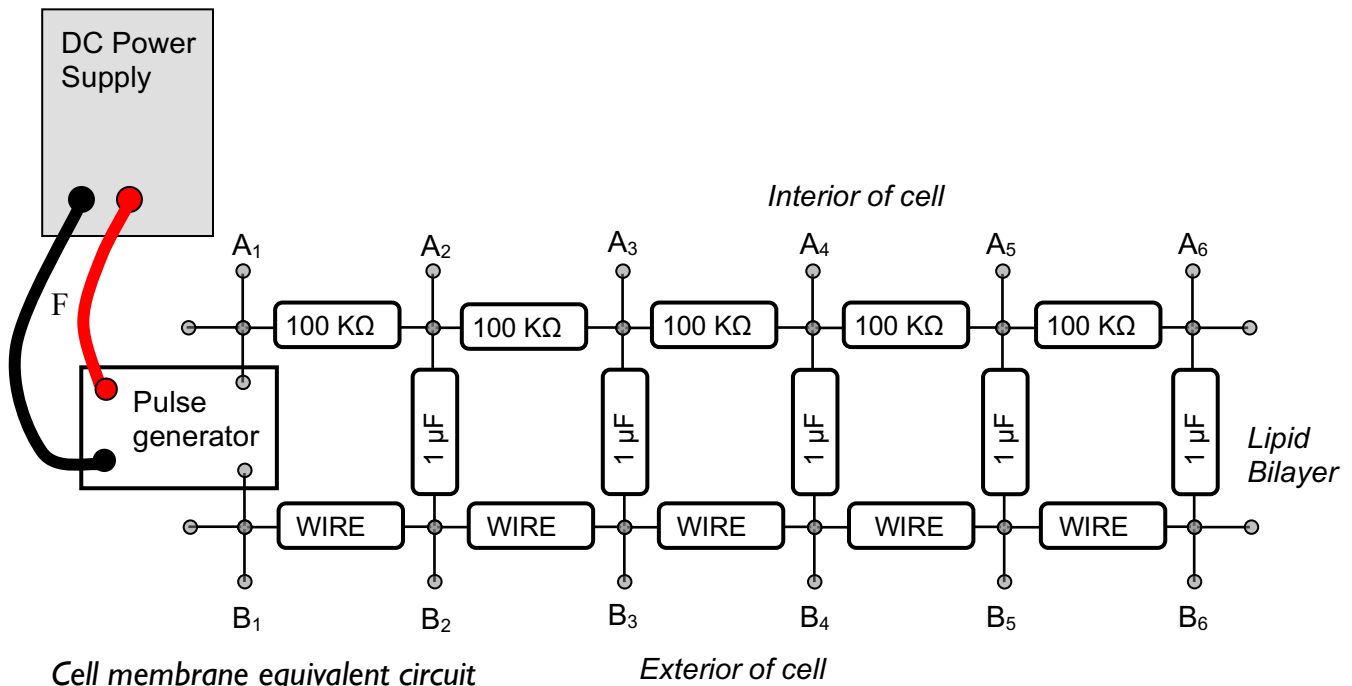
Cell membrane equivalent circuit

As discussed in class, a cell membrane has a potential difference between its interior and exterior. The low-resistance cell exterior is modeled by a low-resistance wire. The medium resistance cell interior is modeled by 100 kΩ resistors. The capacitors model the insulating lipid bilayer. The potential difference arises from charges in the conducting fluids that form the electrodes of the cell-membrane capacitor. These charges move around in the fluids, making the potential difference vary with position. This makes an action potential (generated at the left end) that propagates down the cell membrane.

The switch models an ion channel that is triggered by some external stimulus, mechanical, chemical, or electrical. It could be a channel opening in response to a pinprick in your finger. This causes a change in potential difference at that location.

No other ion channels are modeled here. In a real cell membrane, there are voltage-triggered ion channels distributed throughout. We don't include them here because these are not simple ($V \neq IR$) resistors. For instance, when the potential across the cell membrane reaches a threshold value, the non-Ohmic ($V \neq IR$) resistors reduce their resistance to quickly bring it back to its resting state. This makes the action potential a sharp pulse and sustains its amplitude. This also changes the propagation speed from that with Ohmic resistors.

We use a pulse generator to start the pulse, and also to bring the potential back to its resting value. Here only the resistor-capacitor network is modeled, and not the sustaining effect from the non-Ohmic resistors. So the pulse broadens and decays. But still our model is able to capture some aspects of the action potential propagation.

Hodgkin and Huxley shared the 1963 Nobel prize in physiology and medicine partly in recognition of their analysis of the full non-Ohmic electrical circuit model.

To start the action potential, you will (in the next section) introduce a voltage pulse at A_1,B_1, and watch it propagate down the cell membrane, similar to an action potential.

If you could measure all the potential differences A_i,B_i at two different instants in time (t_1 [squares] and t_2 [triangles]), you might see something like the following.
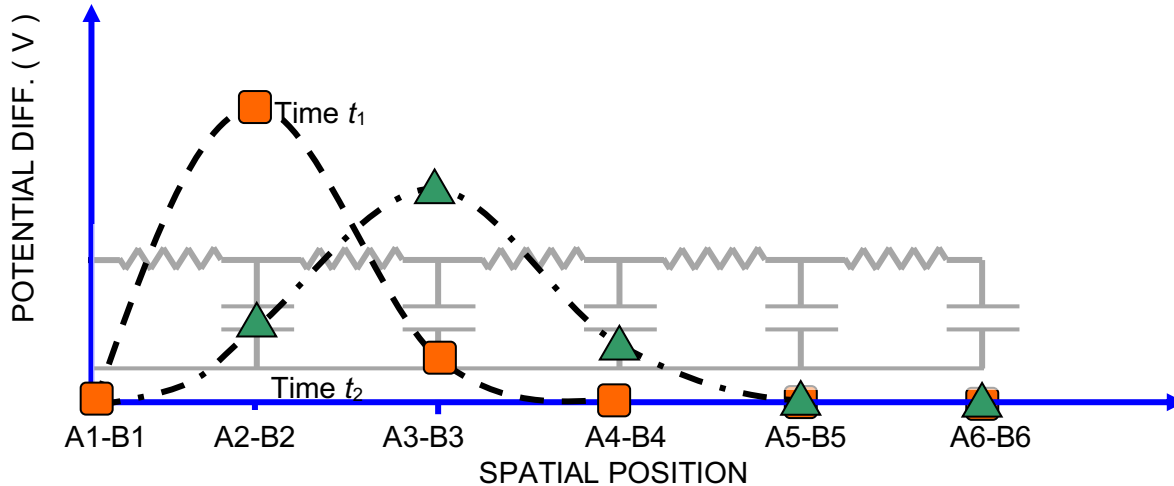
You can only measure potential differences across the capacitors – the squares and triangles represent potential differences measured at these locations. The dashed line is what the voltage pulse might look like in an actual, continuous, cell membrane. The triangles correspond to the voltage differences at slightly later time (t_2) than the squares (t_1). This data indicates that the voltage pulse is traveling to the right at some speed, since the peak voltage position has moved.

You will measure the voltage across each capacitor separately as a function of time. For instance, at position 2, the voltage is large at time t_1 and then smaller at time t_2. The voltage at position 3 is small at time t_1, and has gotten larger at time t_2.

Your job will be to record the voltage vs time for each capacitor in the membrane, and then reconstruct a graph like the figure above that shows a snapshot of the voltage pulse at different times as it propagates down the cell membrane.

Directions for taking data

You investigate the propagation by measuring the potential differences between the pairs A_i,B_i with the computer. Start the data acquisition program by double-clicking Lab5_Settings2.cap file in the Lab Software/208 folder on the Desktop

We use all four analog inputs A, B, C, and D on the front of the interface, and the two inputs XA, XB on the expansion box on the top of the interface. The potential difference at (A_1,B_1) measures the pulse before it propagates down the cell membrane. Connect (A_1,B_1) to the A input. The data acquisition software watches this input to determine when to start recording data. Connect (A_2,B_2) to the B input, (A_3,B_3) to the C input, and so on.

You start a pulse moving down the membrane by generating a single short pulse at one end. After you have the circuit, connected the voltage probes, and have started the data acquisition software with Lab5_Settings2.cap, go get a pulse generator and plug it into your board. Set your voltage supply to 12 V (see Appendix A – *Using a DC power supply*), and connect it to the red and black terminals of the pulse generator. Be sure connect red to red and black to black.

To take data:

1. Start by clicking 'Record' on the data acquisition software.
2. The program is now waiting for you to push the pulse-generator button. Push the pulse-generator button just once, and watch the data roll in. Data acquisition stops automatically after 2 seconds — you don't have to click stop.
3. When you have finished, put your pulse generator back so someone else can use it.

You should now see on the computer monitor a graph of "histories" of voltage vs time for all six positions. The voltage across A1-B1 is called "V1", the voltage across A2-B2 is called "V2", and so on. Look at the data, and answer the following questions.

1) What is the duration and amplitude of the original voltage pulse?

2) Here is a plot of voltage vs. position that could be in your cell membrane:
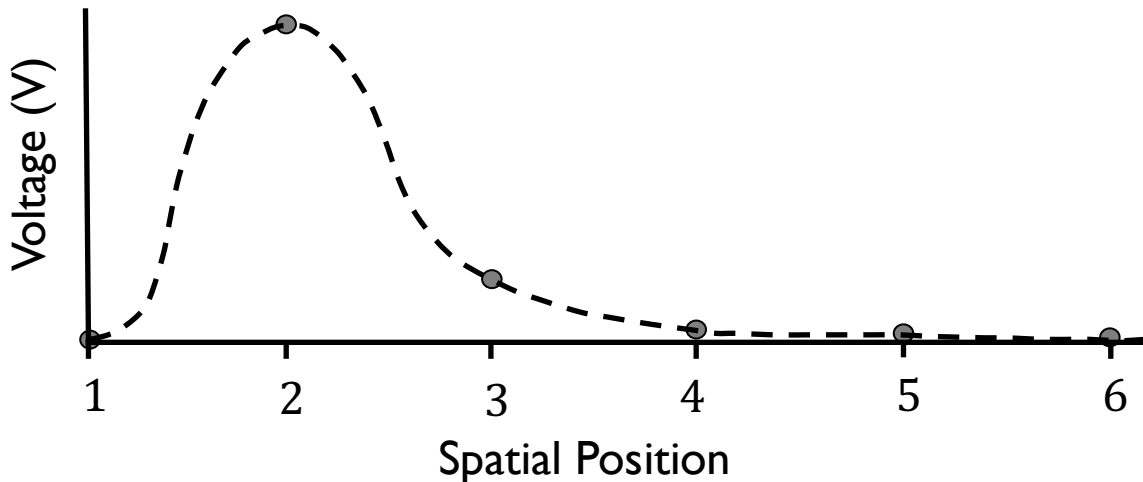
Suppose it is moving to the right. On the axes below, draw a sketch of voltage vs. time for capacitor 2 and capacitor 3. Use a solid line for capacitor 2 and a dashed line for capacitor 3.
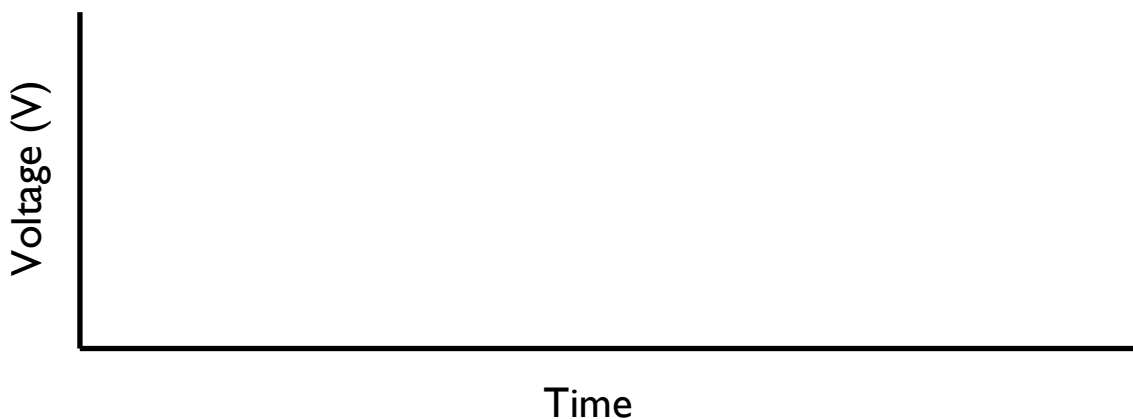
3) Now look at your experimental data. Explain how from this data you could make plots of voltage vs. position at several different times. Will this look like a "pulse" of voltage?

The steps below show how the voltage data can be analyzed in terms of a "voltage pulse" that starts out at A1-B1 and propagates down the cell membrane.

4) This step gives a visual image of what is meant by "pulse propagation". Get a rope, pick a partner, and sit down on the floor about 15 feet from your partner, with the rope resting on the floor between you. The rope should be stretched neither too tight nor too loose. While your partner holds one end fixed, move the other end rapidly sideways and back, ONCE. You should see a shape appear on the rope that propagates away from you. Make a sketch of you, your partner, the rope, and the shape, as if a snapshot had been taken, looking down from above.

5) Find the row in the "Voltages across Capacitors" table corresponding to $t_1 = 0.05$ seconds. Copy and paste the voltages V1 through V6 into the appropriate cells in the "Voltage Pulse" table.
6) On the lower graph, verify that there now appear six data points, corresponding to the six voltages you just copied and pasted. This shows a "snapshot" of the shape of the voltage pulse at $t_1 = 0.05$ seconds.
7) Repeat step 5 for $t_2 = 0.1$ seconds, $t_3 = 0.2$ seconds, and $t_4 = 0.3$ seconds.
8) Based on what you see in the lower graph, describe in words what happens to the voltage pulse as time passes.

9) Discuss with your lab partners how you might use this graph of the propagation of the pulse to determine how fast the pulse propagates. Write down your group consensus here.

Physics 208 Laboratory
Magnetic Fields and Forces

This sheet is the lab document your TA will use to score your lab. It is to be turned in at the end of lab. To receive full credit you must use complete sentences and explain your reasoning clearly.

What's this lab about?
In this lab you investigate magnetic fields and magnetic forces.
There are two parts to the lab:
<u>PART A</u>
 Map out magnetic fields using a magnetic dipole as a probe.
<u>PART B</u>
 Observe and measure the force a magnetic field exerts on a moving charged particle.

Why are we doing this?
Magnetic fields are a bit more complicated than electric fields, but we usually have more experience with magnetic forces than electric forces. In this lab you can start to get a feel for the shape of magnetic fields, and how they exert forces on other magnets and on moving charged particles.

What should I be thinking about before I start this lab?
 As discussed in class, the fundamental 'charge' in magnetism is the magnetic dipole.
 Permanent magnets are approximations to magnetic dipoles. Compass needles also are. You'll use these in the first part of the lab to look at magnetic field lines, the forces between permanent magnets, and torques on magnetic dipoles. A uniform magnetic field will exert a torque on a magnetic dipole. The torque will rotate the dipole toward a direction where it aligns with the local magnetic field.
 Magnetic fields also exert forces on moving charged particles. The faster the particle goes, the bigger the force. The direction of the force is perpendicular to both the particle velocity and the magnetic field.

 This is the first of two labs on magnetism. This lab looks at magnetic fields that are not varying in time (static magnetic fields). In next week's lab you discover some of the surprising behaviors of magnetic fields that change in time (for instance when you move a permanent magnet around with your hand).

A. Mapping a Magnetic Field:

The plastic board has two strong magnets mounted in rotating holders. These produce the magnetic fields that you will map.
You map the fields by looking at how a test dipole aligns with the local field.
You will use:
  A compass
  A grid of small magnets enclosed in a plastic case.

1. Orient the magnets in the plastic so that red (North) of one magnet faces blue (South) of the other.

   At each point in the drawing below, use the compass to find the direction of the magnetic field, and then record the direction by drawing a small arrow at each point indicated in the drawing. Using your arrows as a guide, sketch a set of magnetic field lines covering the plane of the board.
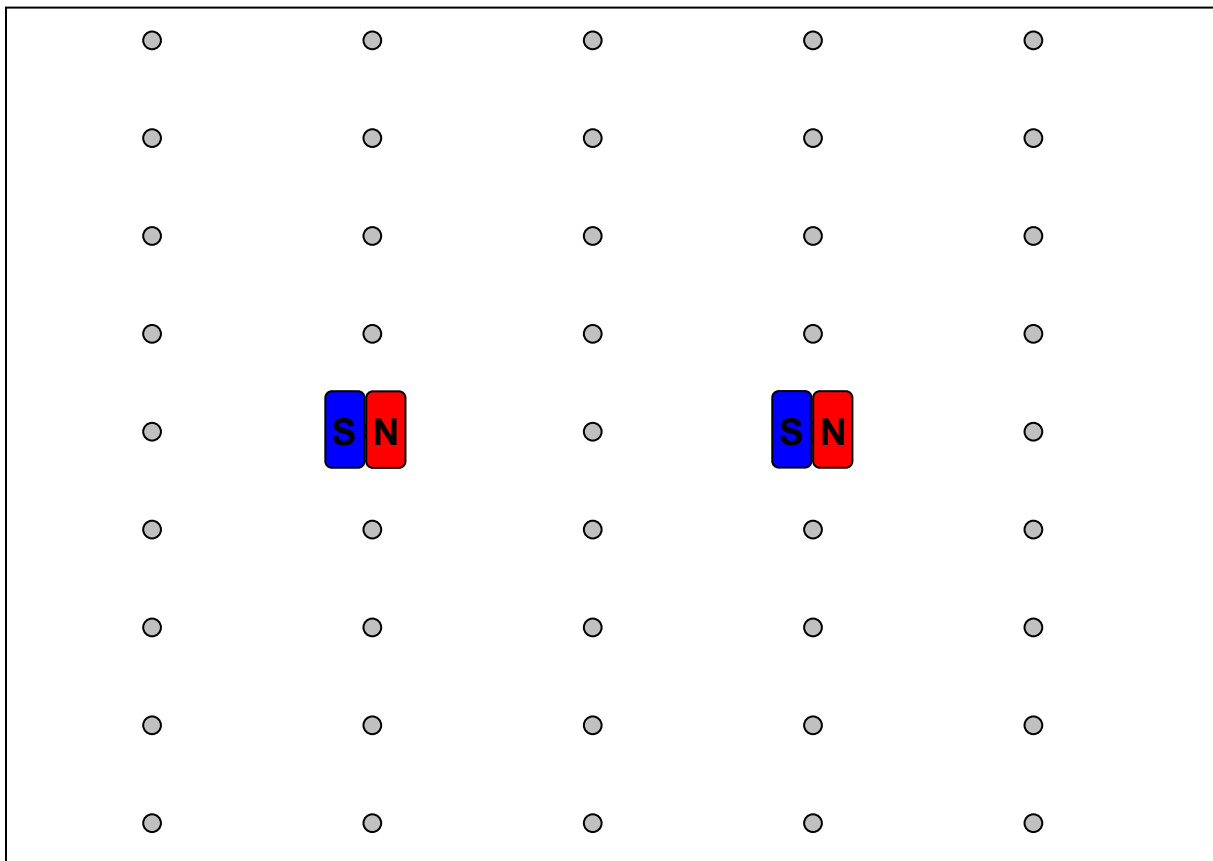
2. Now orient the magnets red to red, and repeat step 1.
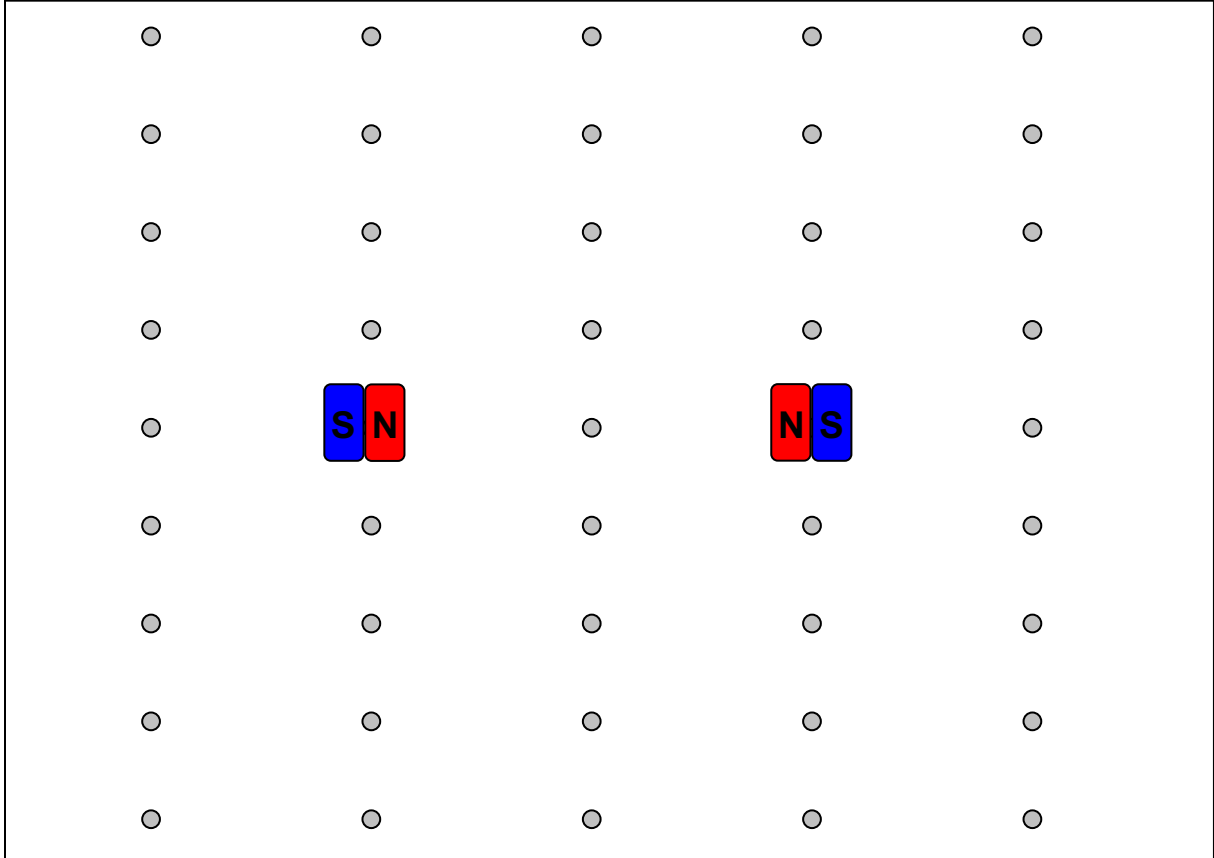
Here is a side view of this setup. Find the field direction at the points indicated, and then sketch magnetic field lines.
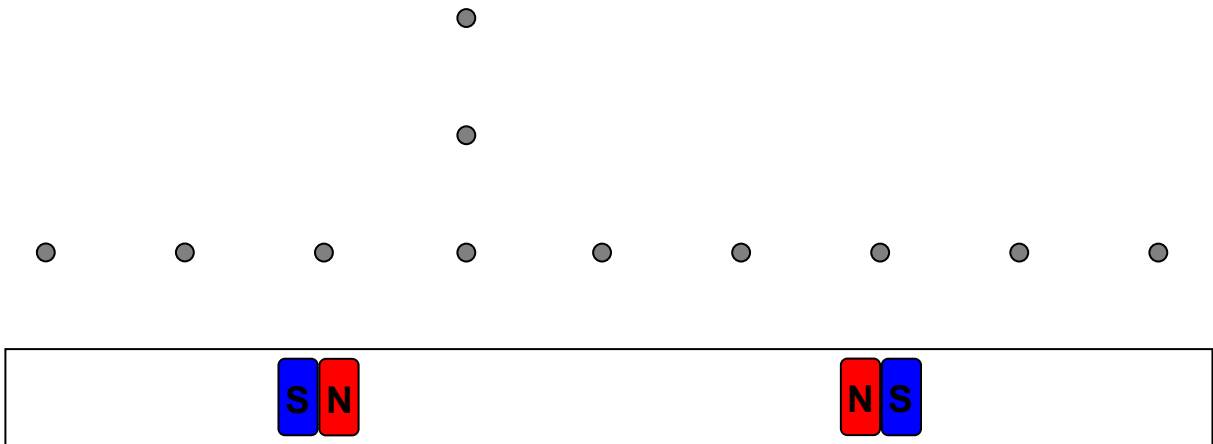
B. Magnetic force on moving charged particles.

In this section of the lab you use the huge apparatus that is taking up most of your lab table. This apparatus allows you to launch an electron beam and measure the effect of an applied magnetic field on the path of the electron beam.

This effect is the Lorentz force, $\vec{F}_B = q\vec{v} \times \vec{B}$

The magnetic field is created by the large rings of current above and below the glass globe. In each of these rings the current is in the same direction. The distance between the rings is equal to the radius of a ring. This configuration of rings is called a "Helmholtz Coil".

Each ring creates a magnetic field that is similar to the magnetic field of a permanent magnet. Which of the magnet orientations in sections 1 & 2 is similar to a Helmholtz coil, dipoles that are aligned or dipoles that are anti-aligned?

What does this suggest about how uniform the magnetic field is between the coils? Explain.

