

# **EXPLORATIONS AND EXPERIMENTS IN PHYSICS**

## **LAB MANUAL FOR PHYSICS 102**

**August, 2003**

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## INTRODUCTION TO THE PHYSICS 102 LABORATORY

### Goals:

The goals of the lab are twofold: (1) for you to see and experience physics at a hands-on level and (2) for you to learn how to use the experimental method to reach conclusions. To accomplish these goals, each week you will make some measurements using specialized lab equipment and then analyze your results. There are two types of activities included in this manual: **explorations** and **experiments**.

The **explorations** are more qualitative, and in many cases, the exploration is done before the topic is covered in lecture. This is intended to give you some direct experience with the phenomena so the lecture will be easier to understand. The **experiments** are intended to give you practice in making quantitative measurements and using these to deduce some physical-mathematical relationships.

### Supplies:

In addition to this lab manual, you will need the following materials in lab:

- Calculator
- Notebook with crosshatched pages for graphing
- 12 " ruler
- Ball-point pen
- 1-2 colored pens or pencils

### Pre-Lab Preparation:

All of your experimental work will be carried out during the 2-hour lab period. Also, your lab reports could be written and turned in during that same time period, but you will need to prepare ahead of time. Read over the experiment or exploration **before** you come to lab and try to understand what you will be doing. Review any material in your textbook that you think will be useful.

### Lab Reports:

Your reports should have the character of a scientific notebook. Using any of reports, you or someone else should be able to reproduce your work. The cornerstone of the experimental method is the ability to repeat the method and get the same results. This can only be done if the experimental work is recorded clearly. You can assume that anyone trying to repeat your experiments will have the same lab manual you have, so you don't have to copy procedures and theory that are included in the manual.

Record your work in ink. Cross out mistakes with a single line to be legible. Keep a record of all you do. Never, never record data on scratch paper and then recopy into

your notebook. Extreme neatness is not required when writing the reports during the lab period.

Your lab report (i.e. notebook) should contain the following parts (not necessarily in this exact order):

**Title and Partners name**

**Introduction**...a sentence or two that describes the main purpose

**Data**...concise, readable form including units. Use tabular format. Estimate uncertainties of each measurement.

**Analysis**...this includes any calculations and graphing of the data

**Results and Conclusions**...This should include a discussion of the results obtained and a brief summary of what you have learned from the experiment. You should also answer any discussion questions posed in the experiment, discuss possible sources of error, and record any special insights you have gained. Your conclusions should demonstrate your understanding of the physics concepts involved in the experiment.

**Grading:**

Your lab report will be graded based on the components listed above. If any of the parts are omitted or poorly done, your instructor will lower your grade and write a brief comment pointing out what is wrong.

It is natural for students and partners to talk to each other and use the same data. Your analysis, graphs and discussion should be your own. Reports that are identical to each other will be downgraded.

Each lab instructor has office hours. Find out where and when in case you need to see him or her out of class.

# **EXPERIMENTS IN PHYSICS**

A lab Manual for Physics 102

UAH

August 2003

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# ELECTRIC CHARGE, ELECTRIC FIELD AND ELECTRIC POTENTIAL

## INTRODUCTION:

This lab activity is an exploration of the concepts of:

1. **Electric Charge,**
2. **Electric Field and Field Lines,**
3. **Electric Potential.**

You will use a computer software program that graphically plots the E-field lines, field vectors  $\vec{E}$ , and potentials that are all used to visualize what occurs in the regions surrounding arrangements of points of electric charges.

## CONCEPTS:

First, let's briefly review these concepts and definitions.

### **Electric Charge...** + and –

There are two types of electrical charges, positive and negative. We know that the negative or minus charge is the property of the electron. A surplus of electrons makes a body negative. The proton in the nucleus of an atom carries the positive charge. Removing electrons from a material (a deficiency of electrons) makes the material positive. How do you know that an electric charge exists? One way is by the forces they exert on one another.

### **Force Between Point Charges...** $F = k \frac{q_1 q_2}{r^2}$ [Coulombs Law]

The force between two sets of point charges is directly proportional to the amount of charge on each, i.e.  $q_1$  and  $q_2$ . The force is also inversely proportional to the square of the distance between them. Note that the force can be either attractive or repulsive.

As more and more charge is added to different places, the calculations of the forces gets complicated but basically is a vector summation of all the individual charges.