Connecting the experiment

The first step in creating the electron beam is to eject electrons from a metal filament. To do this, the filament is heated by passing a current of about 10 mA through it. Connect the Filament outputs to the top and bottom connections on the Teflon plastic connector block on the end of the glass globe.

The second step in creating the beam is to give the electrons some speed by accelerating them through a potential difference. This is done by applying an 'accelerating' voltage between the filament and the cylindrical anode. Do this by connecting a banana plug cable between the Anode output and the 'side' connection on the Teflon plastic connector block.

The accelerated electron beam escapes through a rectangular slit in the anode. They are moving at a speed v determined by how much the electrons were accelerated moving through the potential difference ΔV.
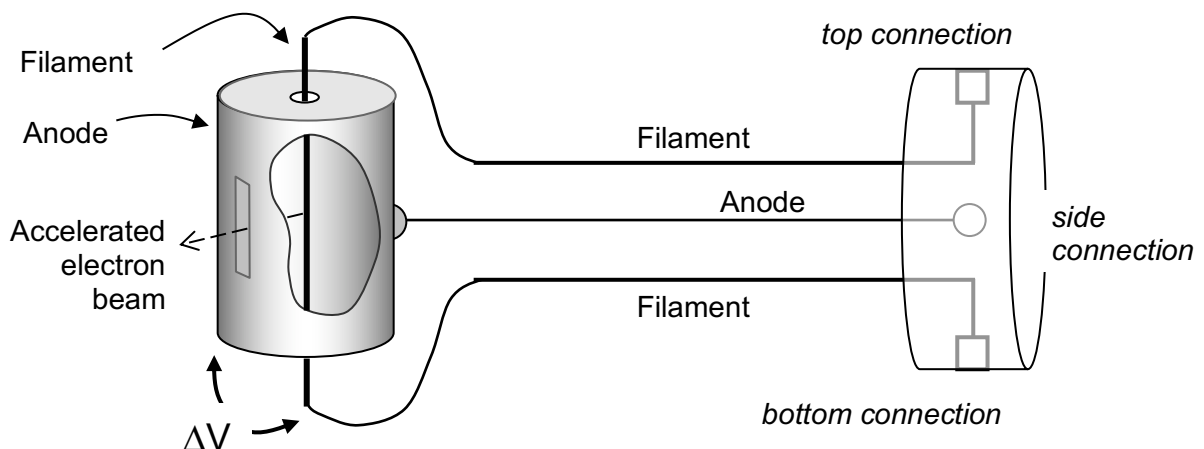
Shown above is the piece inside the glass globe that generates the electron beam.
This diagram helps you connect to the power supply

1. What is the velocity of an electron accelerated from rest through a 22 V potential?

2. If the accelerating potential doubles, by what factor does the electron's velocity change? Explain.

Now turn on the power supply. At this point you should have in place the connections to produce the electron beam, but there are not connections to the Helmholtz coil.
Set the ANODE Volts switch to 22 V.
Supply filament current by turning up the knob below the "ANODE milliamps" display all the way to its maximum value. The "Filament On" lamp should light. You should see the ionization path from the electron beam (dimming the lights helps).

3. Use one of the cylindrical magnets to steer the electron beam (hold it up to the glass globe and move it around). What is happening? Imagine the pattern of field lines from the magnet to determine the direction of the magnetic field at the electron beam, and verify that the direction of beam curvature is in accordance with your determination.
Flip the magnet end for end to check your reasoning.

4. Now connect the "Field" outputs to the banana-plug connections on the Helmholtz coils, and increase the current to the coils until "FIELD Amps" reads about 2 Amps. What are the electrons doing? Vary the field and observe the results. Reverse the field direction by changing the current leads (turn the current down to zero before reversing the leads) and observe the results. Explain.

5. Set the current in the coils to the direction that gives a circular orbit for the electrons. Set the accelerating potential to 44V by flipping the switch under the "ANODE Volts" display. What happens to the orbit? Explain.

6. Return the anode voltage to 22V, and adjust the magnetic field so that the beam of electrons hits each of the "cross-bars".

Crossbar No.	Distance to Filament	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

Do you need to increase or decrease the field to go from crossbar 5 to crossbar 1? Explain.

7. Adjust the magnetic field so that the beam hits crossbar 2. What is the current through the Helmholtz coil?

8. Here you determine the magnetic field generated by the Helmholtz coil. The two identical rings are positioned so that the separation of their planes is equal to the ring radius. This arrangement generates a very uniform magnetic field in the region of the glass globe. Each ring has a radius of 0.33m, and has 72 turns of wire. The magnetic field on the axis of a <u>single</u> turn of radius R, a distance z from the center of the turn, is $B_{loop} = \dfrac{\mu_o}{2} \dfrac{IR^2}{\left(z^2 + R^2\right)^{3/2}}$.

a) Find an expression for the total magnetic field caused by the Helmholtz coil at the center of the glass globe. It should be a constant times I, the current through the Helmholtz coil.

b) Calculate the magnetic field at the center of the glass globe for the current you used in question 7.

9. Calculate the magnitude and direction of the force on a single electron in the beam from this magnetic field.

10. A particle moving at constant speed in a circular orbit is accelerating, since its velocity is continually changing direction. This 'centripetal' acceleration is directed toward the center of the orbit, and has magnitude v^2/r, where r is the radius of the circular orbit.

a) Which force do you predict is causing your electron beam to experience a centripetal acceleration (i.e. to follow a circular path)?

b) Calculate the magnitude of the force required to bend your election beam into a circle (find r from table in question 6).

Compare to your answer to b) to your answer to question 9. Does the comparison support your answer to a)?

c) How big is the magnetic field from the Earth? Did this cause much of an error in your calculation?

11. Calculate e/m for an electron, where e>0 is the magnitude of the electron's charge, using your measurements of v, B, and r. Compare with the accepted value. Discuss any discrepancy.

Name_____   **Section**_____

Physics 208 Laboratory
Time-varying magnetic fields and the Faraday Effect

This sheet is the lab document your TA will use to score your lab. It is to be turned in at the end of lab. To receive full credit you must use complete sentences and explain your reasoning clearly.

What's this lab about?

In this lab you investigate effects arising from magnetic fields that vary in time.
PART A
    Move a bar magnet through a coil of wire to investigate induced EMF and current.
PART B
    Quantitatively investigate Faraday's law by using a time-dependent current through a coil of wire to generate a time-dependent magnetic field.
PART C
    Drop a strong magnet through various metal tubes to investigate the forces caused by induced current.

Why are we doing this?

Time-varying magnetic fields are all around us. We most often see effects generated by physically moving permanent- or electro-magnets, or by changing the current through an electromagnet. The EMF, electric currents, and forces generated by these can be quite impressive, even enough to help brake a train or roller coaster car.

What should I be thinking about before I start this lab?

This week you discover some very unusual properties of time-varying magnetic fields. In particular, a time-varying magnetic field produces an electric field. This means that there is more than one way to make an electric field.

****Any safety issues?****

Yes: The permanent disk magnet you use in this lab is EXTREMELY powerful. As long as you have only one, you are reasonably safe. But two of them attracting together can pinch your skin between them quite painfully. Two of the disk magnets stuck to each other are almost impossible to get apart.

ALSO, keep the magnet away from your credit cards – it will erase them!

A. Induced fields in a loop of wire

You can make an electric field with electric charges, as around a point charge or between charged capacitor plates, but also an electric field accompanies a time-varying magnetic field. Wherever there is a time-varying magnetic field, there is also an electric field. For instance, waving a permanent magnet in the air produces an electric field.

In this case the electric field is said to be *induced* by the time-varying magnetic field. This induced electric field exerts a force on charged particles, and so work is required to move a charged particle against this field. Pretty much like the electric fields we've worked with before, except that there aren't any electric charges around producing this electric field.

A simple way to measure this induced electric field is to put a piece of wire where you want to measure the electric field. At any point in a conductor where there is an electric field, there is also a current, according to $\vec{j} = \sigma\vec{E}$, where $\vec{j}$ is the current density, $\vec{E}$ is the electric field, and σ is the conductivity.

This means that there can be an electric field in the wire, and a current in the wire, without a battery anywhere.

Faraday's law: Faraday discovered a quantitative relation between the induced electric field and the time-varying magnetic field.

He found that the EMF around a closed loop is equal to the negative of the time rate of change of the magnetic flux through a surface bounded by the loop: $\mathcal{E} = -\dfrac{d\Phi}{dt}$.

The EMF around a closed loop represents the work/Coulomb required for you to move a positive charge around that closed loop.

A1. First you measure the EMF induced in coil of wire by a changing magnetic flux. You will start by using the 800-turn coil on your lab table. Remember that this induced EMF will cause a current to flow in the wire. So connect the 800-turn coil to the Digital Multimeter (DMM), making sure that the DMM is set to measure current (see Appendix B – Using a digital multimeter).

The long arrow on the coil indicates that the coil is wound clockwise from the bottom terminal to the top terminal.

Connect the top terminal to the red terminal of the DMM and the bottom terminal to the black terminal for this measurement. Note that the DMM displays a positive number when current flows into its red terminal and out of its black terminal.

Take the NdFeB disk magnet and hold it on top of the coil. Pull it away quickly, watching the current on the DMM. Do the other combinations indicated in the 'motion' column below, and fill in only the 'Dir of induced current' column based on your measurements.
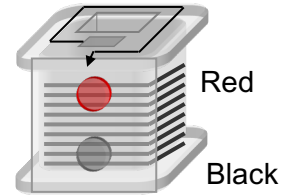
Motion	Sign of flux	Sign of change in flux	Dir of induced current (CW/CCW)	Sign of flux from induced current	Sign of voltage diff. V_{red}-V_{black}
N pole down, pull away from coil					
N pole down, push toward coil					
S pole down, pull away from coil					
S pole down, push toward coil					

Now fill in the rest of the first **four** columns of the table (leave the last one blank for now). For the sign of the flux, define a positive flux through the coil as produced by a magnet field directed down through the coil, and use the right-hand rule to determine the sign of the flux from your measured current direction.

A2. Explain how this table is consistent or inconsistent with Lenz' law.

A3. Now set up the DMM to measure voltage (remember to switch the cables!) and again move the disk magnet toward and away from the coil, and fill in the last column of the table.

A4. You now make a measurement of the EMF with the computer. Plug the coil directly into analog input A of the Pasco interface. Double-click on the Lab7_Settings1.cap file in the folder Lab Software/208 on the Desktop. Take data by holding the disk magnet directly above the coil as before, and pull the magnet very quickly upward away from the coil. Do this several times while recording the data, practicing until you get a consistent peak.

What is the value of the peak voltage? How does it depend on how fast you pull the magnet away? Explain

A5. Now measure the induced EMF in the 400-turn coil using the computer. Try to pull your magnet away in the same way as you did with the 800-turn coil. How does your peak voltage compare to that measured in the 800-turn coil? Explain.

A6. Now center an index card over the coil, and slide the disk magnet from one end of the card to the other while recording the voltage on the computer. Vary the sliding speed, and see how the signal changes. Turn the disk magnet over and repeat. Sketch the shape of the voltage signal vs time below, and explain in terms of the time-dependent flux.

How does the signal depend on the sliding speed?

Red

Black

VOLTAGE

TIME
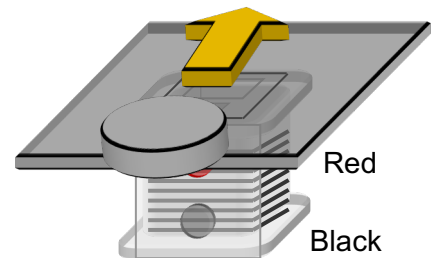
A credit card swipe is based on the effect you just demonstrated in A6. The magnetic strip on the back is made up of many tiny magnetic particles acting as bar magnets. A tiny coil generates a current from the changing flux, reading out a string of 1's and 0's corresponding to N and S orientation of the magnetic particles that encode information about you.

Signal current

Tape head

Swipe

Magnetic field
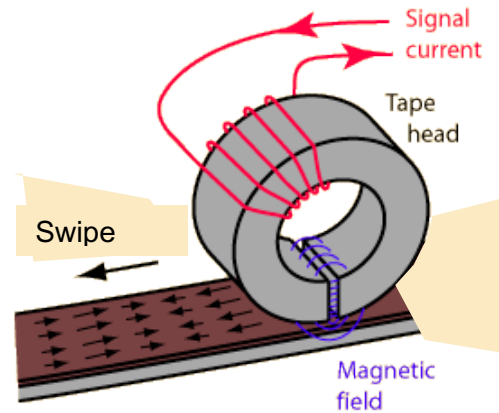
There is a card swipe attached to the computer by the printer. It behaves as a keyboard, and will type whatever information is on your card into an open word-processing program, such as Microsoft Word.

A7. Swipe your card and see what information is on there. (Close the window and open a new one after!) Find the slowest swipe speed (cm/s) at which the card reader works. Why does the swipe speed matter?

Just what might be on your credit card…

There are three tracks of information on the stripe, arranged as below. You can't see the individual tracks: they are just different defined regions of the magnetic strip.

The first track can hold numbers and letters: it starts with a "%" and ends with a "?".
    On a credit card you'll probably find your account # and name.

The second track can hold only numbers: it starts with a ";" and ends with a "?".
   You'll probably find your acct. #, expiration date, etc here.

The third track isn't used very often: it starts with a "+" and ends with a "?".

The read head has three coils with the correct spacing to pick up the three tracks of magnetically encoded information. Circuitry then translates the bits into numbers and letters that you see on the screen.

Track 1
Track 2
Track 3

Three-track read head
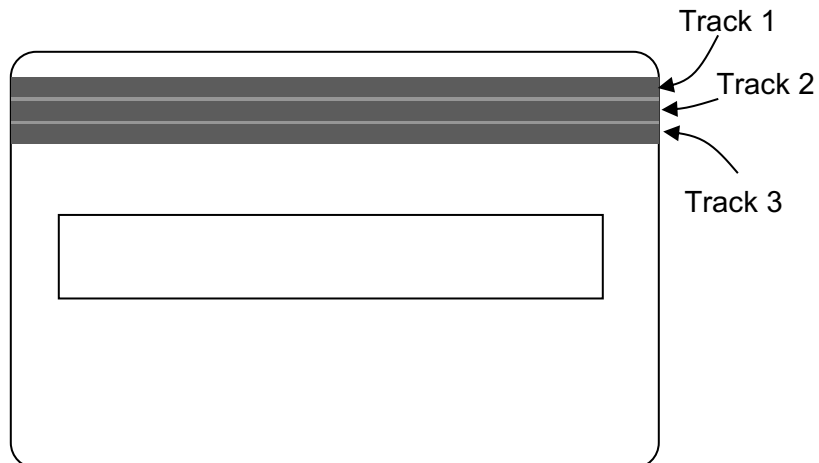
B. Quantitative determination of induced fields.

Moving permanent magnets near coils as in the last section produces clear signals, but it is difficult to make quantitative measurements of induced currents. The magnetic field from a permanent magnet is complicated, and it is difficult to make the flux from it change at a known rate.

In this section you produce a magnetic field by passing a current through a large drive coil. This replaces the permanent magnet you used in the last section. The flux from it changes in time because the current through it changes in time. The sense coil is playing the same role as the coil in the last section.
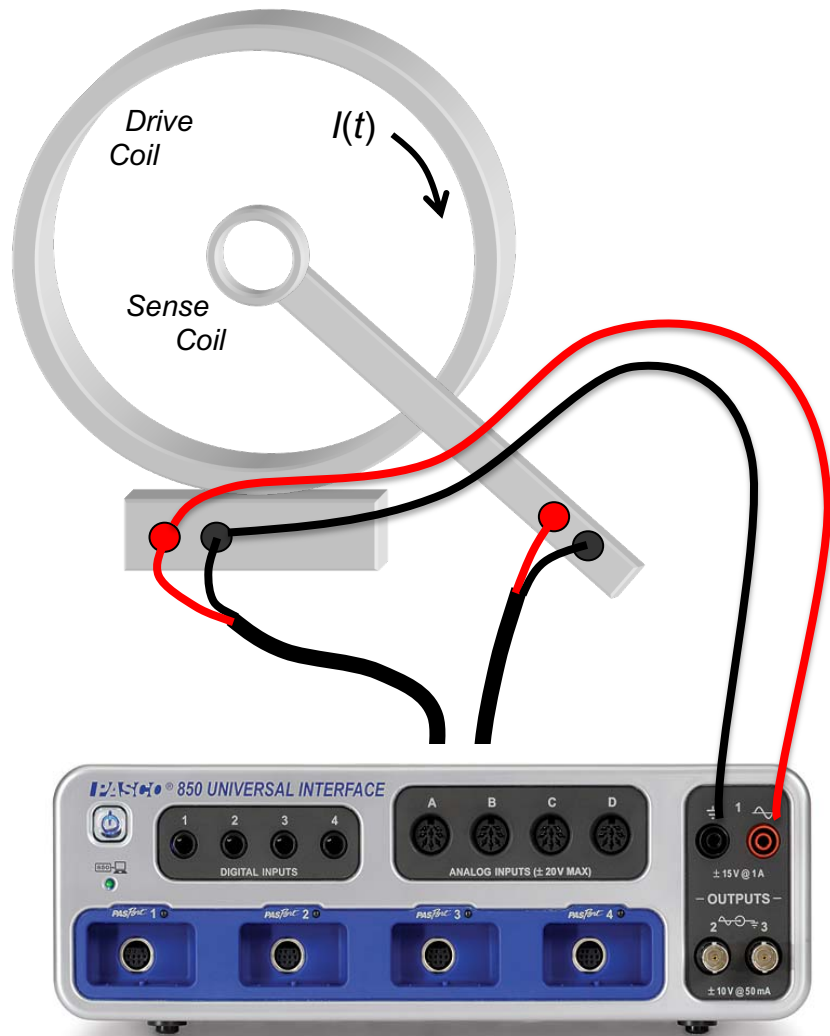
Now hook things up.

1) Connect the Pasco output 1 to the white inputs of the large coil. The frequency generator will be used to set a time-varying voltage V(t) difference across the large coil. The current through the coil is V(t)/R, where $R=7\Omega$ is the coil resistance.

2) Use a voltage probe cable to connect Pasco analog input A to the same white terminals of the large coil as Pasco output 1.

3) Use another voltage probe cable to connect the 2000-turn sense coil to analog input B.

4) Double-click on the Lab7_Settings2.cap file in the Lab Software/208 folder on the Desktop to start the data acquisition system. Click record to begin acquiring data.

The computer shows you real-time graphs of the voltage drop across the large drive coil, and any induced voltage in the 2000-turn sense coil.

If the 2000-turn sense coil is on the metal bar, take it off and move it around, watching the induced EMF (input B) on the computer screen. Then position the sense coil at the center of the large drive coil by sliding it onto the metal bar.

The computer makes the current through the large coil change in time. This produces a magnetic field that varies in time, just as when you moved the bar magnet in the previous section.

Again the time-dependent magnetic field induces an EMF in the small coil of wire. This time it is a movable 2000-turn "sense coil" on a plastic 'wand'.

B1.   This question is just to make sure you understand how you hooked things up.

   i) Channel A measures a voltage. What voltage does channel A measure?

   ii) Channel B also measures a voltage. What voltage does channel B measure?

B2.   Verify that the voltage $V_{coil}(t)$ across the large drive coil is a 10 Hz triangle-wave with 3V amplitude. The current through the coil is given by $V_{coil}(t)/R_{coil}$ where R_{coil} =7Ω. Plot the current through the drive coil, and your measured voltage across the sense coil.

B3. Explain the shape of sense coil voltage waveform using Faraday's law (e.g. why is it not a triangle wave like the drive?)

B4. Take your disk magnet and move it around near the sense coil while the data acquisition is running. Look at your data and explain what is happening.

B5. Take the sense coil off the bar but keep it near the axis of the large drive coil. Slowly change direction of the axis of the coil (e.g. parallel/perpendicular to drive coil axis) and watch the display on the computer. Explain these results. Think about the direction of the magnetic field from the drive coil, and the flux through the sense coil.

B6. Put the sense coil back on the bar, and change the frequency of the triangle wave to 5 Hz. Describe how and explain why the sense coil voltage has changed compared to the 10 Hz frequency setting.

C. Inducing currents in other conducting objects.

A time-dependent magnetic flux will induce currents in any conductor. These are usually called "eddy currents" when they are in an extended conductor. These in turn generate a magnetic field that adds to the original time-dependent flux. According to Lenz' law, the direction of the induced current is such that the flux generated by the induced current opposes the *change* in the original flux.

C1. In the diagram, draw the direction of the induced current in the ring when the magnet is moved as shown.
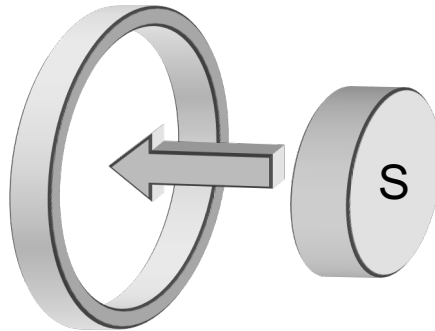
C2. In the same diagram above, draw the direction of the force on the disk magnet exerted by the induced current (you can think about the force on the induced current from the bar magnet, then apply Newton's law about action/reaction).

C3. Write a few words below about how you determined the current direction and the force direction.

C4. How would the current and force direction change if the magnet is flipped so that the South pole points toward the loop, and you move it toward the loop as in C2?

C5. You have a 6" length of 1/8" wall copper tube, and a strong NdFeB disc magnet. Hold the tube vertically above the lab table, and drop the disc magnet down the tube. Start the magnet so that the disc surface is parallel to table. Describe below what happened.
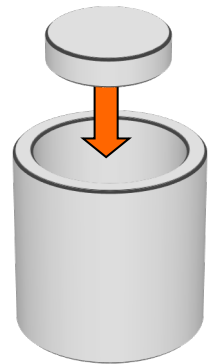
C6. In this part you determine if the magnet changes its velocity as it falls. Drop the magnet through one 6" length of 1" ID tube and time it.
Now stack two 6" lengths of 1" ID tube, and time the magnet's fall through a 12" length.
 Is the magnet accelerating as it falls?

Time to fall 6"

Time to fall 12"

C7. There are two forces on the magnet as it falls:
    1) a force downward from gravity, and
    2) a force upwards from the currents induced in the tube
    (think of the tube as metal rings (as in C1) stacked on top of each other).

Suppose the upwards force is instantaneously smaller than the downwards force. What happens to the speed of the magnet at that time in its fall?

As a result of this change in speed, what happens to the induced EMF around the tube and the currents induced in the tube, and what happens to the upwards force?

Under what conditions will the speed of the magnet stop changing?

C8. Now you make a quantitative measurement of how long it takes the magnet to drift down various tubes. Use your stopwatch to time the drift. Do the measurement several times and average, then calculate the terminal velocity.

You will use: [ID = "Inside Diameter"]

    Two 6" copper (Cu) tubes (1/8" wall, 1" ID) doubled up lengthwise

    One 12" aluminum (Al) tube (1/8" wall, 1" ID)

Tube	Length	Time1	Time2	Time3	AveTime	Term. Vel. (cm/s)
Cu 1/8 W, 1 ID	30.5cm					
Al 1/8 W, 1 ID	30.5cm					
Cu 1/8 W, 7/8 ID	15.25cm					

C9. In this section you qualitatively explain the ordering of the terminal velocities (e.g. why the slowest is the slowest and why the fastest is the fastest). Think of the tube as several rings (as in C1) stacked on top of each other. The induced currents in the tube produce an upward force on the magnet that cancels gravity. The induced currents are determined from the EMF around the ring by the resistance.

i) First think about the two tubes of the same inner diameter (ID), but made from different materials (Al and Cu). The tubes have different resistivities, but have identical geometries.

    In both tubes, the magnet falls at constant [although different] speeds. This means that there is zero acceleration, and hence zero net force — the force on the magnet from the induced currents exactly cancels the force from gravity.

    Discuss why the currents induced in each tube must be the same, even though the magnets are falling at different speeds.

ii)   The relation between the current density $\vec{j}$ and the electric field $\vec{E}$ is $\vec{j} = \vec{E} / \rho$, where ρ is the resistivity.

This *E* is the electric field induced by the changing magnetic flux from the falling magnet. It's direction is approximately around the circumference of the tube, so that the induced $EMF = \oint \vec{E} \cdot d\vec{s} \sim E \times (circumference)$. Look up the resistivities of Al and Cu (e.g. do web searches on "resistivity of aluminum", and "resisitivity of copper", and look for results with units of Ωm) and determine the ratio of the EMFs induced around the tubes that is required to make the current densities equal.

iii) How is the induced EMF related to the falling speed of the magnet? Determine the ratio of the falling speeds in the two different tubes that make equal current densities in the tubes. Compare to your experimental results.

Name_____   **Section**_____

Physics 208 Laboratory
Inductors: *RL* and *LRC* circuits

This sheet is the lab document your TA will use to score your lab. It is to be turned in at the end of lab. To receive full credit you must use complete sentences and explain your reasoning clearly.

What's this lab about?

In this lab you investigate inductors--how they function in *RL* and *LRC* circuits--and one medical application—Transcranial Magnetic Stimulation.

PART A
    A tightly-wound solenoid is a common type of inductor. Predict and measure the magnetic field *B* created by a tightly-wound solenoid.

PART B
    Measure the mutual inductance *M* of a pair of concentric solenoids, and confirm it doesn't matter in which of the solenoids you drive current.

PART C
    Find the self-inductance *L* of a solenoid by measuring the *L/R* time of the solenoid.

PART D
    Measure the self-inductance *L* of an inductor by measuring the oscillation frequency of an *LRC* circuit with a known *C* and a comparatively small *R*. Estimate *R* by measuring the *L/R* time of the circuit. Estimate the energy stored in the circuit, first in the capacitor, and then in the inductor. Simulate Transcranial Magnetic Stimulation by placing a material object near the inductor.

Why are we doing this?

Inductors are necessary components in circuits that are used to move energy from one place to another. This includes everything from motors, which do mechanical work when and where needed, to cell phones, which send and receive information using antennas that include inductors.

What should I be thinking about before I start this lab?

Magnetic fields are invisible and intangible, yet inductors allow us to use them very precisely to move energy around where and when we want it to go.

Any safety issues?

Yes: The *LRC* circuit used in part D generates high voltage.

A. Preliminary: Measurement of B in Inductors

An inductor is a circuit element that is intended to have a precise, well controlled self-inductance. In order to have a precise self-inductance, the inductor must generate a known magnetic field for a given current. A wire wound on the outside of a cylinder is called a "solenoid" and is a common type of inductor. In this part of the lab we'll confirm that a solenoid does in fact generate a specific magnetic field for a given current, and we'll compare that to a predicted value for the field.

Below is an illustration of a long solenoid. The direction of the current in the winding is indicated by the $\otimes$ and $\odot$ symbols, and the direction of the magnetic field is shown by the arrows as determined by the right hand rule.
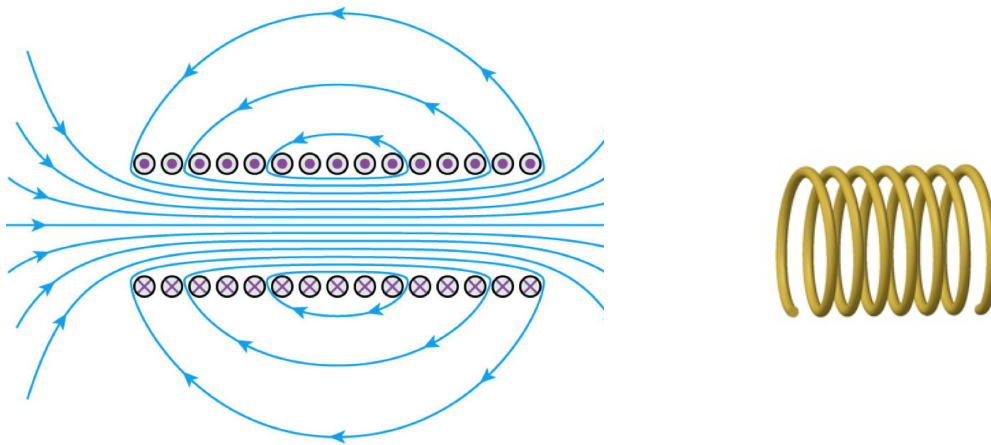

(Left) Cross-section of a long solenoid; (Right) A portion of a long solenoidal winding

The strength of the magnetic field can be inferred by the distance between neighboring field lines. The magnetic field inside the solenoid is very uniform, with nearly constant magnitude and direction. The magnetic field outside the solenoid is nearly zero. In lecture it was shown that the magnitude of the magnetic field inside an infinitely long solenoid is $B = \mu_0 n I$, where I is the current in the solenoid, n is the number of turns per unit length, and the permeability of free space $\mu_0 = 1.257 \times 10^{-7}$ N/A^2 is a universal constant.

A1. Below are the two solenoids we'll investigate in this part of the lab (the "inner coil" and the "outer coil"). Their specifications are:

Inner coil: number of turns, N= 235; length, ℓ = 12.0 cm

Outer coil: N=2920 ; ℓ = 11.0 cm

Outer coil
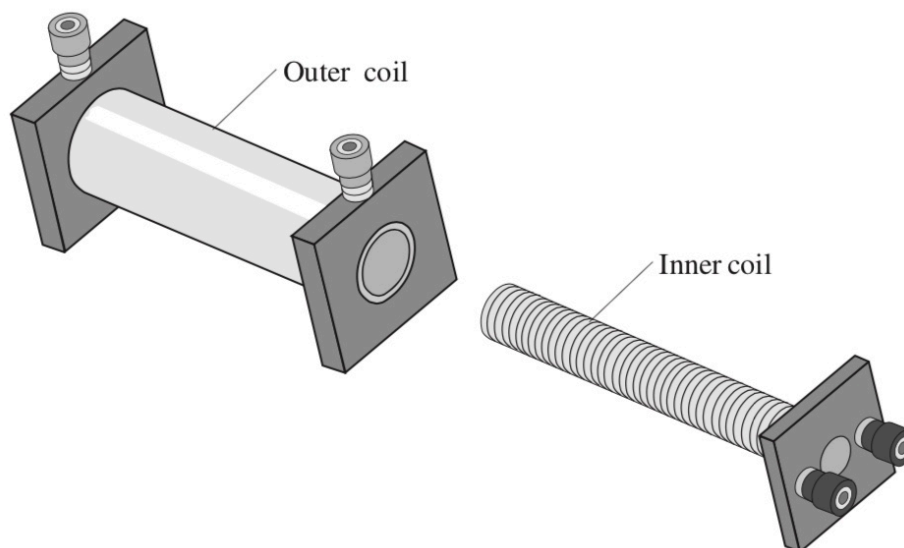
Inner coil

Use the "infinitely-long solenoid" formula $B = \mu_0 n I$ to predict the magnetic field (in Tesla; please use scientific notation) inside the inner coil when the current through the inner coil is 1.5 A, and inside the outer coil when the current through the outer coil is 0.254 A.

$B_{predicted}$ inside inner coil:_____ $B_{predicted}$ inside outer coil:_____

A2. Connect the magnetic field sensor to Analog Input B of the PASCO interface. Make sure the connector is oriented with "top" up before pushing it in. Set the magnetic field sensor "range select" to 10x and the direction switch to "axial". Start the PASCO software by launching the LabL_Settings_1.cap file.

A3. Turn on the DC power supply. Set the current to zero. Connect the inner coil to the DC power supply. Set the current to 1.5 A.

A4. Place the sensor as far as you can from magnetic objects (including the metal frame of the lab table), and orient it in the same direction as the inner coil. Press the "tare" button (this sets the zero of the sensor).

A5. Press "record" to start taking data. Without changing the orientation of the sensor, insert it slowly into the inner coil as far as it will go, then bring it slowly out again. Press "stop" to stop taking data. Set the current to 0 A.

A6. Sketch below the graph of *B* vs time on the screen.

Magnetic Field (T) (vertical axis)

time (s) (horizontal axis)
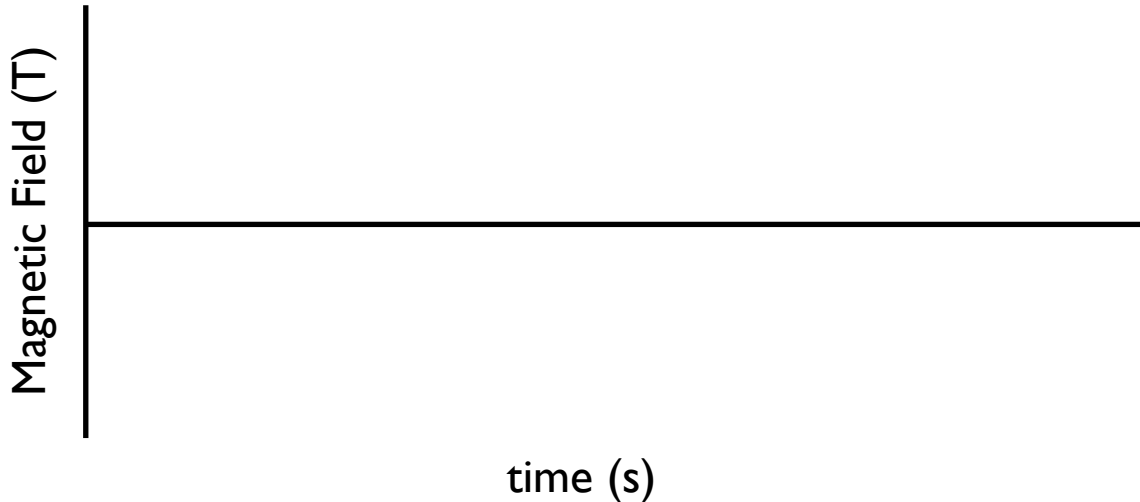
A7. What was the maximum absolute magnitude of the magnetic field inside the inner coil? Was the magnetic field roughly uniform inside the coil?

Maximum $|B_{Measured}|$ inside inner coil:_____

A8. Repeat steps A3-A5 for the outer coil, setting the current at 0.254 A (the maximum the power supply can put through the outer coil, which has a much higher resistance than the inner coil).   What was the maximum absolute magnitude of the magnetic field inside the outer coil?

Maximum $|B_{Measured}|$ inside outer coil:_____

A9. What were the ratios of the measurement to the prediction?

Inner coil $|B_{Measured}|/B_{Predicted}$:_____   Outer coil $|B_{Measured}|/B_{Predicted}$:_____

A10. We expect you saw that the magnetic field inside a solenoid of finite length is nearly constant for much of its length, but drops off sharply near the end of the solenoid.   In the space below, make a graph of the magnitude of the axial component of B inside the solenoid as a function of position. Make sure your graph lines up with the sketch of the B field lines below the graph.
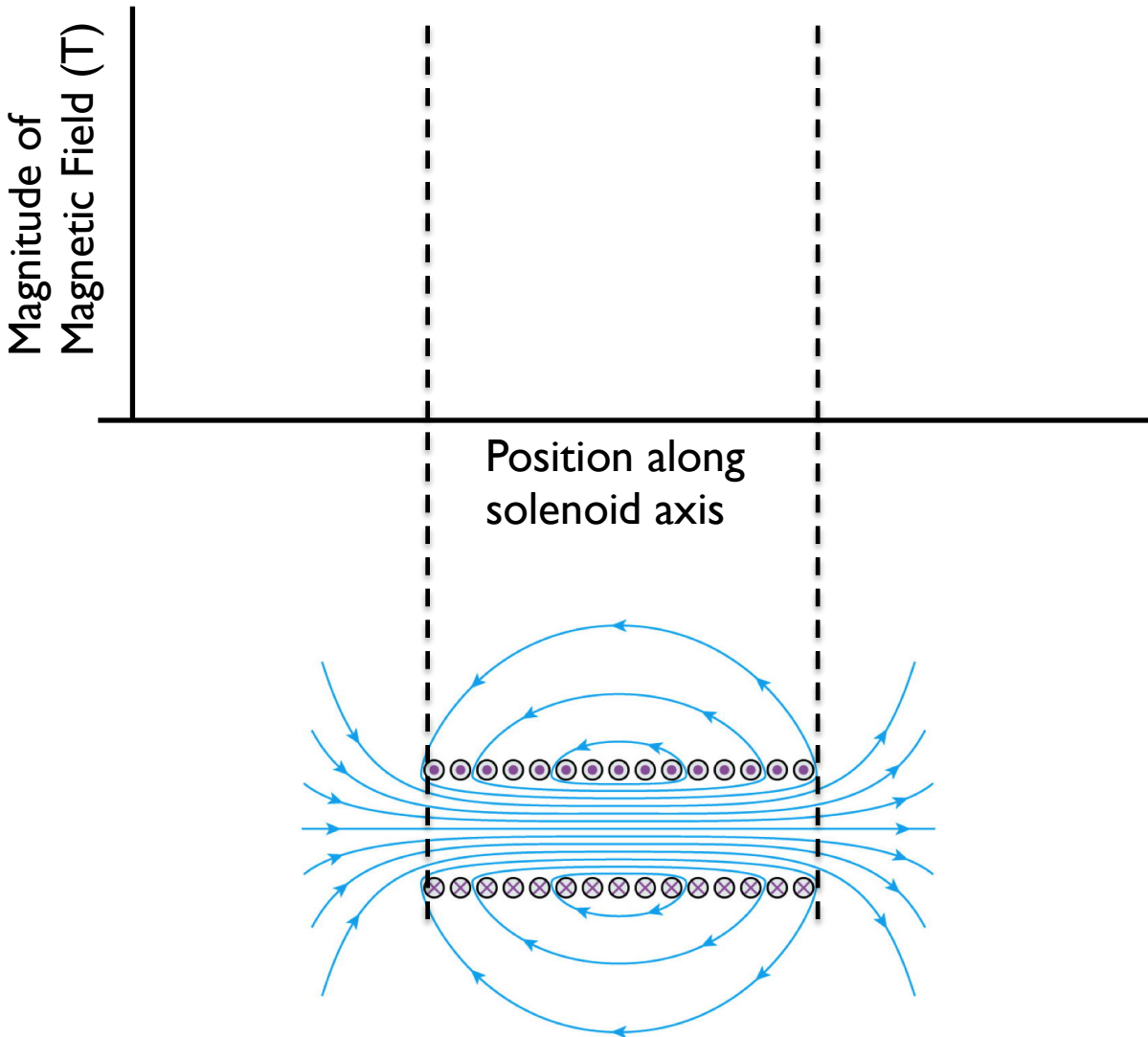
We hope that you have seen that the simple formula $B = \mu_0 n I$ predicts the axial field inside an actual solenoid pretty well, although not perfectly well. There exist more complicated formulas, outside the scope of Physics 208, that can very accurately predict the magnetic field inside an actual solenoid.

B. Mutual Inductance

Mutual inductance measures the magnetic coupling between two circuits (see the chapter of the textbook on "Inductance"). The mutual inductance M satisfies the equations $\mathcal{E}_2 = -M di_1/dt$ and $\mathcal{E}_1 = -M\, di_2/dt$. The subscripts mean the emf in one circuit caused by current in a second circuit and vice versa. Here we'll try to verify that mutual inductance M is a geometric property that has the same value for both circuits.

B1. Suppose you have two solenoids, one with current flowing through it, and one without. The mutual inductance between the solenoids will be large if a lot of magnetic fields lines from the first solenoid pass through the second, and small if few magnetic field lines from the first pass through the second. If the two solenoids are very far apart, will the mutual inductance be large or small?

B2. Now suppose the solenoids are near each other, but their axes are perpendicular. Will their mutual inductance be large or small?

B3. Finally suppose the solenoids are "nested"—their axes are concentric, and one is inside the other. Will their mutual inductance be large or small?

B4. Connect the Voltage Sensor to Analog Input A of the PASCO interface, close out of the PASCO software, and launch the LabL_Settings2.cap file.

B5. Nest the inner coil inside the outer coil. Connect Output 1 to the inner coil. Connect the Voltage Sensor to the outer coil.

B6. Set the output waveform to triangle wave, the frequency to 100 Hz, and the amplitude to 0.06 V. Set the output to "On".

B7. Start taking data, then "Stop" within a second. Zoom in to confirm that you see something that looks like a triangle wave in the right-hand window, and something that looks like a square wave in the left-hand window. Why do you expect the second wave to be a square wave?

B8. Measure di_{inner}/dt (in A/s) by fitting a straight line to the Output Current trace, using the "Linear" fit in PASCO, $I = mt + b$. What are the units of m? How does m relate to di_{inner}/dt?

$di_{inner}/dt=$_____

B9. The Voltage Sensor has a slight offset (it reads about 0.001 V when it should read 0 V). Account for this offset by taking $\mathcal{E}_{outer}$ (in V) = ½ (Maximum Voltage – Minimum Voltage).

$\mathcal{E}_{outer}$=_____

B10. Calculate M (in H): M = _____

B11. Now connect Output 1 to the outer coil and connect the Voltage Sensor to the inner coil.

B12. Set the amplitude to 10 V and the frequency to 10 Hz.

B13. Take data as before.

B14. Use the same method as before to measure d_{outer}/dt (in A/s) and $\mathcal{E}_{inner}$ (in V):

d_{outer}/dt=_____ $\mathcal{E}_{inner}$=_____

B15. Calculate M (in H): M= _____

B16. Compare M as calculated in steps B9 and B14. What is the discrepancy between them, in percent?

C. Measurement of L by measurement of L/R time constant

Typically, it is difficult to measure directly the flux Φ_B passing through an area, so is rarely possible to measure the self-inductance L of an inductor by measuring Φ_B and then using $L=N\,\Phi_B/\,i$. Often it is easier to put the inductor in a circuit with a known resistance R, measure the time constant $\tau = L/R$, and then calculate L as $L=\tau R$. In fact, many inductors have sufficiently large resistances we don't even have to add an extra circuit element in order to do this, as we will now see.

In what follows we will call the inner coil the "smaller coil" and the outer coil the "larger coil", in order to prevent any confusion regarding the nature of self-inductance, which is a property of each individual inductor.

C1. Use the digital multimeter (DMM) as to measure the DC resistance of the larger coil:

R_{larger} = _____ Ω

C2. Draw a circuit diagram below, showing a voltage source, the inductance L_{larger} which we are trying to measure, and R_{larger}, all in series.

C3. Move the smaller coil off to the side, so it is far away from the larger coil. Connect Output 1 to the larger coil, and also connect the Voltage Sensor to the larger coil (red to red, and black to black).

C4. Set the waveform to square wave, the frequency to 100 Hz, and the amplitude to 3 V. Make sure the sample rate (bottom of window) is 20 kHz.

C5. Take data for a brief time. Zoom in to confirm you see a square wave on the right-hand window, and a square wave with an extra "spike" on the left-hand window. The extra "spike" is evidence that the Voltage Sensor is connected to something that has a significant self-inductance. Zoom in on the spike. It should look like a decaying exponential (there are two graphs in the textbook section on "The R-L Circuit" that show decaying exponentials).

C6. Use the "selection" tool to select the data in the spike. Using the PASCO "fit" tool, select "natural exponential", $y=Ae^{-Bt}+y_0$, and fit a decaying exponential to the spike. Verify that the fit fits the data pretty well.

C7. Write down the fit parameter B. What are its units? What is the relation between τ, the time constant of the circuit, and B?

C8. What is τ in s?

C9. Using your measurements of R_{larger}, what is L_{larger} (in H)?

L_{larger} = _____ H

C10. Disconnect the larger coil, and in its place connect the smaller coil.

C11. Set the amplitude to 0.1 V

C12. Briefly take data. Verify data looks as expected, especially that the inductive "spike" is visible in the left-hand window.

C13. It is possible to deduce $R_{smaller}$ from the data currently shown on the screen.   Hint: after the inductive effects have decayed away, the voltage and current are related by $V=IR$. Record here the two values you used to deduce $R_{smaller}$, and $R_{smaller}$ itself.

Value #1: _____ (Units = _____)   Value #2: _____ (Units = _____)

$R_{smaller}$ = _____ Ω

C14. Use the same fitting procedure as before to find τ for the smaller coil.

What is τ in s?

C15. Using your measurement of $R_{smaller}$, what is $L_{smaller}$ (in H)?


$L_{smaller}$ = _____ H

For comparison, the coil manufacturer states that L_{larger}= 63 +/- 3 mH (R_{larger}= 76 +/- 2 Ω), and $L_{smaller}$= 78 +/- 22 μH ($R_{smaller}$ = 0.4 +/- 0.1 Ω).

## D. *LRC* Circuits, Stored Energy, and Transcranial magnetic stimulation

In this section we'll investigate oscillation frequency, decay time, and stored electric and magnetic field energy in a series *LRC* circuit. The value of *R* is small enough that we can ignore it, or not, as we choose for our purposes. Our *LRC* circuit is very similar to circuits used in the medical procedure Transcranial Magnetic Stimulation, described below.

Below is a photo of our series *LRC* circuit:
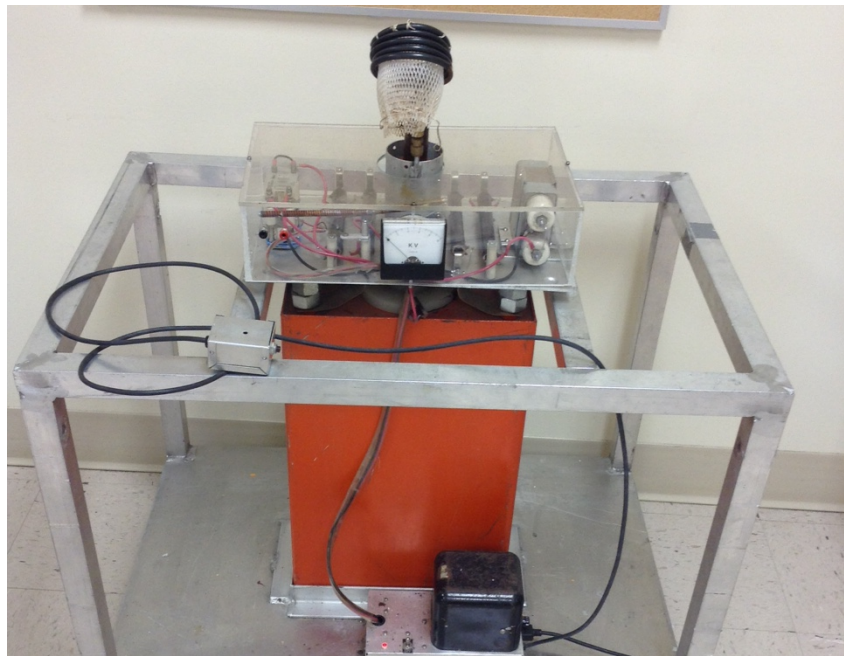
The capacitor (capacitance *C* = 62 μF) is the large orange thing at the bottom of the circuit. The inductor is the five-turn solenoid at the top (it is made of copper tubing, wrapped in black insulator). The *LRC* circuit is constructed so that when you press a button, the capacitor starts charging, and when you release the button, the capacitor is simultaneously disconnected from the charger, and connected to the inductor (all the other hardware in the picture is needed to accomplish this "switching").

Transcranial Magnetic Stimulation is a non-invasive clinical technique that has shown therapeutic potential in a wide variety of neurological and psychological ailments. A coil is placed on or near the patient's scalp, and a pulse of current is sent through the coil, creating a pulse of magnetic field, and thus an emf, in the cortex of the brain. Muscles that receive corticomotor input from that part of the cortex are stimulated.
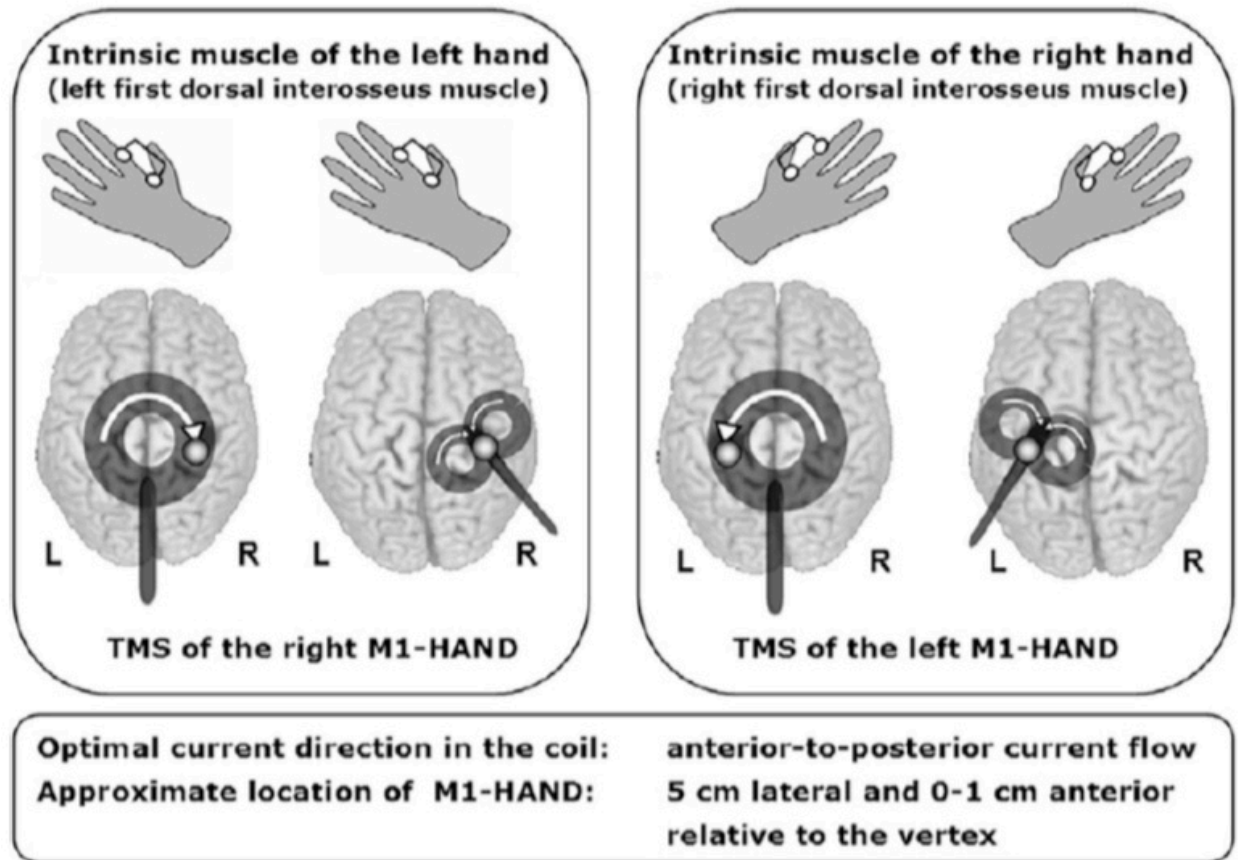
(Figure above from S. Groppa et al., "A practical guide to diagnostic transcranial magnetic stimulation: Report of an IFCN committee", Clin. Neurophysiol 2012 May; 123(5): 858-882.

The basic circuit used to produce the current pulse is an *LC* circuit, as we have studied in Physics 208 (various complications which make the circuit simpler and safer to use, and cheaper to manufacture, are omitted). Below is a figure from a textbook on TMS, which we hope is accessible to you based on what you have learned in Physics 208. The circuit diagram shown below is the same as the circuit diagram for the our *LRC* circuit shown above—the *R* is non-zero because in real life it's hard to make a circuit with exactly zero resistance. Sometimes it's desirable to have a non-zero *R*.
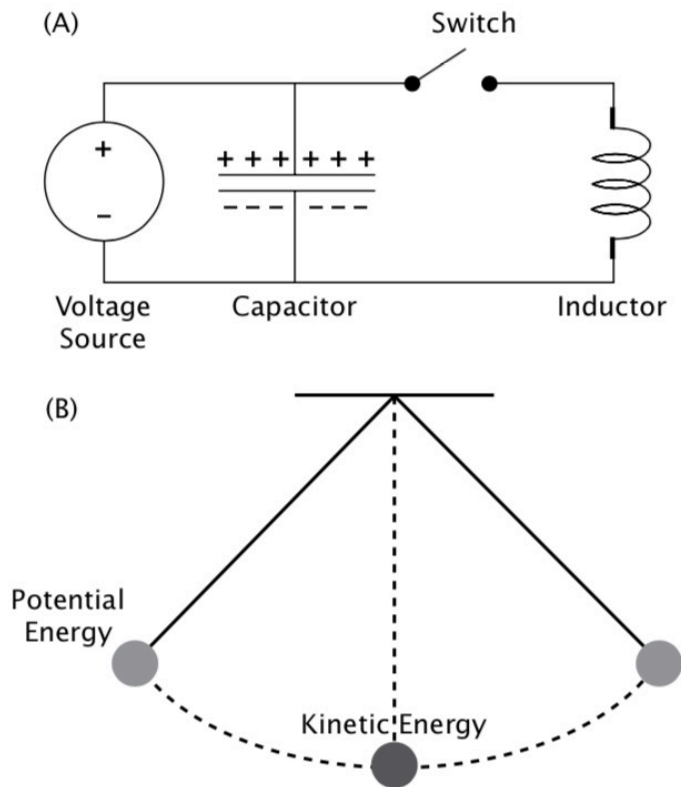
FIGURE 2.1 (A) Circuit 1 is the most basic type of TMS circuit. It includes a voltage source, a capacitor, a switch to release the current, and an induction coil. (B) A simple pendulum, which is analogous to the basic TMS circuit. When the pendulum is raised to one side, it stores potential energy, similar to a charged capacitor. Once the pendulum is released and reaches bottom, all of the energy is kinetic, just as all the energy of the TMS circuit is in the coil when the current is maximum. The pendulum and the TMS circuit can swing back and forth repeatedly between states of stored and kinetic energy.

(Figure above from Holtzheimer, P.E. et al (Eds.), "A clinical guide to transcranial magnetic stimulation", Oxford Univerity Press (2014); Chapter 2)

D1. We will be charging the capacitor to 2000 V. How much energy, in J, is stored in the capacitor when it is charged to 2000 V? (Hint: $U = C V^2/2$).

$U_{Capacitor}=$_____

To gain information about our circuit, we're going to place a one-turn solenoid (ie a loop) of wire near the circuit. Let us call this the "pick-up" loop. We have no idea of the mutual inductance M between the 5-turn solenoid and the pick-up loop, but we'll use the pick-up loop for the sole purpose of measuring the oscillation frequency and decay time of the LRC circuit, so we don't need to know M.


We'll use an oscilloscope (rather than the PASCO software, or a DMM) to measure the emf induced in the pick-up loop, because oscilloscopes have much better time resolution. The signal displayed on the screen of an oscilloscope is typically a voltage, shown as a function of time.

D2. Turn on the oscilloscope and connect the pick-up loop to Channel 1 of the oscilloscope. Set the scope to Single trigger mode.

D3. Place a bottle of sports drink in the coil (make sure it is tightly capped). The sports drink has electrical characteristics not unlike tissue *in vivo*.

D4. Place the pick-up loop near the 5-turn solenoid, about two inches from the end, and orient the pick-up loop so its axis is parallel to the axis of the 5-turn solenoid.

D5. Charge the capacitor to 2000V, and then release the button. The scope should trigger, and you should see an oscillation on the screen (the oscillation is damped because the R of the circuit isn't exactly 0). Sketch the oscillation below.
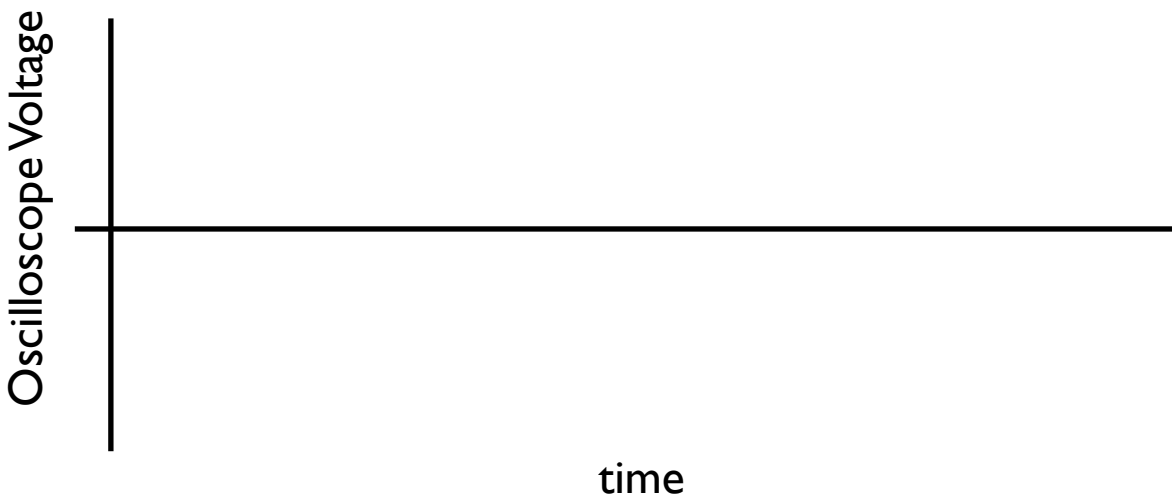
D6. Use the scope "Cursor" function to measure the time ΔT between of five complete periods of oscillation:

$\Delta T =$ _____ s.

D7. From this, calculate the angular frequency ω of the oscillation:

$\omega =$ _____ rad/s

D8. Use your value of ω to estimate the self-inductance L, in H, of the 5-turn solenoid:

$L=$ _____

D9. If R were really zero, all of the energy that had been stored in the (electric field inside the) capacitor would, after half an oscillation, be stored in the (magnetic field surrounding the) inductor.

Use that the energy stored in an inductor is $U_{Inductor} = LI^2/2$ to estimate the current I, in A, flowing in the inductor: $I =$ _____

D10. The 5-turn solenoid is really not a very long solenoid at all, but we can still estimate the magnitude of the magnetic field using $B=\mu_0 nI$, even though we know this equation isn't exact. Measure the length ℓ of the solenoid, and record your estimate of B:

$\ell =$ _____m $B =$ _____ T

We can tell that R is not really zero because the oscillations shown on the oscilloscope decay with time. We can measure the decay constant, and infer R.

D11. Use the cursor function to measure the decrease in voltage between two maxima of the oscillation. Record $F > 1$, the voltage ratio between the maxima (the one with the larger voltage goes on top), and ΔT, the time between the maxima:

$F =$ _____ , $\Delta T =$ _____ s.

D12. The time constant τ of the decay is then $\tau = \Delta T/\ln (F)$. Calculate τ: $\tau =$ _____ s

D13. From τ and L, calculate R, the (small) resistance in the circuit: $R =$ _____Ω

D14. The signal shown on the oscilloscope is proportional to the current induced in the pick-coil (we don't know the constant of proportionality). Is the current induced in the pick-up coil proportional to B, the magnetic field created by the 5-turn coil, or to dB/dt?

D15. Copy your sketch from D5 onto the axes below, and infer from it the time evolution of B. Make sure the features on the two graphs correspond to each other.

Oscilloscope Voltage

time

Magnetic Field (T)

time (s)
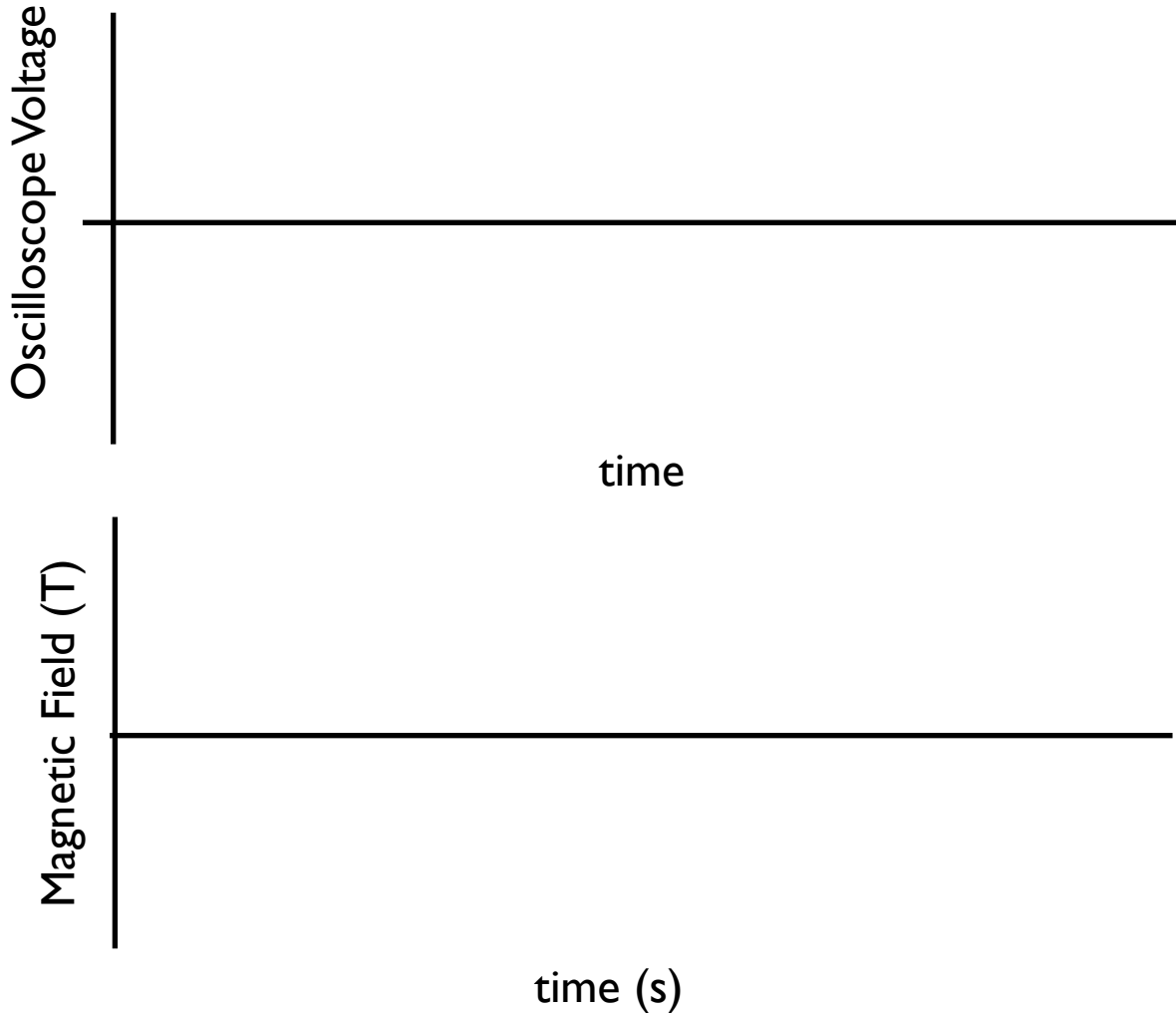
For comparison, actual TMS machines typically operate with pulsed currents of up to 5000 A, creating magnetic fields of approximately 1 T, with duration approximately 1 ms.

Further reading:

A.T. Barker, R. Jalinous, I.L. Freeston, "Non-invasive magnetic stimulation of human motor cortex," Lancet. 1985 May 11;1(8437):1106-7. doi: 10.1016/s0140-6736(85)92413-4.

R. Jalinous, "Technical and Practical Aspects of Magnetic Nerve Stimulation," Journal of Clinical Neurophysiology **8** (1): 10-25 (1991).

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Name_____   **Section_____**

Physics 208 Laboratory
Polarization of Light

This sheet is the lab document your TA will use to score your lab. It is to be turned in at the end of lab. To receive full credit you must use complete sentences and explain your reasoning clearly.

What's this lab about?

In this lab you investigate effects arising when using polarized light.
<u>PART A</u>
   Use a polarizer to explore common occurrences of polarized light
<u>PART B</u>
   Use a polariscope to understand how polarized light waves can be superposed, or decomposed into components.
<u>PART C</u>
   Create and investigate circular polarization.
<u>PART D</u>
   Use the ideas of circular polarization and superposition to see how polarized light interacts with biological sugar molecules.

Why are we doing this?

Understanding polarized light is important for applications such as microscopy, as well as in understanding the properties of electromagnetic waves.

*What should I be thinking about before I start this lab?*

Suppose an electromagnetic wave is propagating through your area at the speed of light. If you could take a snapshot, you could freeze the electric and magnetic fields at a particular instant in time so that you could look at them. At each point in space around you, and at each instant in time, you would see electric and magnetic fields with these properties:

i) $\vec{E}$ and $\vec{B}$ are always perpendicular to each other, and also to the wave propagation direction (such that $\vec{E} \times \vec{B}$ is in the propagation direction).

ii) The magnitudes $\left|\vec{E}\right| \equiv E$ and $\left|\vec{B}\right| \equiv B$ are related as $B(x_o,y_o,z_o,t_o) = (1/c)E(x_o,y_o,z_o,t_o)$.

iii) $\vec{E}$ and $\vec{B}$ both oscillate in time with a frequency $f = v/\lambda$ (*v* is the propagation speed).

iv) It takes a time *T*=1/f (the period) for the fields to complete one complete cycle at a fixed point in space, and a distance λ (the wavelength) to complete one complete cycle at a fixed time.

A. Making and detecting polarized electromagnetic waves

In a *linearly polarized* electromagnetic wave, the electric field varies in time and space, but it always lies in a *plane of polarization*. Since the associated magnetic field is always perpendicular to this, we can describe the polarization completely by describing the orientation of the electric field.
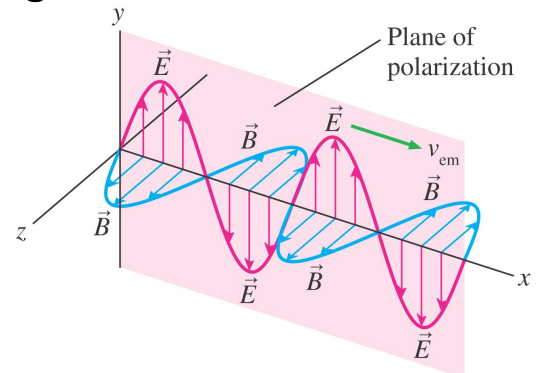
Light doesn't often look like this unless it is specially prepared. It is usually a superposition of all possible polarizations, which we call unpolarized light.

A linear polarizer can be used to investigate the polarization state. It completely transmits linearly polarized light aligned with its transmission axis, and completely absorbs light linearly polarized perpendicular to its transmission axis.

A1. Polarization by reflection.

Light is partially polarized whenever it is reflected. You can check this by using the linear polarizer from the polarization kit on the lab table. Raised lines on the black plastic disc that holds the polarizing material mark the transmission axis.

i) First look through the kit polarizer directly at the black desk lamp on your lab bench. Does the desk lamp produce polarized light? How did you tell?

ii) Now aim the lamp at the lab bench at about a 30° to 45° angle (from the horizontal), and look through the kit polarizer at the reflection of the bulb in the bench top.

Is this light polarized? In what direction is the plane of polarization?

iii) Many sunglasses have linear polarizers as lenses. They operate on the same principle as your kit polarizer. In what direction is the transmission axis of sunglass lenses? Explain.

iv) Use your kit polarizer to look at your cell-phone display or a computer LCD monitor. Describe the light emitted by these. For online students: if you have sunglasses, check to see whether the lenses are polarizers by looking through a lens at a cell phone or computer display while rotating the lens around the line of sight. Do you see changes in brightness as you rotate the lens?

B. The polariscope

Your polariscope has two polarizers:

The bottom one sits directly over the (unpolarized) incandescent bulb, and is fixed in place. In a two-polarizer system, it is usually called "the polarizer", since it produces linear polarized light from an unpolarized source.

The top one can rotate. It is usually in-line with the bottom polarizer, but can also be swung to the side. In a light microscope, it is usually called "the analyzer", since it analyzes whether a sample placed above the bottom polarizer has altered the polarization.
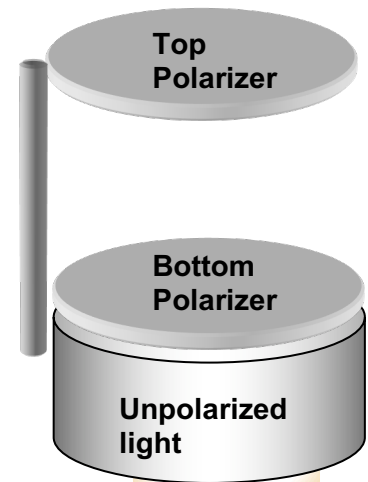
B1. Turn on your polariscope and look down into the top polarizer. Describe the intensity variations while rotating the top polarizer through 360°.

B2. Find the transmission axis of the bottom polarizer using the kit polarizer (mounted in a black plastic ring) from your box, which has its transmission axis marked with two ridges in the plastic. Explain your procedure and use a piece of masking tape to mark the transmission axis on the rim of the polariscope.

Find the transmission axis of the top polarizer and mark it also.

B3. What angle is between the transmission axes of the two polarizers when there is: Maximum transmission?

No transmission?

You have just seen that a linear polarizer transmits a light wave whose electric field vector is parallel to the transmission axis, and blocks (absorbs) one with electric field vector perpendicular to that direction.

For angles not 0° or 90° with respect to the transmission axis the polarizer transmits the *component* of the *E*-field along the transmission axis and absorbs the rest.

B4. Below is the electric field of an electromagnetic wave throughout its period *T*.   The electric field has an amplitude E_0. It is linearly-polarized 45° away from the y-axis. Draw the x-and y-components.

t=0

t=T/6

t=2T/6

t=3T/6

t=4T/6

t=5T/6
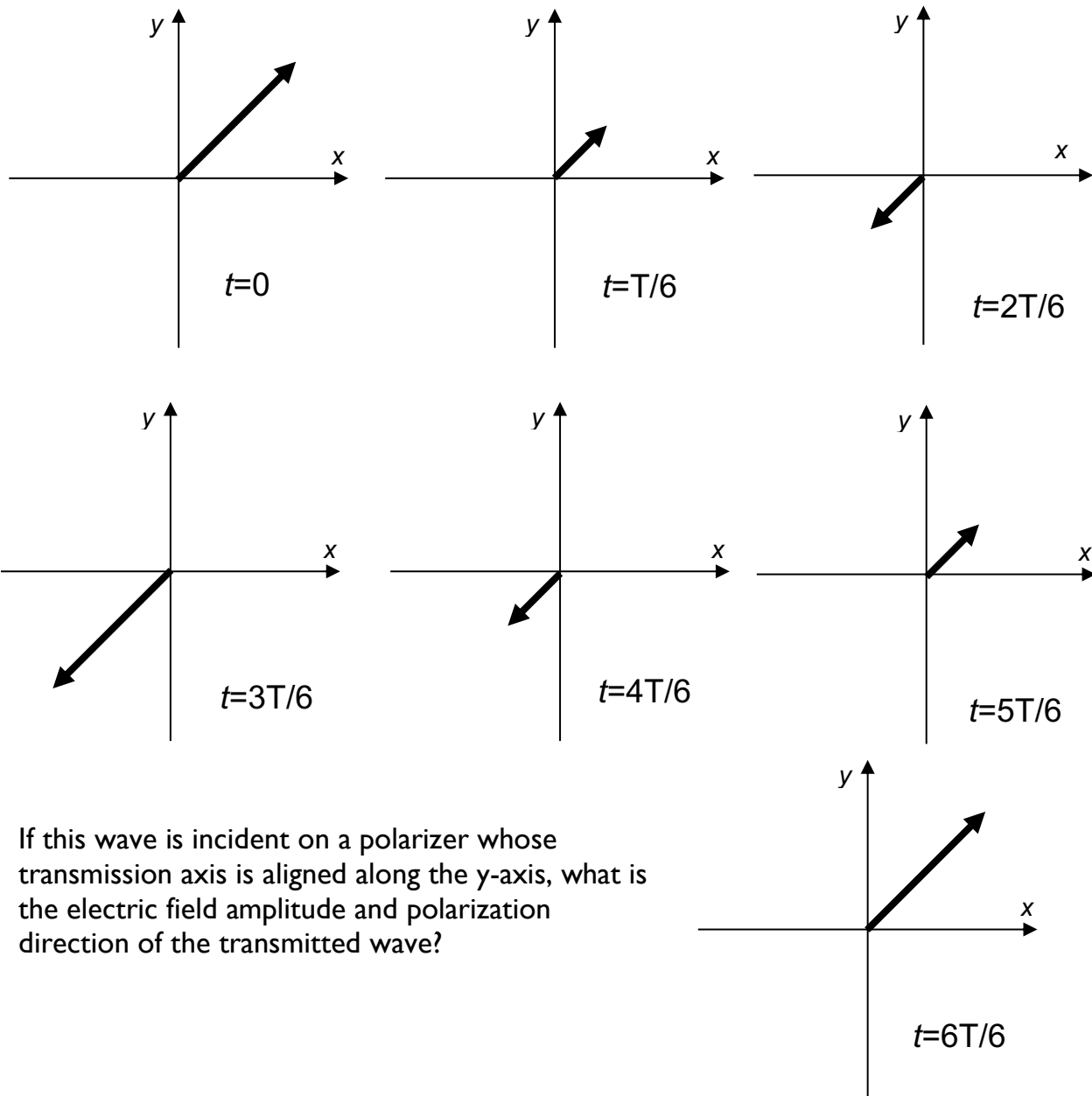
If this wave is incident on a polarizer whose transmission axis is aligned along the y-axis, what is the electric field amplitude and polarization direction of the transmitted wave?

t=6T/6

B5. Set the top polarizer on your polariscope so that no light is transmitted. Now insert the kit polarizer between them and rotate it.
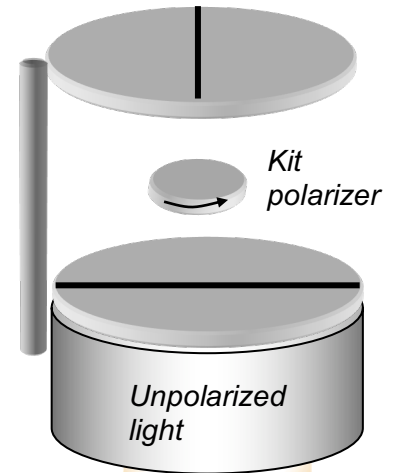
Kit polarizer

Why does light now get through at some angles?

Unpolarized light

B6. Rotate the kit polarizer through a full 360˚. From your experimental observations, qualitatively sketch the intensity through the top polarizer vs angle of the kit polarizer transmission axis relative to the transmission axis of the bottom fixed polarizer.

0˚   90˚   180˚   270˚   360˚
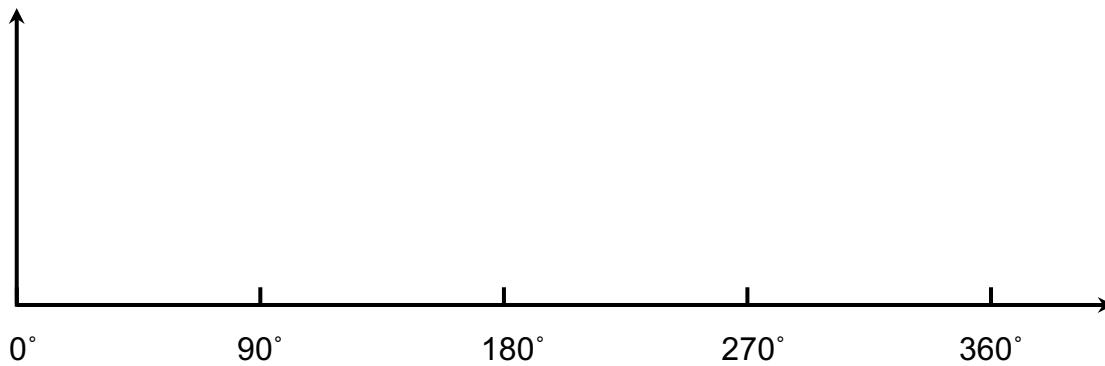
B7. At what angles of the kit polarizer do you get maximum intensity? Explain.

C. Circular Polarization:

The polarization state describes the electric field vector of the EM wave. We studied linear polarization in part B. Other polarization states can be understood as the superposition of linear polarization states. Circular polarization is an important polarization state; it is a superposition of waves with a quarter period (90°) phase shift.
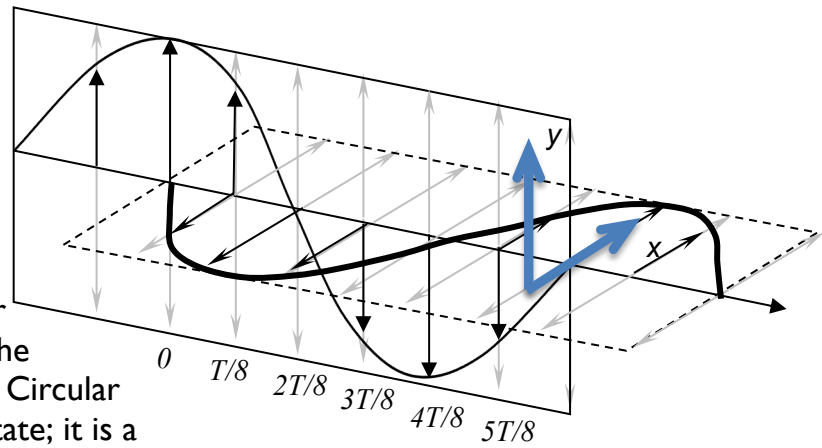
C1.   The graphs below show the *E*-fields of the two linearly-polarized waves at time intervals Δ*t*=*T*/8 (*T* is the wave period). Draw the vector sum of the two *E*-fields on each graph below. The vector with the big arrowhead is the E-field of the wave polarized along the y-axis. The vector with the small arrowhead is the E-field of wave polarized along the *x*-axis, that starts later in time. If a particular vector does not appear, the E-field of that wave at that time is zero.
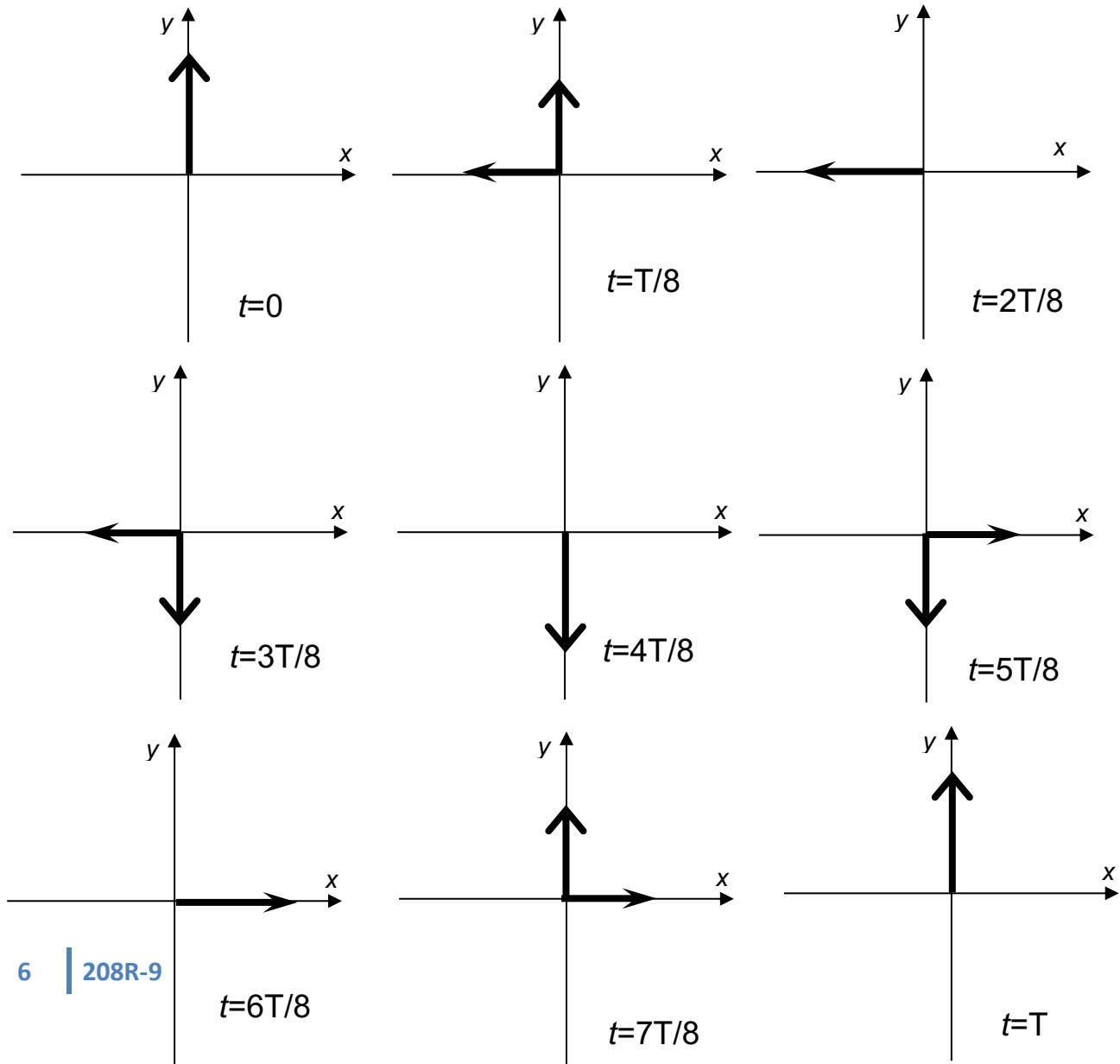
C2.   Describe the time-dependence of the total *E*-field (direction and magnitude). Does the magnitude change in time? Does the direction change in time?

When the horizontal component starts ¼ period earlier (-90° phase shift) rather than later, the electric field vector rotates in the opposite direction. These two polarization states are **right and left circular**.

Making circularly polarized light As you showed above, you can make circularly polarized light by combining two linearly polarized waves, with their plane of polarizations at right angles, and with a relative delay of ¼ wavelength.

There is a very easy way to do this. Some materials are optically anisotropic, meaning that light waves polarized along different directions travel at different speeds. This means that the slower one is delayed relative to the faster one. If the thickness of a plate is such that the time delay is ¼ of the wave oscillation period *T* (equivalent to a ¼ wavelength delay, or 90° in phase), the plate is called a "'¼-wave plate".

Analyzing circular polarization: Set the ¼-wave plate on the lower polarizer of the polariscope. Align the ¼-wave plate so that the linearly polarized light enters with its plane of polarization halfway between the fast and slow axes of the ¼-wave plate. (The fast axis is marked on the brass holder)

Now *x*- and *y*-components of the linearly polarized light have equal amplitude, and are aligned with the fast and slow axes of the ¼-wave plate.

C4.   Explain why this should produce circularly-polarized light.
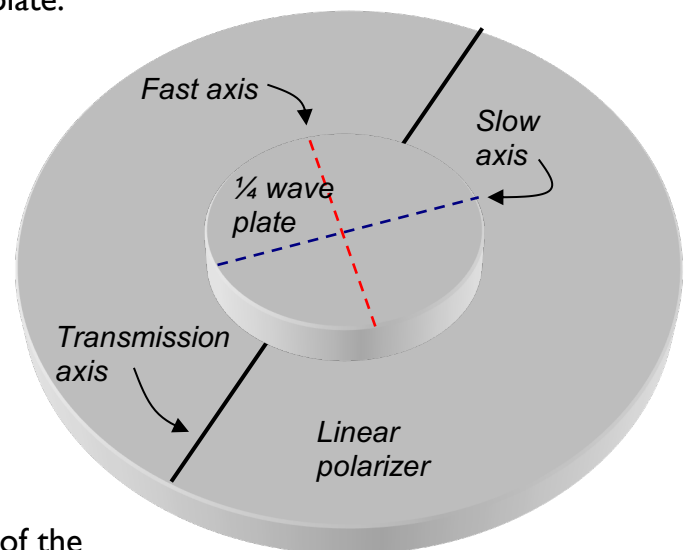
C5.   Now rotate the top polarizer. The intensity of the light transmitted through the wave plate remains approximately constant as you rotate the top polarizer [you may need to slightly adjust the ¼-wave-plate angle]. Explain why this happens.

D. Chiral molecules and polarized light

We discuss circular polarization because many molecules interact differently with left-handed and right-handed light due to their molecular "chirality", or "handedness". Amino acids (shown at right in both chiralities) and sugars are chiral. Your body uses and produces only *D*-sugars (right-handed) and only *L*-amino acids (left-handed).
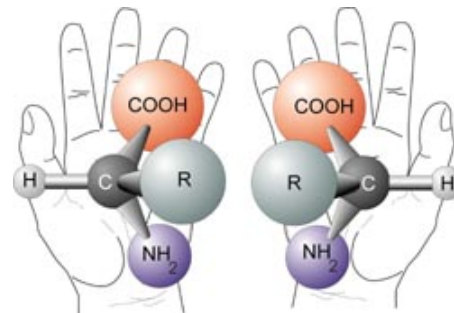
D1.   Explain why the molecules in the figure above are not identical.

In a biological (right-handed) sugar solution, right and left circularly polarized light interact differently with the right-handed molecules. The result is that the EM waves propagate at different speeds. To observe this, we could have a race between right- and left-circularly polarized light. We would start them at the same time, and see which one arrived first at the other end of the sugar solution. Sounds complicated, but it turns out that right- and left-circularly polarized light together is something you've seen before:

D2.   Below are plots that let you superimpose two EM waves with right and left circular polarizations. At t_o both have their *E*-fields pointing along the *y*-axis. One rotates clockwise and the other counter-clockwise. Add the *E*-fields as vectors as you did the two linear polarizations in C1. Draw the resultant vector at each time step.
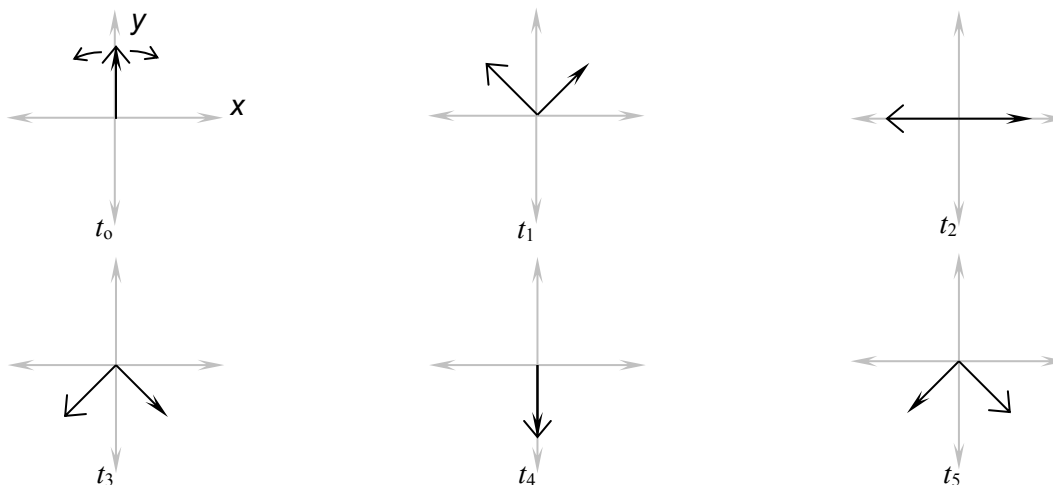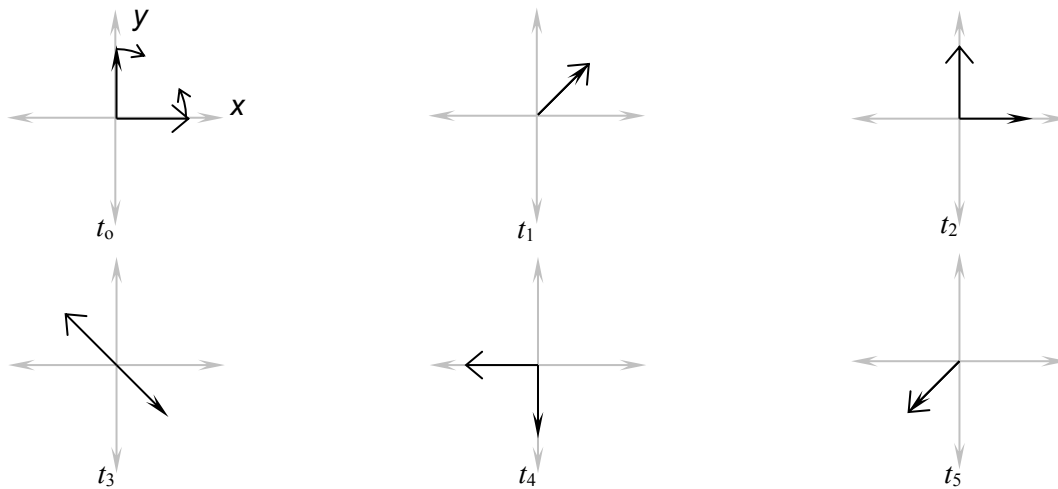

Describe the polarization of the EM wave that is the sum of these two circularly polarized waves. Is it circularly polarized? Linearly polarized? Explain.

This means that you can race right- and left- circularly polarized light through a chiral solution by sending in linearly polarized light. In D2 above, the right and left-circularly polarized light start together (in-phase), ready to race.

But they propagate at different speeds, so that one will arrive sooner at the other end. This results in a relative delay between right- and left- circular polarization when they leave the chiral solution.

D3. Below are plots that let you superimpose the electric field vectors of right and left circularly polarized EM waves with a relative delay. The left-handed light is delayed $(\phi_{left} - \phi_{right})=90°$ (1/4 period) from the right-handed light. Add the E-fields as vectors as you did the in D2. Draw the resultant vector at each time step.

Describe the polarization of the sum of these two circularly polarized waves.

D4. The relation between the polarization angle θ of the resulting linear polarization, and the relative phase delay $\phi_{left} - \phi_{right}$ between the left- and right-handed polarization components, is $\theta_{pol} = (\phi_{left} - \phi_{right})/2$. Explain how this is consistent with the plots you made in D2 and D3.

Now you do the experiment, sending linearly polarized light through a concentrated biological sugar solution. We use Karo corn syrup because it is a very concentrated *chiral* solution of right-handed molecules (sugars) only, and is also commonly found in kitchens in the US.

The right- and left-circularly polarized components of the linearly polarized light propagate at different speeds. They start at the same time, but arrive at the other end with a relative delay, which you just showed appears as rotated linearly polarized light.

You have a set of four jars of Karo syrup (three small and one large, with different heights of syrup). Don't tip them: the syrup takes time to run back down into the jar.

D5.   Place the large jar (lid off, open end up) on the bottom polarizer and rotate the top polarizer while looking through the polarizers and syrup. You should see colors in the syrup. In what order do the colors appear as you rotate the top polarizer clockwise?

Since the rotation appears to be different for different colors (wavelengths), place a color filter (colored transparency) under the syrup so you are only looking at "one color" (see spectral transmission below).
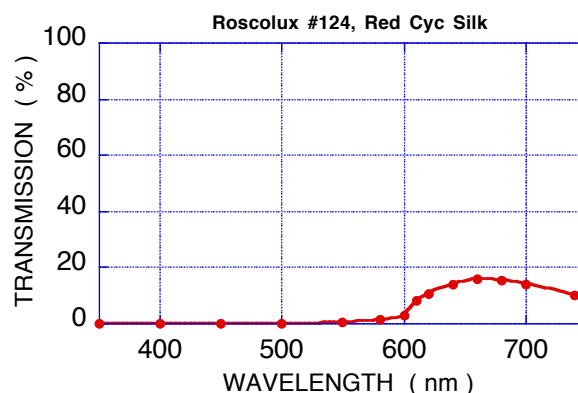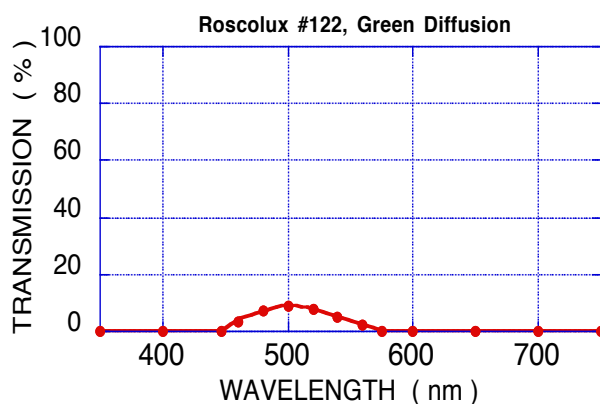
Rotate the top polarizer so the light outside the jar is extinguished. Then rotate the top polarizer until the light through the syrup is extinguished.
    The difference of these angles is the angle by which the Karo has rotated the light.

D6.   What direction (clockwise or counter-clockwise, looking from the top) is the plane of polarization rotated? How did you tell? (Hint: a little bit of Karo rotates the polarization a little bit, and a lot rotates it more, so look at the jar with a little Karo).

Record the polarization rotation of the <u>large jar</u> for the red and green filters.
Filter color: Relative rotation (deg):

D7.   Do this for the other jars and record all your data below.

Sugar depth	Green angle	Red angle

D8. Plot the data for the two colors on the axes below.
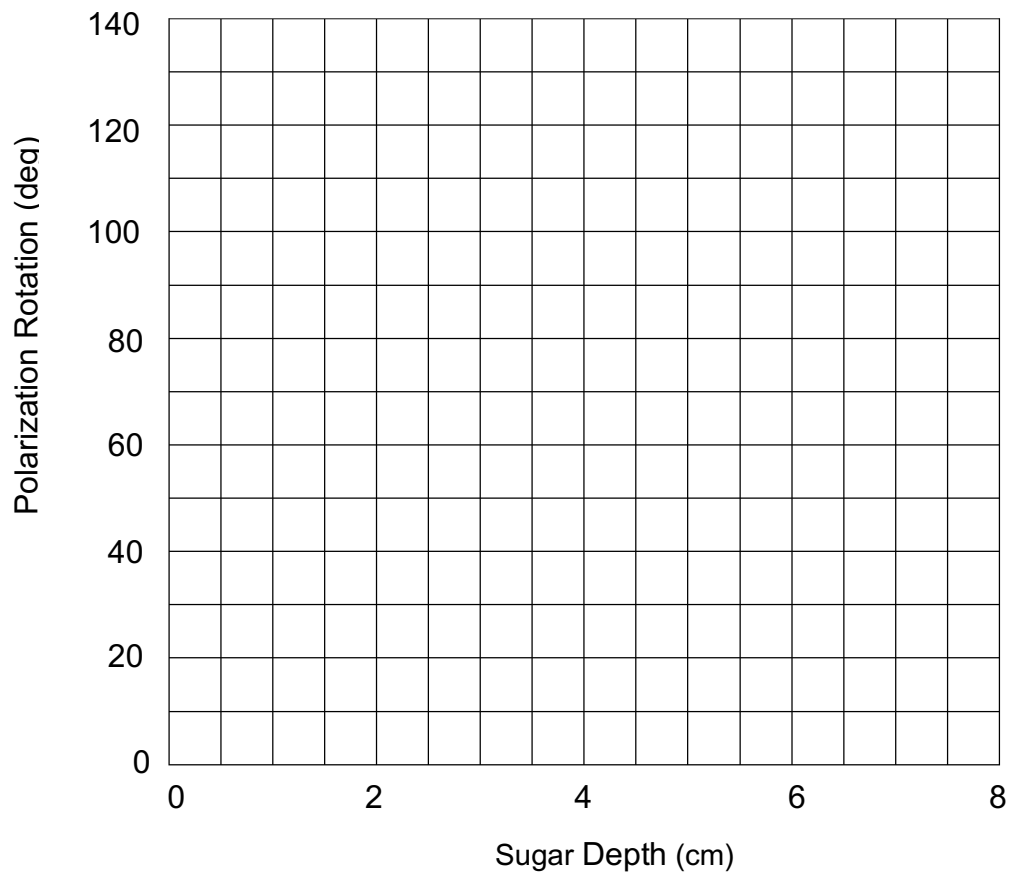
Now you analyze the data.

D9. Suppose that the right-handed component moves at 0.999997 the speed of the left-handed component ($v_{right}/v_{left} = 0.999997$). Then the left-handed component arrives at the top of the syrup a short time Δt before the right-handed component. What is Δt after traversing 8 cm of Karo? (take $v_{left} = \dfrac{c}{n_{Karo}} = \dfrac{3 \times 10^8 \, m/s}{1.5} = 2 \times 10^8 \, m/s$).

The phase difference between the right- and left-handed components depends on the arrival time difference Δt and on the oscillation period T. For instance $\Delta t = T/2$ corresponds to a phase shift of π (180°). $\Delta t = T/4$ gives a phase shift of $\pi/2$ (90°).

D10. The peak wavelength of red light you used above is about 660 nm in vacuum. This has an oscillation period $T = \lambda/c = 2.20 \times 10^{-15} \, s$.
What is the phase difference $\phi_{left} - \phi_{right}$ between the left- and right-handed components for the time delay Δt calculated in D9?

D11. The peak wavelength of green light you used above is about 520 nm in vacuum. This has an oscillation period of $T = \lambda/c = 1.73 \times 10^{-15} \, s$
What is the phase difference $\phi_{left} - \phi_{right}$ between the left- and right-handed components for the time delay Δt calculated in D9?

D12. Using $\theta_{pol} = \left(\phi_{left} - \phi_{right} \right)/2$ from D4, what polarization rotations are these?

Red Light rotation:

Green Light rotation:

D13. Why did the same arrival time difference result in different polarization rotations for different colors of light?

D14. Explain whether your answer to the question above describes the order of the colors you observed in D5, assuming that the arrival time delay does not depend on wavelength.

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Name _____   Section _____

Physics 208 Laboratory
Lenses and the eye

Your TA will use this sheet to score your lab. It is to be turned in at the end of lab. You must use complete sentences and clearly explain your reasoning to receive full credit.

What are we doing this time?

You will complete three related investigations.

PART A:
    Use a single lens on the optical track to understand what it means to be "in focus", the lens equation, and the difference between real and virtual images.

PART B:
    Build a microscope and a telescope on the optical track to understand how the image formed by the objective lens acts as an object for the eyepiece lens.

PART C:
    Investigate near-sightedness and far-sightedness using an eye model filled with water.

Why are we doing this?

The way lenses use refraction to bend and reform light rays to make an image has myriads of applications. Understanding this will help you get the most out of research instruments such as microscopes.

What should I be thinking about before I start this lab?

You should be thinking about images produced by lenses, and how either a real image or virtual image can act as an object for another lens, such as the one in your eye.

Any safety issues?

The light sources get a bit hot.

A. Lenses

Go to https://www.compadre.org/Physlets/optics/illustration35_1.cfm. Add a converging lens to the virtual optics bench by clicking "Lens" and then clicking near the middle of the screen. Then select "Object" and click and drag to draw an arrow somewhere to the left of the lens. Notice that the principal rays are shown automatically. Click and drag on the lens to move it back and forth and observe what happens to the image. Click and drag on the object to make it bigger and smaller, and turn it upside down. Click and drag on the lens's focal points to adjust the focal length. Use "Clear All" to start over, or experiment with different elements available on the optics bench.

A1. Imagine there was a screen at some fixed location on the other side of the lens from the object. If the screen is too close to the object, it's not possible to form an image on it. If the screen is not too close to the object, is there always the same number of lens positions at which a sharp image forms on the screen? Explain what you found.

Now you will use the Pasco track, the light source, the color-coded converging lenses, and a white screen to view images. Position the light source accurately at 0 cm on the track, and the white screen at 30 cm. Put one of the red lenses on the track between the screen and the light source.

A2. Find all the positions of one of the red lenses that give a sharp image on the screen (there is more than one position, but there may not be four)

Lens position (cm)	Image distance (cm)	Object distance (cm)	Magnification

A3. From the data of A2, use the lens equation to calculate the red lens focal length.

B. Microscopes and Telescopes

This section involves two-lens systems.

These will make a lot more sense if you remember these things:

1. The first lens (objective) forms a real image.
2. The image formed by the objective is used as the object for the (eyepiece) lens. The eyepiece lens forms a virtual image.
3. A *real image* will appear on a screen placed at the image location, but a *virtual image* will not. However, your eye can focus the rays from a virtual image onto your retina.

Compound Microscope

Go to https://www.physics.wisc.edu/instructional/phys208/ray-optics/microscope/. This is a web-based ray tracing tool that will let you explore the function of a microscope. You should see the screen below, which represents the functionality of a microscope. The blue circle at the right represents the location of an observer's eye. The blue beams are light cones coming from a focused image on the far left. The green squares represent to endpoints of a small object. The orange squares represent the position of the image as seen by the observer, which is enlarged, virtual, and inverted.

If you do not see the picture below when you open the link in your browser, try clicking the "Seen by Observer" button near the top center of the screen. If that doesn't work, download the microscope settings file from the lab's Canvas Page, and then click the "Open" button at the upper right of the applet to load the settings file. You will have to navigate to the location of the downloaded settings file saved on your computer.
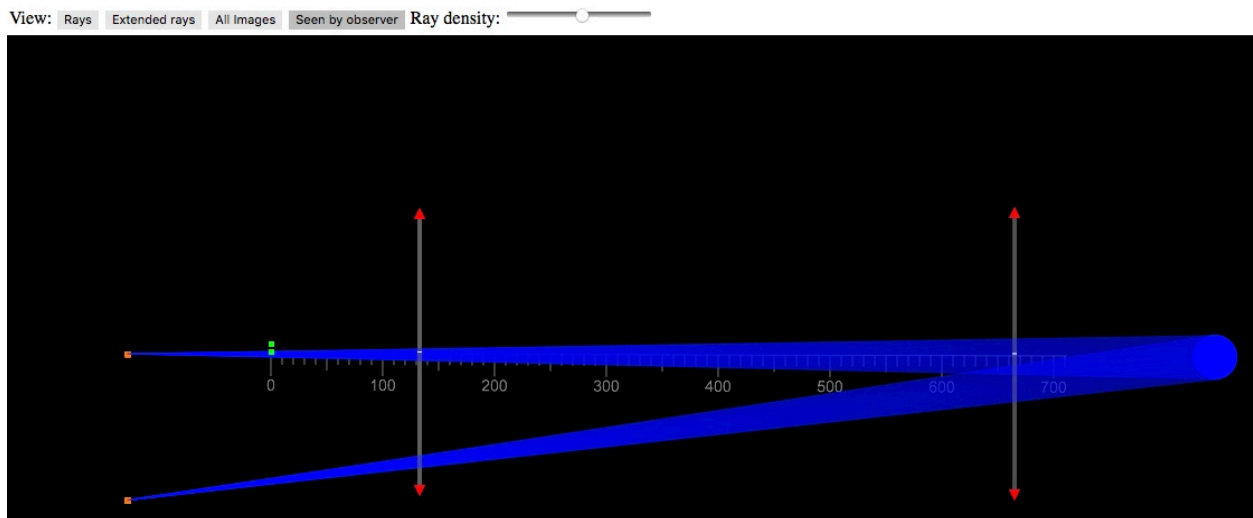
Below is a close-up of the left side. The two green squares represent the ends of an object.
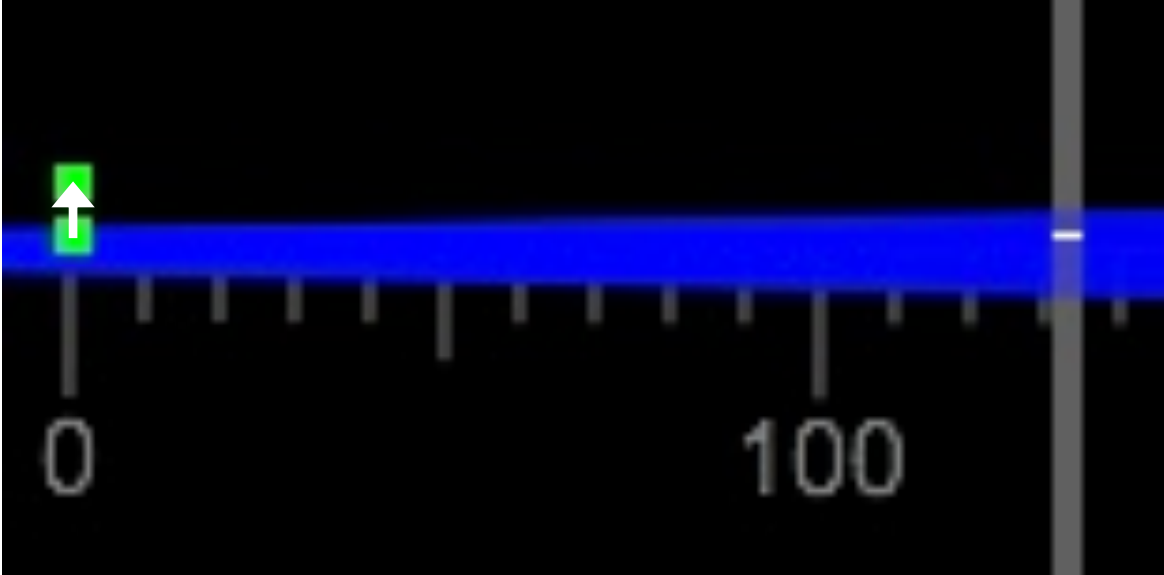
The blue circle at the right represents the eye of the observer. The red squares represent the image seen by the observer (which is enlarged, virtual, and inverted).
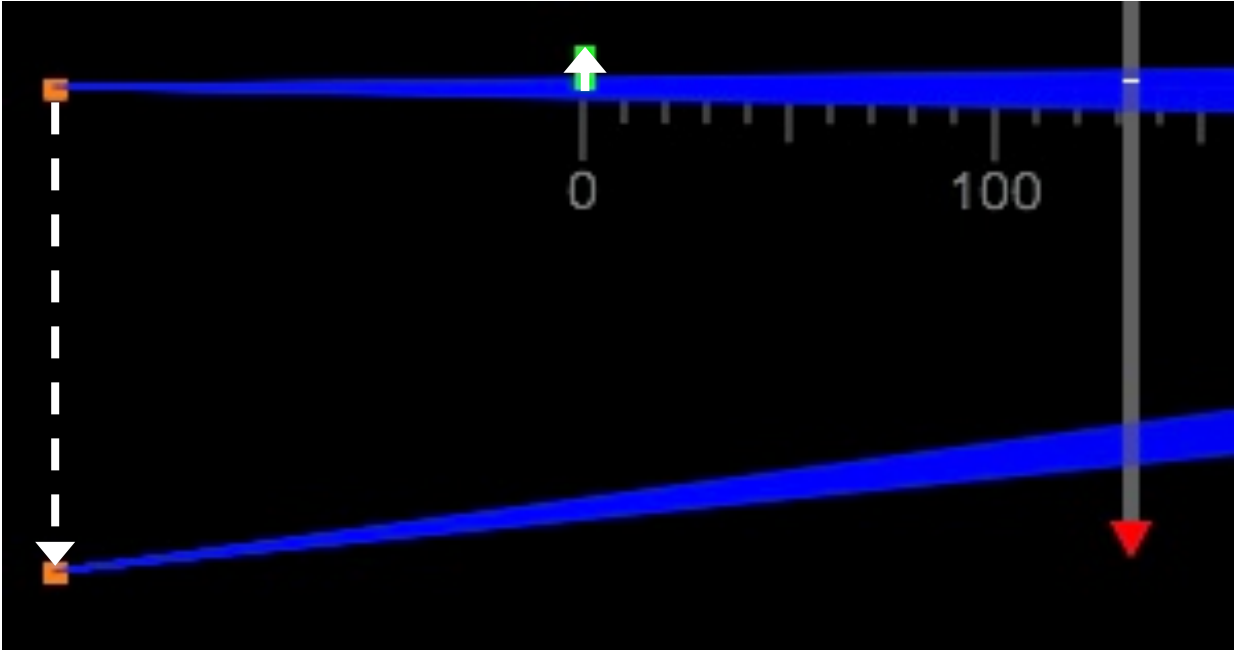
B1. Click on the "All Images" button near the upper left corner. This shows the images produced by both the objective (the yellow squares) and the eyepiece (the red squares mentioned previously). Click the "Rays" button. This shows all the rays emanating from the top and the bottom of the object. Finally, click on the "Extended rays" button. This shows the virtual rays as well as the real rays. Toggle back and forth between the four views (Seen by Observer, All Images, Rays, and Extended Rays) until you are confident you understand the relation between what the observer sees and the ray systems created by the point sources.

B2. Is the image formed by the objective real or virtual?

B3. Click-and-hold on the center of a lens to move it around. Go to the "Rays" view. How does the position of the image formed by the objective move when you change the objective position?

B4. Move the objective so that it forms an image just to the left of the eyepiece, as it did at first. How does the position of the image formed by the eyepiece move when you change the eyepiece position?

B5.   Why does changing the distance between the objective and the object (moving the stage in a microscope) focus the microscope?

Next, use the two red lenses to make a compound microscope, and use the light source on the track as a sample that you will observe through the microscope. You will use the objective lens (closest to the sample) to make a large, real image of the sample. You will then add an eyepiece lens (lens closest to your eye) that will act as a simple magnifier so that you can see more detail in the image formed by the objective lens.

B6. Use one of the red lenses as the microscope objective to form an image of the light source on your white screen somewhere on the track. Try to make the image about twice as big as the object--use your measurement of the red lens focal length from Part A to help plan how to do this. Measure the positions of the objective and image and fill in the following table:

Distance of objective from light source	Distance of image from objective

B7. Hold the 2nd red lens in your hand and use it as a simple magnifier to read the following question:

When these words are in focus, what is the approximate distance between the lens and the page?

What is the object distance? How does this tell you where on the track the red lens should be positioned?

B8. Complete your microscope by removing the screen, putting the eyepiece at the appropriate location, then moving the eyepiece slightly until you see a magnified image of the light source when you look through the eyepiece with your eye.

Objective lens location:

Eyepiece lens location:

B9. Now use the 125mm focal length lens (look on the bottom of the lens holder) for the eyepiece.

Objective lens location:

Eyepiece lens location:

Looking through the eyepiece, how is this microscope different than the previous one?

B10. Draw your microscope here, as it is made from two red lenses, following instructions below.

Remember that the objective lens will form a real image that you can see on a screen. The eyepiece is used as a magnifying glass to look at this real image.

a: Draw a diagram of your microscope at right, drawing each lens at the position you have it on the track. Also indicate the focal points of each lens. Do this for the 60mm focal length eyepiece only.

b: Label the point on the diagram at right where the image is formed by the objective, as you found in B6 using the white screen.

Light source

0 cm

10 cm

20 cm

30 cm

40 cm

50 cm

Optical axis
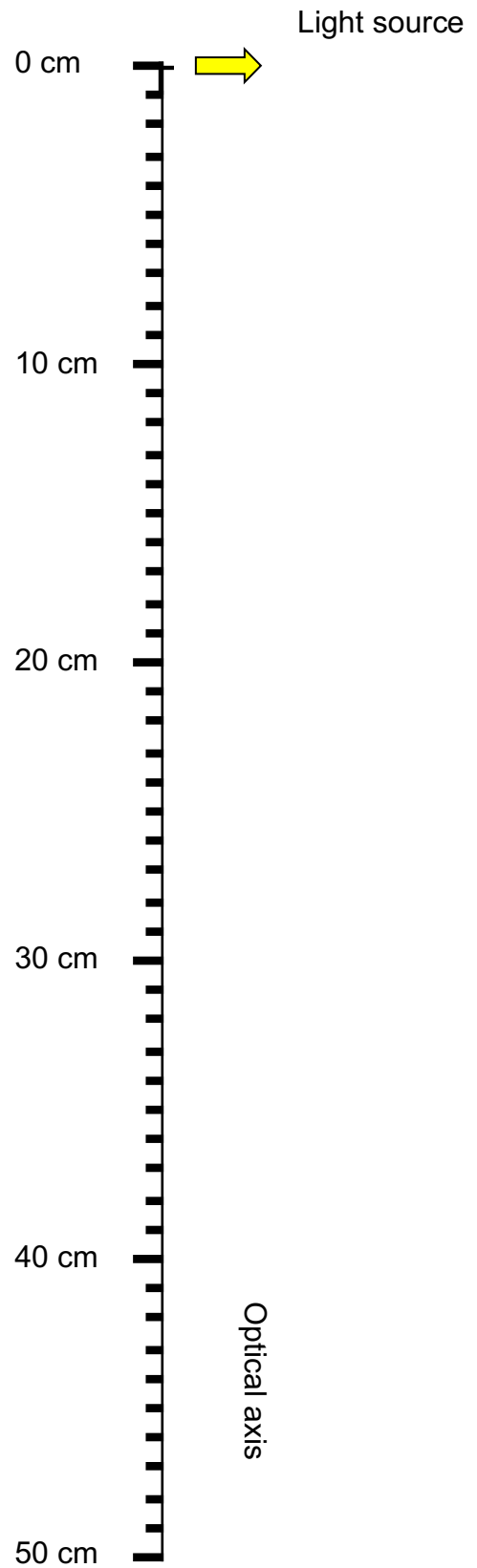
Telescope

A telescope is an optical instrument that uses two lenses to make a distant object appear closer. The objective lens points toward the distant object (such as the building across the street) and forms an image on the opposite side of the objective lens. The eyepiece is used as a simple magnifier to look more closely at this image.

Go to https://www.physics.wisc.edu/instructional/phys208/ray-optics/telescope/. You should see the screen below. The two systems of rays on the left-hand side of the screen represent the parallel rays arriving at the telescope from two distant objects, such as two stars (the green bars at left do not represent objects).

If you do not see the picture below when you open the link in your browser, download the telescope settings file from the lab's Canvas Page, and then click the "Open" button at the upper right of the applet to load the settings file. You will have to navigate to the location of the downloaded settings file saved on your computer.
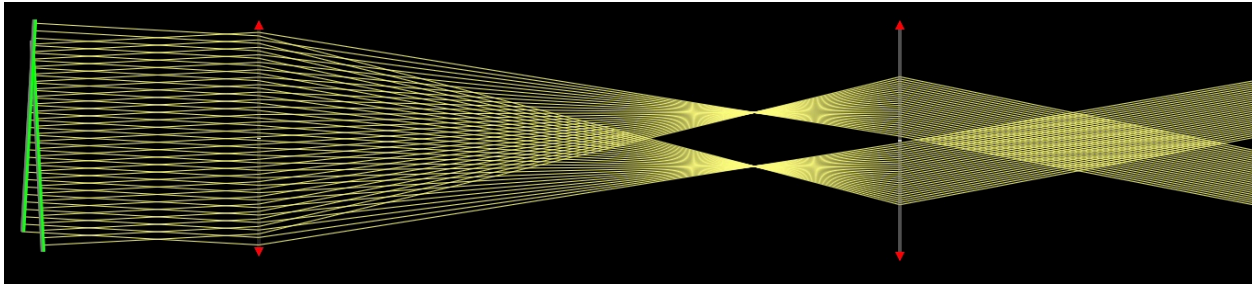
B11. Change between the four views (Rays, Extended rays, All Images, and Seen by observer) until you are confident you understand how they relate to one another.

B 12. This image formed by the eyepiece of this virtual telescope is located at infinity, for comfortable viewing by the relaxed normal eye. Explain how you can tell that the image of the eyepiece is at (or near) infinity by looking at the "rays" view.

B13. The sketch below shows the angle θ between the two distant objects, as seen by the observer O when O is not looking through the telescope. Complete the diagram by showing the apparent angle θ' between the two distant objects, as seen by O when O looks through the telescope.

B14. Using a ruler, make measurements on your screen and estimate the ratio f_1/f_2 of the focal length of the objective (f_1) and the focal length of the eyepiece (f_2).

$$f_1/f_2 = \underline{\hspace{3cm}}$$

B15. Click on a lens to see what the focal length actually is. What is f_1/f_2 according to the simulation?

B16. As you know, the magnification of a telescope is $M = -f_1/f_2$. Change the focal lengths of the objective and eyepiece, and see how large a value of f_1/f_2 you can achieve, while still keeping both lenses and the observer on the screen.

Now build a telescope using a green lens (200mm focal length) and a red lens (60mm focal length). Remove the light source from your track, and arrange the lenses on the track to make a telescope. The telescope is used to view objects far away, so <u>aim the telescope out the window,</u> or at a light board at the other end of the lab room. (You can prop up one end of the track on the eye-model light source)

B14. Use the green lens as the telescope objective to form an image of the distant object on your white screen somewhere on the track.

What is the distance of the image from the objective?

B15. At what location should you position the red lens (as the eyepiece) so that you can look through the eyepiece and see a magnified image of the distant object?

B16. Complete your telescope by putting the eyepiece at the appropriate location and look at various objects.

B17. Now use the orange lens (500mm focal length lens) for the objective, with red lens as the eyepiece. Look again – how is the telescope different?

C. The eye

Your eye also has multiple "lenses", although they are referred to as the "cornea" and the "crystalline lens". Both of them do some refracting – these are two closely-spaced lenses. If you wear eyeglasses, that is a third lens! Here is a diagram of your apparatus – it should be full of distilled water to model the vitreous humor.
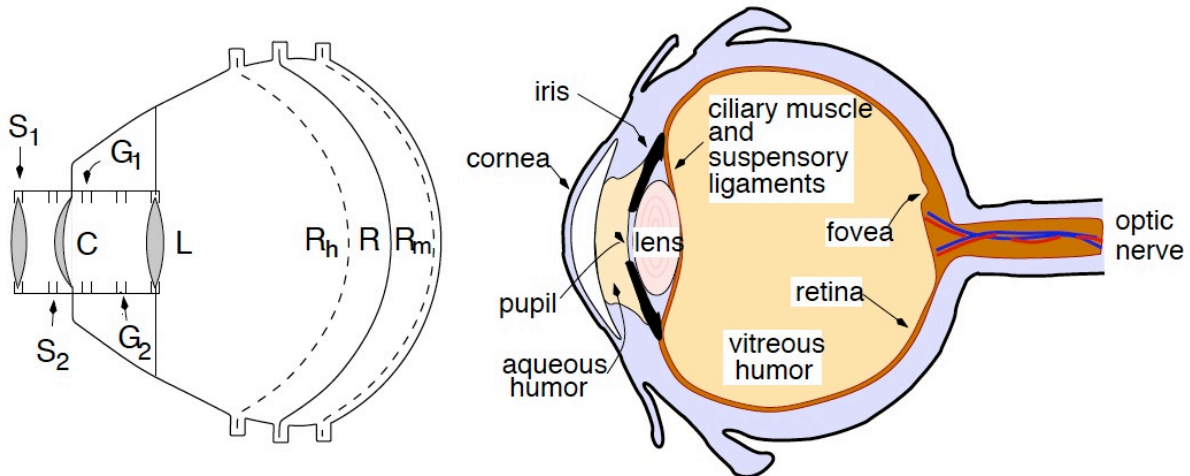
R_h, R, and R_m are three positions for the retina, letting you model far-sighted, normal, and near-sighted eyes.

C is the cornea – this separates the fluid-filled eye interior from the outside.

L is the crystalline lens – in a real eye its focal length is adjusted by the ciliary muscle. In your eye model, you adjust the focal length by interchanging with different lenses from your box of lenses.

S_1 and S_2 are locations at which you can add lenses modeling corrective glasses.

You will use four lenses from your lens box:
Converging spherical   strength +7 diopters
Converging spherical   strength +20 diopters
Converging spherical   strength +2 diopters
Diverging spherical   strength -1.75 diopters

The image formed by the cornea is used as an object for the crystalline lens, just as in the microscope and telescope. But because the lenses are closely spaced, the image formed by the cornea is on the other side of the crystalline lens (the same side as the image formed by the crystalline lens). This means that when the crystalline lens uses this image formed by the cornea as its object, the object distance entered in the lens equation will be negative, since it is on the same side as the real image.

C1. ACCOMMODATION:

With the retina in the normal position, point the eye model at a window or other bright object 4 to 5 meters away. Insert the +7 diopter lens in the water at the inside mount farthest from the cornea (see diagram on previous page). An image of the bright object should be in focus on the retina.

Next use the lamp box as the object and place it about 30 cm from the cornea. The image is blurry until you replace the +7 diopter lens by the +20 diopter lens. This change illustrates accommodation. Eye muscles make the lens thicker for close vision.

a) What are the focal lengths in air of the two lenses you used? (The power in diopters is stamped on the lens holders)

b) How are the focal lengths of these lenses different when in water in the eye model (are they longer or shorter than for the lens in air?). Explain

c) Both the cornea and eye lens refract the rays to produce an image on the retina. But it can be easier to talk about this pair as a single lens with an 'effective' focal length (just as multi-element camera lenses are labeled with a focal length). Assuming that this combination lens is halfway between the cornea and eye lens, what range of focal length was necessary to focus on objects at infinity and at 30 cm? This is the eye range of accommodation.

C2. NEAR and FARSIGHTEDNESS (MYOPIA and HYPERMETROPIA):

Keep the lamp box at 30 cm and the 20 diopter lens at L. With the retina in the position for a normal eye (R) the image is in focus as before. Now place the retina in the position R_h (far-sighted eye). A far-sighted person cannot focus on a nearby object without corrective lenses. Determine which lens placed in slot S_l will bring the image into focus.

Now point the eye at a window or bright object 4-5 meters away. Put the +7 diopter lens in the eye lens position (L). An eye with the retina in the normal position would be able to focus with this focal length eye lens. Make the eye nearsighted by moving the retina to R_m. A nearsighted person cannot focus on a distant object without corrective lenses. Determine the proper corrective lens to place in front of the eye to bring the image into focus.

	Nearsighted	Farsighted
Lens power required		

Explain in words the sign (+ or -) of the lens required in each case.
Nearsighted:

Farsighted:

C3. *Cataracts*: A cataract is a cloudy crystalline lens, which usually requires surgical removal. Once the lens is removed, light rays are bent only by the cornea, which alone does not have enough refracting power to form a sharp image on the retina.

Put the retina back in the middle (normal vision) position, and carefully remove the eye lens using your best surgical technique. Verify that without the eye lens a sharp image never forms on the retina, regardless of the light source location. Historically the eye lens was not replaced, and eyeglasses were used to provide the additional focusing power. In this case it is important to determine the focusing power (hence focal length) of the cornea alone.

a. Put in the +7 diopter lens (outside the eye, as glasses) and adjust the light source distance so that a sharp image is formed on the retina. Draw your setup below, indicating positions of the object, image, eyeglass lens, and cornea.

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Name _____   Section _____

Physics 208 Laboratory
Interference and Diffraction

Your TA will use this sheet to score your lab. It is to be turned in at the end of lab. You must use complete sentences and clearly explain your reasoning to receive full credit.

What are we doing this time?

You will complete three related investigations.

PART A:
    Use a laser and narrow slits to produce multiple coherent light sources that demonstrate interference.

PART B:
    Determine the track spacing on a CD and DVD using diffraction.

PART C:
    Investigate thin-film interference by observing dichroic "art glass" and a multilayer plastic bow.

Why are we doing this?

Interference and diffraction are observed wherever there are waves. For instance sound waves, water waves, and light waves all show interference effects. In fact, the colors seen in some birds and insects are not from pigments, but from light interference generated by small-scale structures on their feathers/scales.

What should I be thinking about before I start this lab?

You should be thinking about waves, and how the phase difference between waves causes constructive and destructive interference.

Any safety issues?

The light source is a laser diode, with a wavelength of about 650 nm. Carefully read the laser handling precautions in the lab manual: the laser diode is a source of extremely intense light, which can damage your or someone else's vision if mishandled.

When diffracting from the replica grating, CD, and DVD, the diffracted beams can go in unexpected directions. Make sure you aren't beaming somebody in the eye!

Part A. Interference

Here you will be investigating two-slit interference. The two slits illuminated by the laser beam act as two sources of spherical waves of light that are of the same frequency and same phase. These spherical waves form an interference pattern throughout all space. That is, at all points in space, the total light is a superposition of light originating from the two slits. You investigate the interference pattern visually by looking at the reflection from a white screen, and you record quantitative information on the computer with a light sensor that you move manually across the interference pattern.

Your equipment consists of:

1) A "diode laser" (light source);
2) A "multiple-slit set" (circular wheel of double slits of various widths and spacings);
3) A diffraction grating mounted to a holder that fits on the optical track;
4) A detection assembly consisting of a high-sensitivity light sensor/aperture bracket/translation wheel (see photo at right). Use the translation wheel to move the light sensor perpendicular to the beam path to quantitatively measure intensity variations of the interfering or diffracted light. The different slits on the aperture bracket allow different amounts of light into the light sensor, and set the spatial resolution of the light sensor.

aperture bracket
translation wheel

5) A "beam block" (an aperture used to block reflections, mounted to a holder that fits on the optical track);
6) A white screen;
7) An optical track on which all these pieces can be mounted.
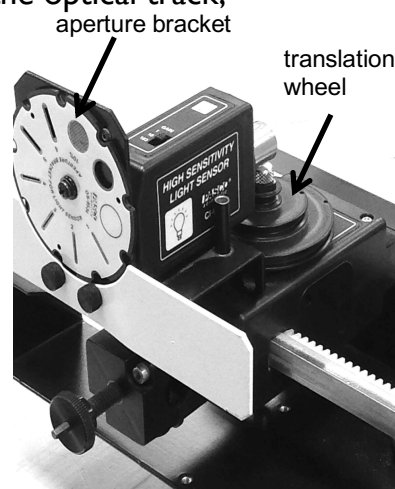
Setup: Position the "multiple slit set" on the track so that circular wheel lines up with the 110 cm mark, and the diode laser directly behind it.

Twist the ring on which the circular wheel is mounted, and (independently) twist the circular wheel itself, so that the two slits labelled "a=0.04 mm, d=0.25 mm" are not only in front of the laser beam, but also vertical.

Place the detection assembly on the track so that the aperture bracket is at 10 cm. Twist the aperture bracket so that slit #2 is in front of the light sensor input. Set the "gain" on the light sensor to 10. (If this turns out to be too sensitive, there will be flat tops to the diffraction peaks--use a gain of "1". If it isn't sensitive enough, use "100".) Use the translation wheel to center the light sensor on the track.

If the diffraction pattern doesn't fall on slit #2, use the thumbscrews on the back of the laser to adjust its angle

Put the white screen on the track in front of the light sensor, at 50 cm.

A1) Describe or sketch what you see on the white screen.

A2) The wavelength of the diode laser is about 650 nm. Calculate approximately how many wavelengths of laser light are in the space between the slits and the white screen.

A3) Now take off the white screen. Turn on the interface.

Connect the rotary motion sensor output (1/4" phono plugs) to digital inputs 1 and 2 (yellow in 1, black in 2). Connect the light sensor to analog input A ("top" up).

On the Desktop of your lab computer, find the PASCO folder. Double-click Lab Software/208/Lab1_Settings.cap to start the data acquisition program.

Use the computer to record the intensity pattern: click "record" and **slowly** move the light sensor across the interference pattern by turning the translation wheel with your hand. Enlarge the data on the computer so only the central peak and two peaks on either side fill the screen. Record the separation between the central maximum and the immediately adjacent minimum, and the next maximum.

From central peak to nearest minimum	From central peak to neighbor peak

A4) Here is a sketch of your experimental setup, but not to scale. The slit spacing d is much smaller than shown, and the screen distance L is much larger than shown. The two slits act as two in-phase sources of light. The waves travel out in all directions, and hit the screen in all places – the lines are just to indicate the path of the light that hits the light sensor at point x.

Top view—looking down on lab table from above

$\delta = d\sin\theta = path\ \ length\ \ difference$
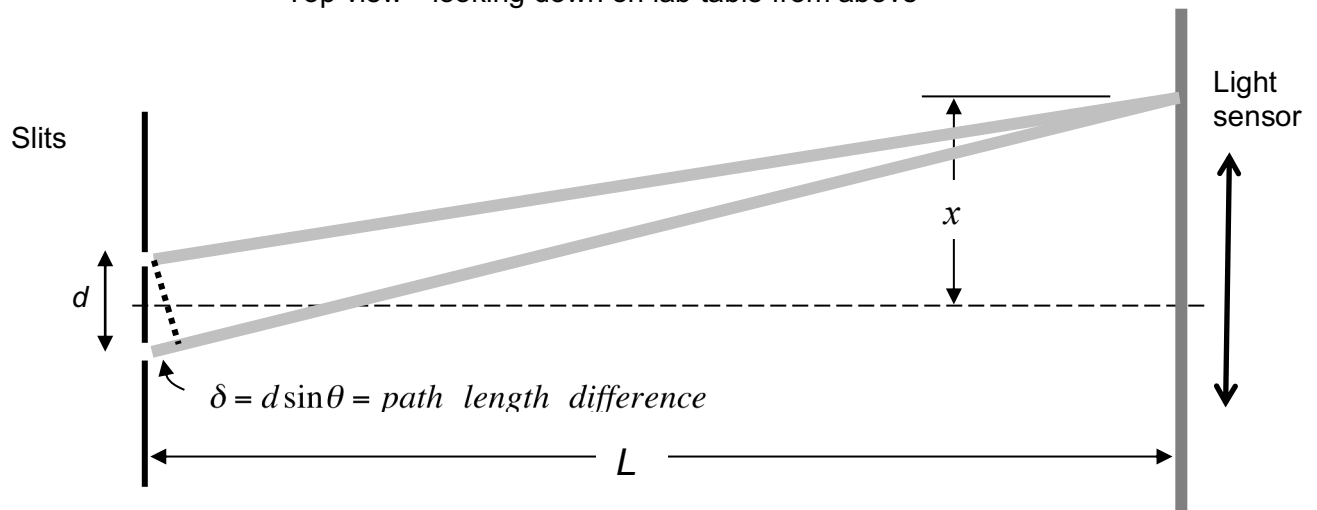
We showed in class that one path is longer than the other by an amount $\delta = d\sin\theta$, as long as $L \gg d$. Here θ is the angle of the light sensor away from the dashed centerline.

Using this relation, find the path length difference for the maximum and minimum in the previous question. (Hint: $\tan\theta = x/L$)

	1st minimum	Next maximum
θ		
δ in millimeters		
δ in nanometers		
δ in wavelengths of laser light		

A5) The waves from each slit start out in phase, but they propagate different distances to reach the light sensor. What is the condition on δ that they

Interfere constructively?   Interfere destructively?

How does this compare with the results in your table above?

A6) Find the spot on the wheel that has groups of 2, 3, 4, and 5 multiple slits (width of each slit: 0.04 mm; spacing between slits: 0.125 mm). These all have the same slit separation, and slit width, just different numbers of slits. Take data on the computer for each of these. This will result in four graphs. Examine the graphs by zooming in to the central 5 peaks of each. If you always start the light sensor at the same spot, and move it in the same direction, the graphs will be mostly aligned with each other on the computer screen.

Do the following aspects of the interference pattern increase, decrease, or stay the same as the number of slits increases?

	Separation between max	Width of max	Height of max
Increase, decrease, or stay the same			

A7) In this part you use a 'replica grating'. This is an extended version of the multiple slits above, with 'slits' ruled continuously across it at a density of 1000 lines/mm. Shining the laser beam through the grating is like shining it through the multiple slits in A6) but with more than 1000 slits, since the laser beam covers several millimeters of grating.

Take out the slit wheel, and put the replica grating (clear sheet in black holder) on the track about 10 cm in front of the light sensor. Put the "beam block" (black cardboard with hole, in black holder) up against the grating on the laser side to block some of the reflections from the grating – you may need to line up the laser beam with the hole by using the thumbscrews on the back of the laser. The grating should be closest to the sensor, and the beam block closest to the laser.

Use the computer to measure the intensity vs position (as before, rotate the translation wheel to move the light sensor).

i) At what angle away from the central maximum does the next maximum occur?

ii) Is this angle "small" or "big" in regards to the small-angle approximation?

iii) Determine the wavelength of the laser light using the positions of the interference maxima, the slit separation of the grating, and the distance between the grating and the screen.

B. Interference from a compact disc and digital video disc.

CDs and DVDs have information recorded on closely-spaced tracks spiraling around the disc. Neighboring tracks are separated by a fixed distance. These tracks can act like the slits you used above, but in reflection. This is another type of 'diffraction grating'. In this section you measure the track spacing on a CD and DVD by interference.

Put the white screen in front of the light sensor and tape the CD to it, using masking tape, so that the laser hits the CD directly above the hole in the CD. Make sure the light coming from the CD doesn't go near anyone's eyes, and turn off the laser when you are not using it.
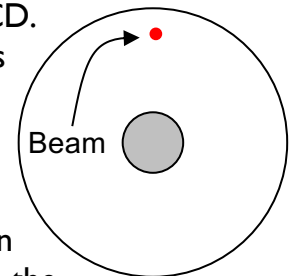
Punch a hole in a blank sheet of graph paper using the hole punch, and tape the graph paper to the block using masking tape. Position the block so that the laser shines through and hits the CD, and the graph paper is about 10 cm in front of the CD. The goal is to observe simultaneously on the graph paper the central max and the two diffraction spots above and below it, as in the pictures below.
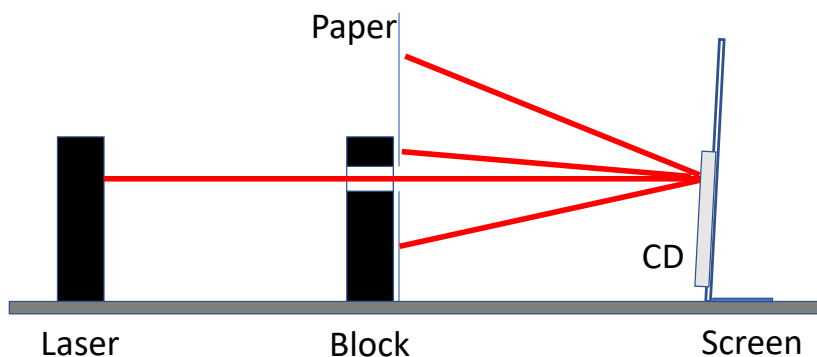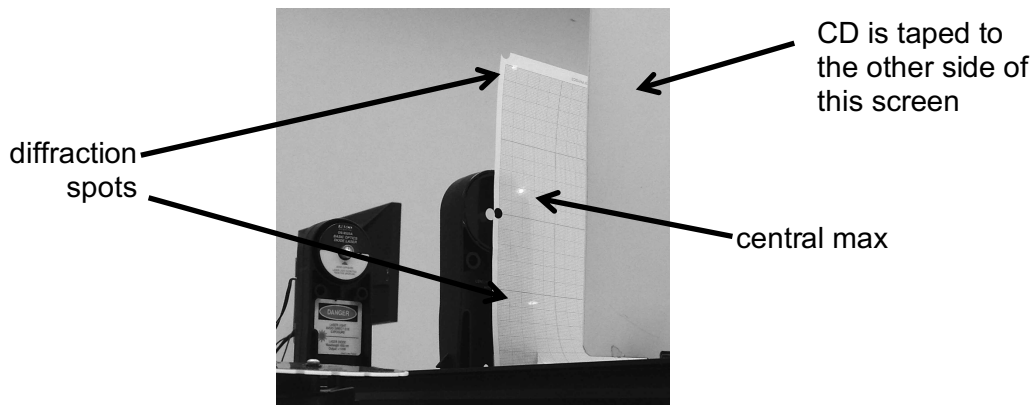
B1) Estimate the track separation on the CD from the pattern on the paper.

B2) Repeat for the DVD. The graph paper may need to be closer to the DVD than 10 cm.

B3) Look up typical track spacings for a CD and DVD on the web, and compare.

B4) Why do you see colors when white light reflects from the CD/DVD?

C. Thin film interference

In parts *A* and *B*, you saw how the interference of regularly-spaced light sources can result in constructive or destructive interference. In the first part of the lab, each slit in the wheel or diffraction grating became a tiny source of transmitted light. In the second part, highly reflective tracks on a CD or DVD each became a tiny source of reflected light.

In both of these cases, the light sources were arranged regularly along a surface.

But there are many cases where the reflections are arranged through the *thickness* of the material. A common example is the soap bubble we discussed in lecture, where reflections from the top and bottom surface of the soap film act as two light sources, which interfere at your eye. When white light shines on the film, some wavelengths (colors) of the light will interfere constructively, and some destructively. You see the colors that interfere constructively.

$n_{air}=1.0$

$n_{film}=1.5$

$n_{air}=1.0$
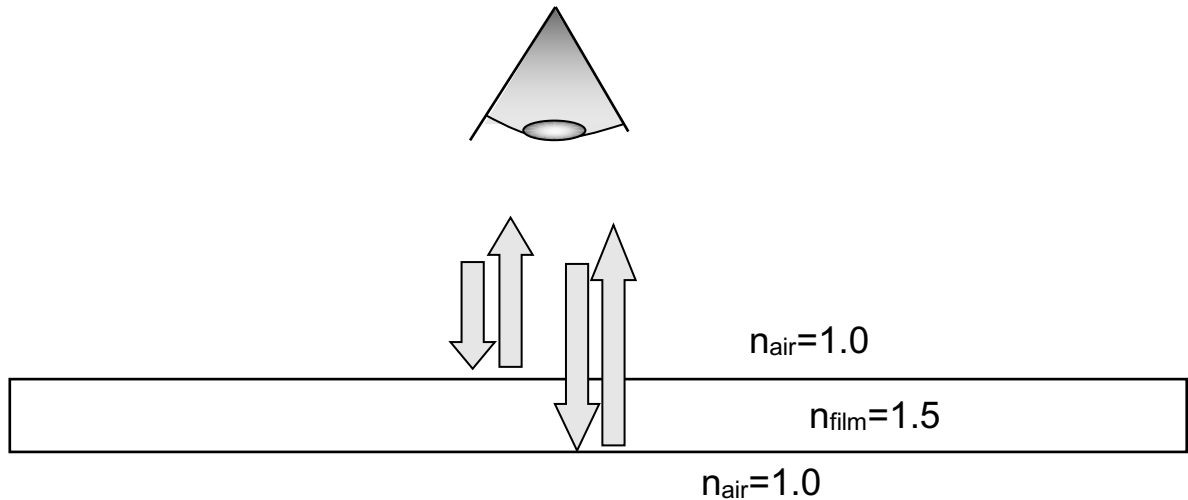
C1) Make a numbered list of the factors that contribute to the phase difference at your eye of the two reflected beams.

C2) Make a rough estimate of the thickness in millimeters of the thinnest film like the one above that would appear yellow ($\lambda_{yellow} \approx 570nm$) when illuminated with white light.

C3) A film like the one above is extremely fragile because it is so thin. Since the year 2000, companies have developed processes to efficiently produce microlayer plastic films consisting of hundreds of alternating polyester (n=1.8) and acrylic (n=1.5) layers.

This is analogous to a diffraction grating, with a reflection at each interface between layers in the plastic in the same way that the film interference on the previous page was analogous to two-slit interference.

Here the grating is through the thickness, rather than across the surface as in a CD/DVD.

The *Luminesque Fireworks Bow* is made from such plastic. Not all tables have these – borrow from another table if you don't have one. You should at least have some multilayer plastic cut from a lower-quality bow, but it is not as uniform.

You should also have a piece of "dichroic" glass. This glass appears colored because of a multilayer thin-film deposited on its surface.

Look at the bow/glass in three different ways and describe what you see:

i) Hold the bow in front of a window (best) or other light source, and look through the front of the bow at the light source

ii) Tilt the bow in various ways, continuing to look at the transmitted light from the light source. Try to observe colored shadows.

iii) Look at the light reflected from the bow.

C4). The figure below is a drawing of a multilayer plastic film as if it had only two layers rather than hundreds. Assume normal incidence of the light, so that there is no refraction at any interface. There is one path the light can take from the light source to your eye in which it is never reflected, and three paths the light can take in which it is reflected exactly twice. Sketch all four paths.

Air (n=1)

Polyester (n=1.8)

Acrylic (n=1.5)

Air (n=1)

White
light
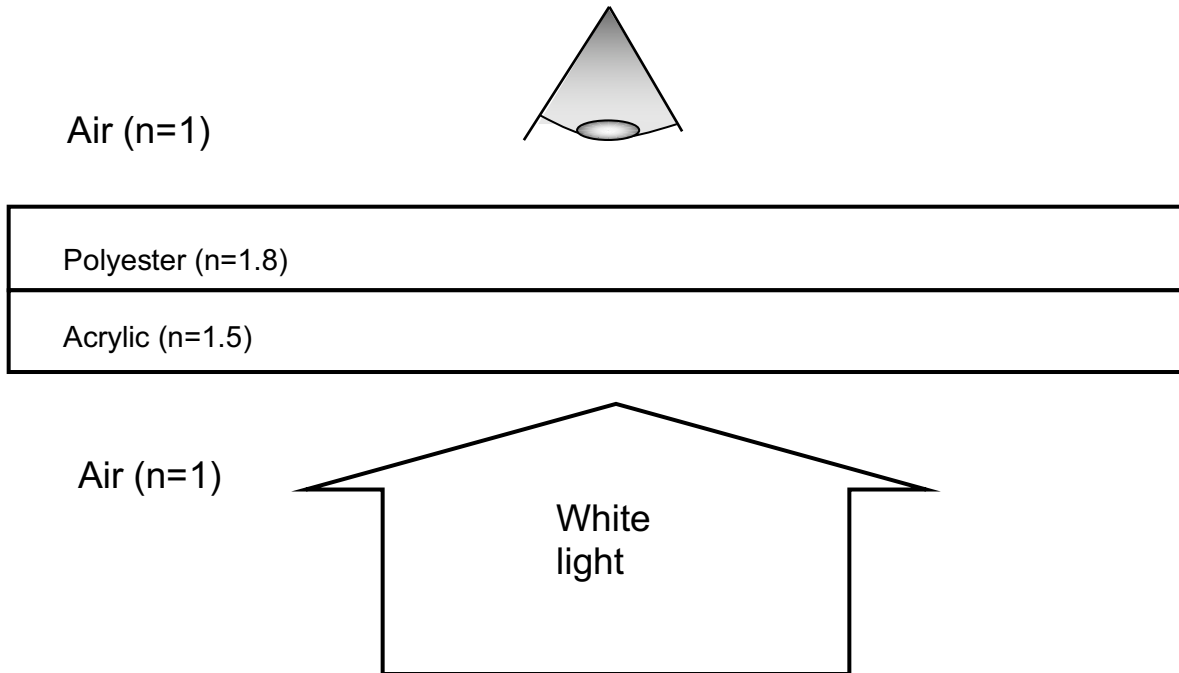
C5) Choose the path with no reflections, and one of the other paths, and write down the phase difference between them. Do this in terms of one or both of the layer thicknesses $t_{polysester}$ and $t_{acrylic}$ and one or both of the indices of refraction.

C6) What layer thicknesses are required to give constructive interference for the observed wavelength (~450nm)?

C7) What is one reason that the transmitted color might change when the bow is tilted?

Physics 208 Laboratory
Spectroscopy and the hydrogen atom

This sheet is the lab document your TA will use to score your lab. It is to be turned in at the end of lab. To receive full credit you must use complete sentences and explain your reasoning clearly.

What's this lab about?

This is the first lab about quantum mechanics. Your goal is to measure emission lines of the Hydrogen atom, and correlate them with transitions of the atom between different quantum states. You do this by measuring the wavelength of photons emitted by Hydrogen atoms in excited quantum states. You use a diffraction grating to disperse the wavelengths at different angles (by constructive interference), and a spectrometer to accurately measure the angles.

Why are we doing this?

Emission and absorption spectra can be a unique fingerprint of an atom or molecule. The photon energies and wavelengths are directly related to the allowed quantum energy states of the system.

What should I be thinking about before I start this lab?

Think about what happens when a quantum system makes a transition from a high-energy state to a low-energy state. Think about what the quantum states are for a hydrogen atom, and the connection between atomic transitions and photons.

*Any safety issues?*

The coated glass filter in front of the Mercury source blocks ultraviolet radiation from the bulb, so don't remove it. The Mercury source also can become very hot – be careful not to touch it, or to let the black cloth rest against it.

Be careful not to touch the metal electrodes attached to the tube of the Hydrogen source. It is relatively high voltage, and can shock you.

A. The diffraction grating

The equipment in this lab allows for very accurate measurements of the angles for which constructive interference occurs for light passing through a diffraction grating. Remember from the first lab of the semester that a CD or DVD, consisting of many closely spaced tracks acting as slits, behaves as a reflective diffraction grating. The grating you use in the spectrometer here works in transmission, but is otherwise the same: it has many closely spaced slits, with a density of 600 slits/mm.
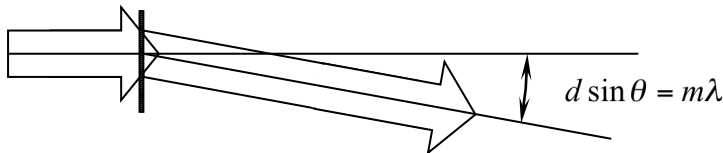
This is actually close to the 1.6 μm track spacing that you found for the CD. In that experiment you aimed a red laser at the CD and found that each groove acted as a source of spherical waves, and these canceled by destructive interference except at particular angles θ determined by the wavelength according to $m\lambda = d\sin\theta$. Here d is the slit spacing and m an integer indicating the order of diffraction.

In that experiment you had a single wavelength. Here the incoming light may be made of several different wavelengths. Each wavelength will diffract constructively at particular angles given by the above formula. The job of the spectrometer is to accurately measure those angles, and so determine the wavelengths making up the incoming light.

A1. Suppose you see only four diffracted rays from the diffraction grating, at angles of $\theta = 20°$, $\theta = 23°$, $\theta = 43.16°$, and $\theta = 51.4°$. You detect these with your eye, so you know they are **all in the visible spectrum**. What wavelengths are in the incoming light?

B. Measuring the diffracted angle with the spectrometer

The spectrometer has three main pieces (shown below)

> 1. A collimator (makes rays hitting the diffraction grating parallel)
>
> 2. Diffraction grating (discussed above)
>
> 3. An observation telescope (to accurately view the spectral lines)
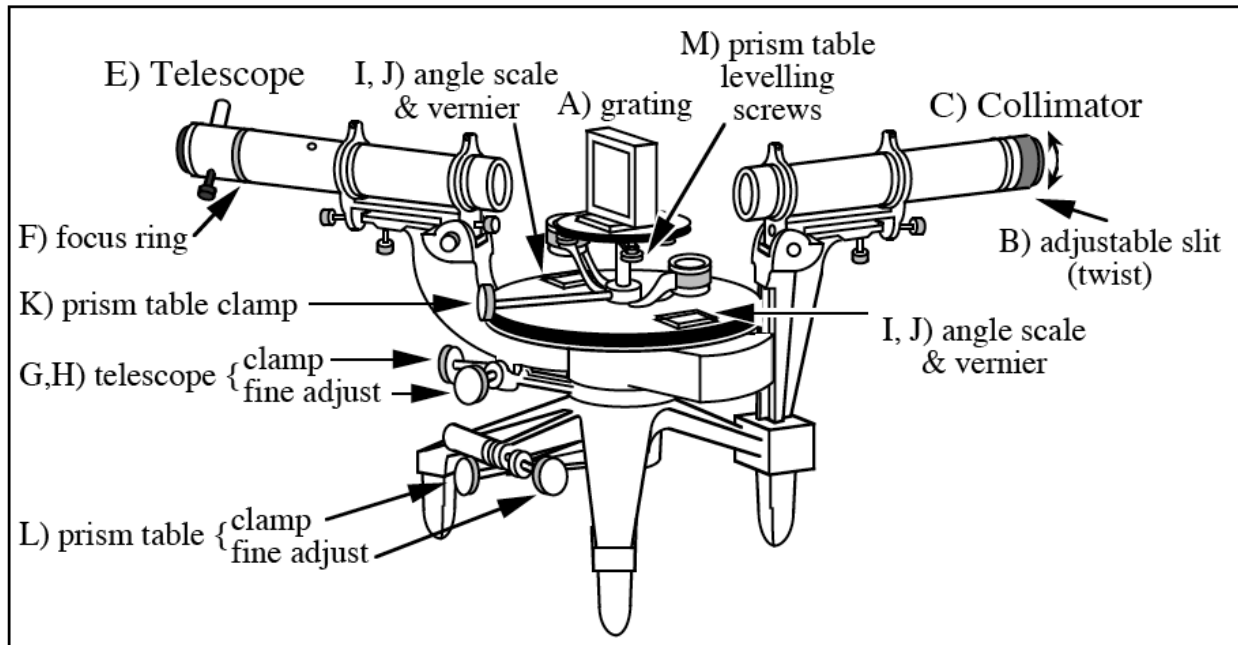
There are also several mechanical adjustments, as shown in the figure above. Don't adjust K and L. These are to make the grating perpendicular to the collimator, and to adjust the angle scale so that it indicates 0° when the viewing telescope is aligned exactly on the axis of the collimator.

The **collimator** has a slit on the far end, and a lens on the near end that makes the light rays from the slit parallel. You turn the knurled knob C) to open and close the slit. Opening the slit gives a brighter image, but less angular resolution.

The **viewing telescope** can be focused, and its angle can be changed.

Two adjustments to focus the viewing telescope:

> i) Slide the eyepiece tube in or out until the crosshairs are in focus.
>
> ii) Turn the knurled knob until the image of the slit (lit by desk lamp) is in focus

Two ways to move the viewing telescope:

> i) loosen the telescope clamp and move the telescope with your hand (coarse adjust)
>
> ii) tighten the telescope clamp, and turn the fine-adjust knurled knob (fine adjust)

C. Using the spectrometer *First you look at light from an incandescent bulb. This light appears white to your eye, but is a continuous superposition of all wavelengths in the visible range. You view these wavelengths separately with the spectrometer.*

Make sure the grating is in place, and turn on the desk lamp so it shines through the slit. Put the black cloth over the spectrometer to block out stray light. Unlock the telescope and rotate it left and right while viewing to find the continuous spectrum on either side of the central maximum. If you can't see the continuous spectrum, part of the black cloth may be blocking the light. Try adjusting the slit width.

1. Is the order of the colors what you would expect from $d \sin \theta = m\lambda$? Explain

2. Pick a color or edge of a color in the spectrum with the telescope crosshairs and lock the telescope in place. Use the angle scale and vernier to determine the angle away from the central maximum. (Read carefully the description of measuring angles with the vernier scale on the last page of this handout.)

3. Unlock the telescope and align it with the same color or edge of a color on the *opposite* side of the central maximum. Record the angles of the spectrometer away from the central maximum.

4. Average the two angle readings and compute the wavelength of color you chose. Show your calculations. We use the average to account for slight misalignments of the grating, which should be, but isn't, exactly perpendicular to the collimator.

D. Accurately measure *d*, the line spacing of the grating

Your grating is a *replica* grating. It is plastic that is stamped like a CD from a master grating. Because of this it could be slightly stretched or compressed, so that the line spacing is not exactly as written on the grating holder. Here you accurately determine the line spacing by measuring the diffraction angle of the $\lambda = 546.1\ nm$ spectral line of mercury.

Replace the desk lamp with the Hg lamp. Make sure the coated glass filter is in place (the filter blocks the UV part of the spectrum).

D1. Following the same procedure as in part C, write down the angles (left and right) for the first order line for λ = 546.1 nm. It is by far the brightest green line in the spectrum. You should be able to see the green line, the doubled yellow line to the left, and some faint blue lines. If you can't resolve the two yellow lines, reduce the width of the spectrometer entrance slit until you can.

D2. Use the known wavelength and your measured angle for the first order line to calculate *d* and the lines/mm for your grating. Show all your work and compare the result to the value written on your grating.

Use your measured value for the grating line spacing *d* in the next section.

# E. Measuring spectral lines of the hydrogen atom

Replace the Hg lamp with the hydrogen source and position it exactly in front of the slit (if it is not, the lines will not be bright enough to see). Repeat the measurement procedure for every line in the first order spectrum on both sides of the central maximum. Organize your data and calculations in the table at the end of this page.

1. Pick the line (color) farthest from the central maximum and fill in color, angle-left, and angle right in the table.

2. Determine θ from the average and write it in the table also. Show your work here.

3. Using your measured grating line spacing from section D to calculate the wavelength of the hydrogen spectral line in nm.

4. Calculate the photon energy for this line and show your work here. Use $hc = 1240 \ eV \cdot nm$.

5. Before going on make sure your procedure is sound and your numbers make sense. Ask your TA before going on if you are uncertain.

6. Repeat the above process for the rest of the lines in the spectrum to fill in the table.

color	angle-left	angle-right	θ	λ_{photon}	E_{photon}

F. Atomic energy levels for hydrogen

F1. Using $E_n = -\dfrac{13.6}{n^2}eV$, mark the energy levels for hydrogen on the graph at right.
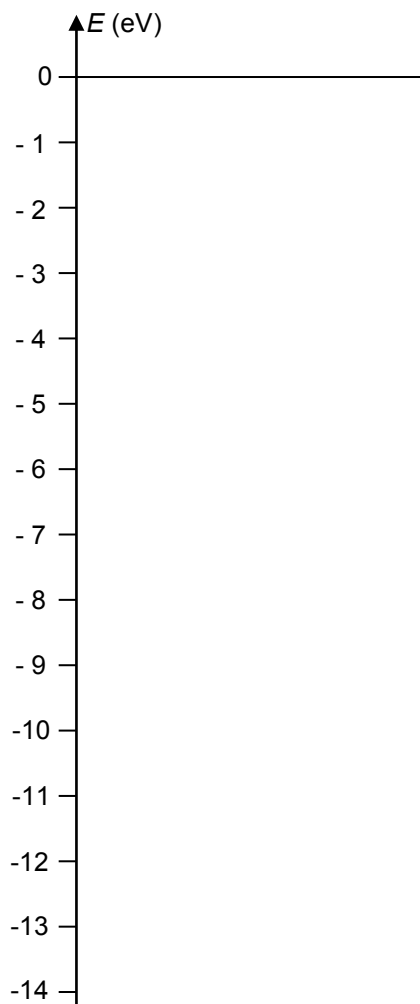
F2. Determine which transitions are responsible for the spectral lines in your table. Mark those transitions on the energy level diagram with an arrow drawn from the initial state to the final state. Indicate which spectral line (color) goes with which arrow. Explain your reasoning and give examples of why other transitions cannot be responsible for these lines.

E (eV)

```
  0 ─────────────────────────
- 1 ─
- 2 ─
- 3 ─
- 4 ─
- 5 ─
- 6 ─
- 7 ─
- 8 ─
- 9 ─
-10 ─
-11 ─
-12 ─
-13 ─
-14 ─
```

Appendix: Reading the vernier scale on the spectrometer

The verniers have 30 divisions per half degree. Hence each division is $(1/30) \times (1/2) = (1/60)°$ or one minute (') of arc.

The knurled ring about the collimator, B, controls the slit opening.

Staff have already focused the collimator for parallel light and have set collimator and telescope perpendicular to spectrometer's rotation axis.

REMINDER ON READING A VERNIER

1) Position and tighten the telescope.

2) Move the magnifying glass to see the scale marking

3) Look where the zero mark on the upper scale is located. The degree reading is the first full degree mark to the left of the zero ($210°$ in the top figure; $229°$ in the bottom figure).

4) Now make the minute reading: if the zero mark on the upper scale comes after a ½ degree mark (the short lines on the lower scale) then start at 30', otherwise at 0'.

5) Next look for the two lines which match up *best* between the two scales. Read the number of the appropriate line on the upper scale and add it to either 30' or 0' (according to the result of step 4). In the top figure the zero mark is just past a degree mark so we begin with 0'. The 15' mark is the one that lines up best so we get $210°15'$ for the top reading. In the bottom figure the zero mark is just past a ½ degree mark, and the 16' mark lines up best, so we get $229°46'$.

6) Now convert to decimal degrees. Top figure: 15/60 = 0.25, so $= 210.25°$ Bottom figure: 46/60 = 0.77, so $= 229.77°$


$210° \ 15'$

$229° \ 46'$
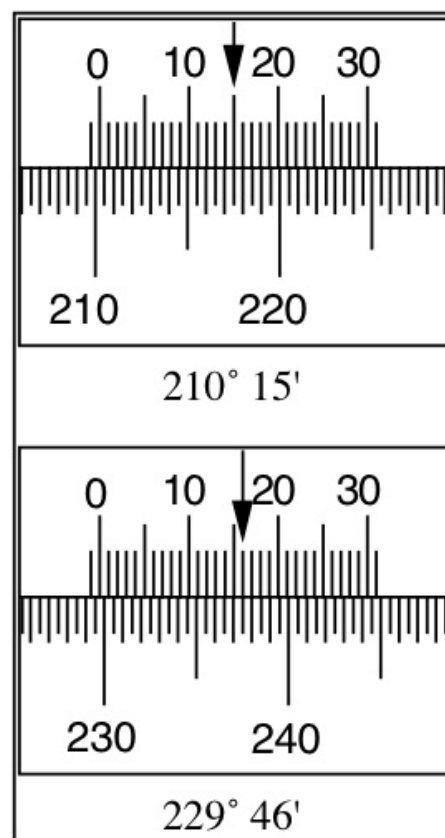
Appendix A – Using a DC power supply

A DC power supply is a device that provides (as you may have guessed) electrical power in a very regular and specific way. Our supplies are designed to deliver a current at a specified voltage, in accordance with Ohm's Law.

The supply you will use in the lab is pictured to the right. It is capable of generating a maximum of 3 Amps at 18 Volts, or 54 Watts of electrical power. For example if you connected the supply set at 10V in series with a 1kΩ resistor, you would draw a current of 10mA and provide 100mW of power to the circuit.

Here are the commonly used features of the supply:
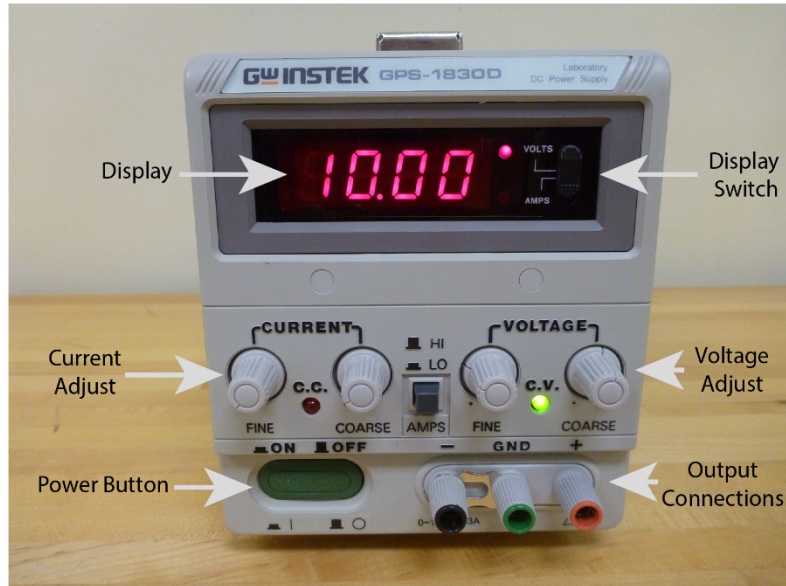
Power Button: Turns the device on/off

Display: Shows the currently provided current or voltage

Display Switch: Toggles the display mode between current and voltage. For the purposes of this course, it should always be on 'Volts'.

Current Adjust: There are two knobs that adjust the current, fine and coarse. For the purposes of this course, both knobs should be turned fully clockwise. You want the maximum amount of current possible.

Voltage Adjust: There are two knobs that control the voltage. These will be the most common adjustments you will make. The 'Fine' adjustment knob has a range of about 2 Volts. The 'Coarse' adjustment knob has a range of about 17 Volts. You will need to turn both of these fully counterclockwise to deliver 0 Volts.

Output Connections: You will attach your cables to these. The red connection marked '+' is the output path for the current. The return path for the current is provided by either the green connection marked 'GND' or the black connection marked '-'. Notice that these have a thin metal bar connecting the two connections.

Setting a voltage:

- Turn off the supply using the power button.
- Use only banana cables (see right) to connect the supply to your circuit. Red goes to '+' and black goes to '-'.
- Turn both **current adjust** knobs fully clockwise.
- Turn both **voltage adjust** knobs fully counterclockwise.
- Press the power button to turn on the supply. The display should read 0V and the green light should be on.
- Use the coarse **voltage adjust** knob clockwise to increase the voltage to the desired value. If you are setting 18V, you will also need to turn the fine voltage adjust knob.

Troubleshooting:

- You may hear some clicking noises as the supply adjusts itself to the desired output – this is normal.
- If the displayed voltage does not increase or the red light turns on, try turning the **current adjust** knobs fully clockwise.
- If the red light persists, you very likely have a problem with your circuit. Examine your circuit carefully for 'shorts', direct connections between the terminals of the power supply.

Appendix B – Using a digital multimeter

A digital multimeter (DMM) is a device that measures a variety of electrical properties. In this course, we will use two of these features: measuring a DC voltage and measuring a DC current.

Measuring a DC Voltage:

At right is the DMM configured to read a DC voltage.

- Turn the knob to the $\overline{\overline{\mathbf{V}}}$ symbol for DC volts.
- The red probe connection is plugged into the **right-most** terminal.
- The black probe is plugged into the **center** terminal.

Connect the DMM in parallel with the component across which you want to measure the voltage. Circuit elements connected in parallel have identical voltage drops. In this mode, the DMM acts like a very large resistor so that is does not draw much current away from the circuit.

At bottom right is an example of the multimeter connected to a circuit and measuring the voltage drop across a resistor. Note that the sign of the voltage will change if the red and black probes are switched.
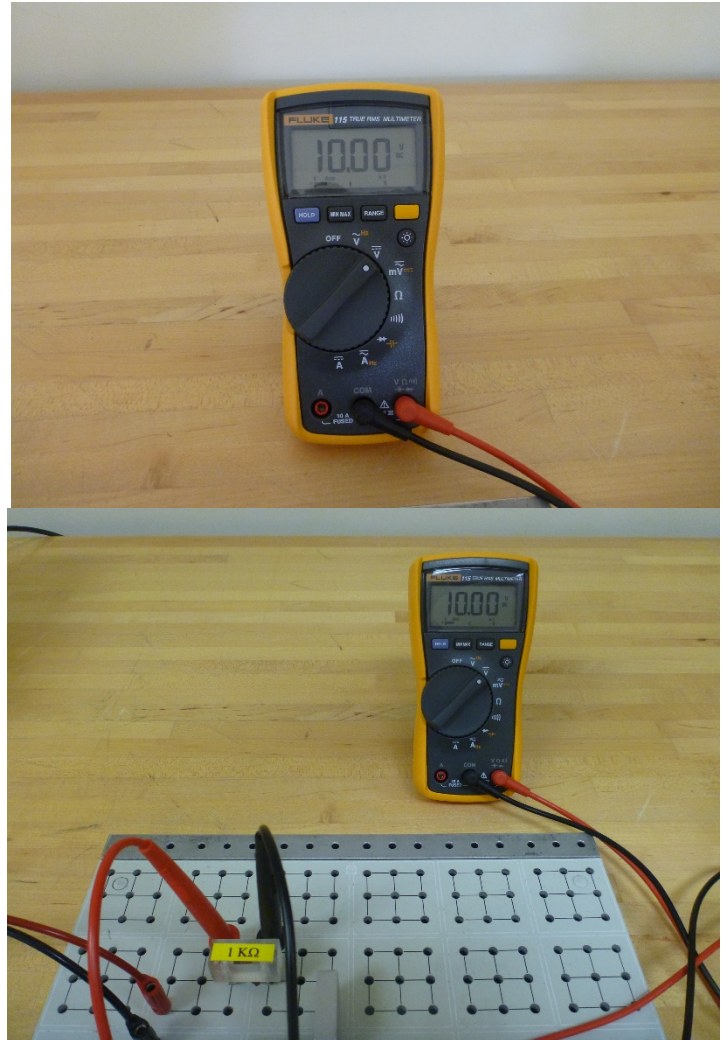
Measuring a DC Current:

At right is the DMM configured to measure a DC current.

- Turn the knob to the $\overline{\overline{\mathbf{A}}}$ symbol for DC current.
- The red probe is plugged into the **left-most** terminal.
- The black probe is plugged into the **center** terminal.

Connect the DMM in series with the component through which you want to measure the current. Circuit elements connected in series have the same current flowing through them. In this mode, the DMM acts like a wire with very little resistance. The voltage drop due to the DMM is negligible.

At bottom right is an example of the multimeter connected to a circuit and measuring the current flowing through a resistor. Note that the sign of the current will change if the red and black probes are switched.
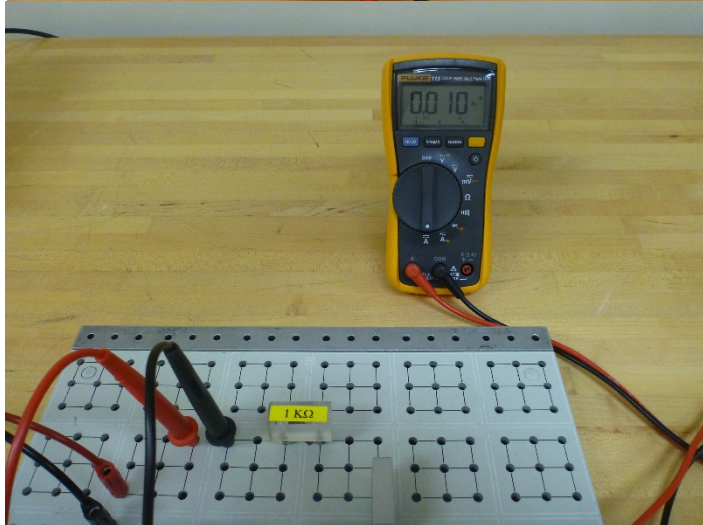

Troubleshooting:

- If the DMM turns itself off, just turn the knob to the 'off' position and then back to the correct setting.
- If any buttons are pressed accidentally or the DMM is acting strangely, turn the DMM to 'off' and then back on again.
- Double check the leads! Current measurement require the red probe connected to the **left-most** terminal. Voltage measurements require the red probe connected to the **right-most** terminal.
- Double check the knob! Current measurements should use the $\overline{\overline{\mathbf{A}}}$ setting, while voltage measurements should use the $\overline{\overline{\mathbf{V}}}$ setting.
- Double check your circuit! Current measurement require the DMM to be configured in series. Voltage measurements require the DMM to be in parallel.

Appendix C – Using an electrometer

An electrometer is a device that measures a DC Voltage. It is distinguished from a digital multimeter by being equivalent to an extremely large resistor: our electrometer (pictured below) has an input impedance of 10^{14} Ω, as compared to the <10 MΩ input impedance of the DMM. The advantage of this device is that it is capable of measuring voltages across components like capacitors without quickly draining the charge that resides on that component.
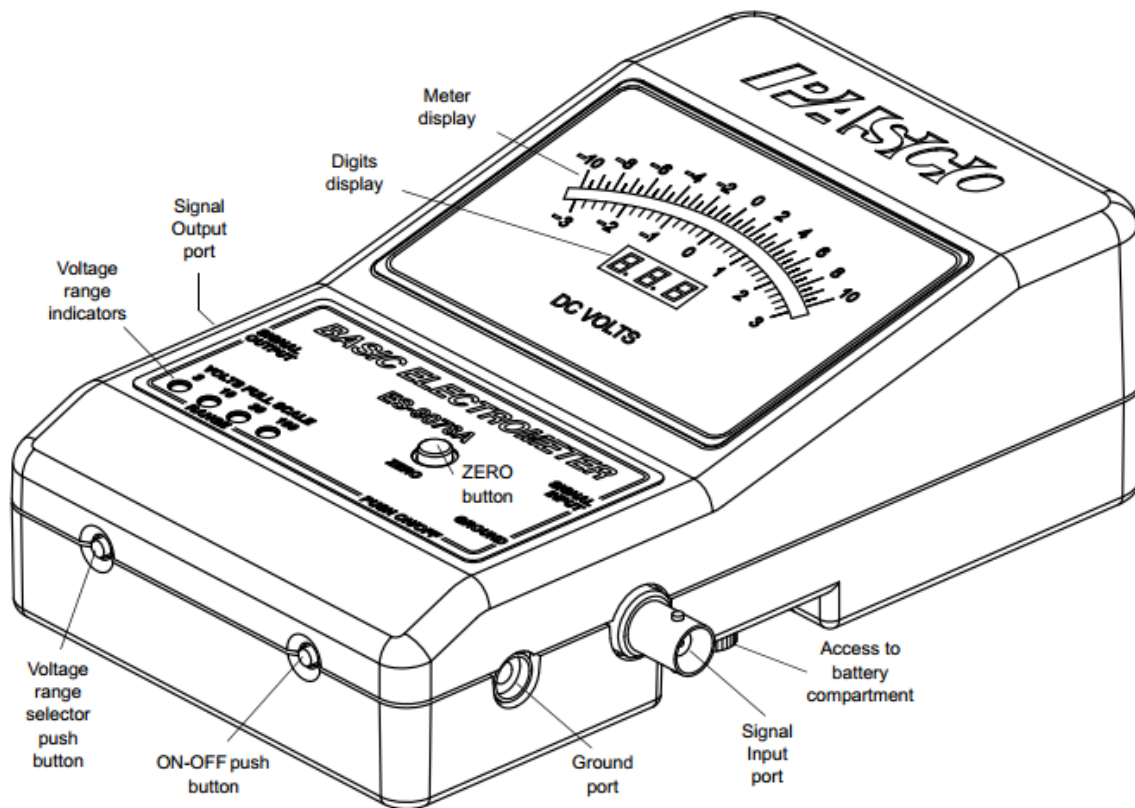
Measuring a voltage:
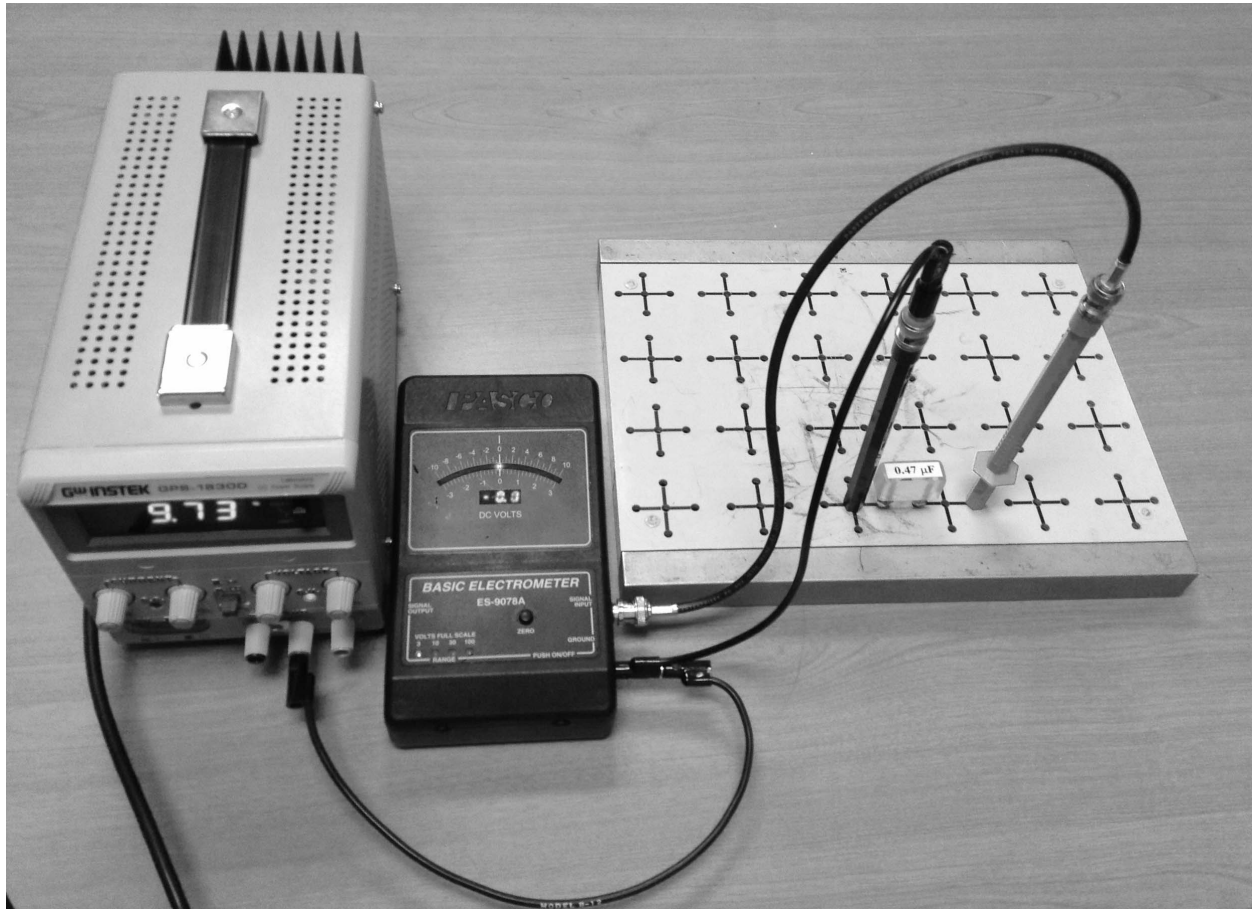
The electrometer configured to measure the voltage drop across a capacitor.

- Press the **ON-OFF** button to turn on the electrometer.
- Set the scale to the smallest number that is larger than the voltage you are supplying by repeatedly pressing the **voltage range selector button**. The present voltage range is displayed on the **voltage range indicators**. The electrometer will not change voltage ranges automatically. If the measured voltage is larger than the voltage range setting, the electrometer will not read correctly, and you will need to change the voltage range.
- Press the **Zero button** to zero the meter. Do this **before** connecting to your circuit as it will short your circuit and remove all of the charge you are trying to measure. If the meter display doesn't read zero, see the troubleshooting section on the next page.
- Connect the black probe to the electrometer **Ground** via a black banana cable and a BNC-banana adapter (shown at right).

- Connect the electrometer **Ground** to an earth ground, such as the "GND" terminal of the DC power supply
- Connect the red probe to the electrometer **Signal Input** via a BNC cable (shown at right).
- Make electrical contact in **parallel** to the component you are measuring by putting the red probe in electrical contact with one side of the component and the black probe in contact with the other side.

When done measuring voltages, press the **ON-OFF** button to turn off the electrometer so as not to drain the batteries.

Troubleshooting:

The range indicator light flashes when the battery needs to be replaced.

For good results, connect the electrometer ground to an earth ground (such as the ground wire from a 120 VAC socket), unless otherwise directed by the write-up.

It is also helpful if the experimenter is grounded.

Keep the effects of triboelectricity in mind:

--it is not difficult to charge the electrometer to more than 100 V by dragging the signal input probe tip across a surface (such as an article of clothing);
--it is also easy to charge the electrometer to ~1 V during insertion of the signal input probe tip into the plug board (i.e. by rubbing of the metal of the probe tip against the metal of the plug board);
--when the cable connecting the signal input probe tip to the electrometer is flexed, the wire inside the cable rubs against the insulation surrounding it, and this can also charge the electrometer to ~1 V, in a reversible fashion (ie if one flexes the cable back and forth, the voltage goes up and down).

If the electrometer display does not return to 0.0 when the "zero" button is pressed, assume that there is some residual charge on the electrometer. To remove the residual charge from the electrometer:

connect both the signal input probe tip and the ground probe tip to an earth ground simultaneously, and then press the zero button. Verify the electrometer display reads 0.0 before removing the probe tips (because the act of removing the probe tips can easily cause the electrometer to charge to ~1 V via triboelectric effects, as mentioned above).

For good results, remove residual charge on the electrometer before each measurement.   If this isn't done, residual charge on the electrometer may compromise the measurements.

If flexing the cable causes the display to oscillate by significantly more than ~1 V, replace the cable.

Remember that introducing an earth ground into the middle of your circuit (as will happen if the ground of the electrometer is connected to an earth ground, as suggested above) may affect the function of the circuit. It is possible to use the electrometer without connecting its ground to an Earth ground, but this will render it susceptible to charge build-up, and resultant loss of accuracy.

If nothing above clarifies the trouble with the electrometer, put it on the spare equipment table, with a trouble card indicating the nature of the problem.