### **Electric Field...** $\vec{E} = \frac{\vec{F}}{q_2}$

The concept of an electric field surrounding an electric charge is analogous to the gravitational field surrounding a mass. A single point with an electrical charge of amount  $q_1$  can be thought of as creating an electric field  $\vec{E}$  that surrounds the space around it. If another point charge,  $q_2$ , is placed somewhere in the “ $\vec{E}$  field”, this second charge experiences a force that is equal to  $\vec{F} = q_2 \vec{E}$ . Both  $\vec{F}$  and  $\vec{E}$  are vector quantities that have a direction as a magnitude. When you have a collection of point charges, there is an

electric field that is the vector summation of the electric fields from all the individual point charges.

### **Electric Field Lines...**

These are drawn to show the “direction” of the electric field,  $\vec{E}$ . The field line starts on “+” charges and end on “-” charges. By definition, the  $\vec{E}$  field vectors are all tangent to the field lines. However, the strength of  $\vec{E}$  [length of the vector] depends on the distance from the charge.

### **Electric Potential...**

Electric potential is a concept related to “work”. Specifically, it’s about how much “work” is done on moving an electric charge around in the electric field. Again, this is analogous to moving a small mass around in the earth’s gravitational field, with the added complication that the charge and field are both positive and negative. We can write the equation for the work [force times distance] done on a charge  $q_2$  as,

$$w = \vec{F} \cdot d\vec{S} = q_2 \vec{E} \cdot d\vec{S}$$

Notice that if you move the charge perpendicular to the  $\vec{E}$  field, no work is done. That is an “equipotential path”. Work and energy are of course referenced from some arbitrary starting point. In electrostatics, one measures or computes the amount of work in moving a test charge,  $q_2$  from infinity to some position on the  $\vec{E}$ -field.

### **Potential Difference...**

A related concept is potential difference; this is the amount of work done to move a test charge between any two points in the  $\vec{E}$ -field.

### **OBJECTIVES and APPARATUS:**

You’ll use a computer simulation program, the “EM Field”. We want you to use this program to draw field vector  $\vec{E}$ , field lines and equipotential lines for several different arrangements of charges. As a minimum, you’ll look at

- a. single charges, both plus and minus,
- b. pairs of charges, and
- c. two lines of several charges.

## PROCEDURE:

### Part I. A Single point Charge

1. Double click icon “EM Field” to open the EM Field program window.
2. Click “Sources” in the menu bar. And select 3D point charges.
3. Click Display menu, and select show grid.
4. Drag a “+ 1” charge near the center of the display.
5. To see the electric field,  $\vec{E}$ , go to the “Field and Potential” menu and choose “Field Vectors”. Then, click on the screen. You’ll see an arrow drawn that represents the  $\vec{E}$ -field. The direction of the arrow is the direction of the field. The length of the arrow is the relative magnitude of the  $\vec{E}$ -field. Try placing or “clicking” at four different distances from the charge, 1 unit, 0.5 units, 2 units and 3 units.

Questions: With a positive (+ 1) charge, which direction are the  $\vec{E}$ -field vectors? Does the  $\vec{E}$ -field vary inversely with the distance from the single charge? Record the relative lengths of each to compare with other values of charge.

6. Next, try dragging off the + 1 and replace with – 1 charge.

Question: What happened to the direction of the  $\vec{E}$ -field?

7. Replace with + 2 charge. Again, note the relative lengths of the  $\vec{E}$ -field.

Question: Now what happened to the magnitude of the field relative to + 1 charge?

8. Try another “Field and Potential” option by selecting “Field Lines”. Then click the screen at points near your  $\vec{E}$ -field vectors.

Question: Are the field lines and field vectors tangent? So, what do the field lines indicate?

### Part II. Two Point Charges

Next, you can simulate the more interesting case of two charges. First, Clean up Screen by selecting this option in the “display” menu.

1. Drag up an additional charge two units away from the first. To begin, make one a +1 charge and other -1 charge. Then, draw 4 or 5 field lines.
2. Finally, draw several  $\vec{E}$ -field vectors along the field lines. Make a sketch or print out of a display that you can discuss in your report.

Questions: In which general direction does  $\vec{E}$ -field vector point? If a small test (positive) charge were placed at that position in the  $\vec{E}$ -field, in which direction would it move? Would this test charge always move in direction of the field lines? (Assuming that it had zero initial velocity.)

3. Click on the  $\vec{E}$ -field precisely \_ way between two equal charges.

Question: Assuming that you could find the precise \_ position, what would the magnitude of the  $\vec{E}$ -field vector be?

### Part III. Two Charged Plates

Select “Get charges or currents from file” from the File menu, and then open the file “qplates.emf”. This adds two rows of charged rods that approximate a pair of charged plates.

1. Draw a several field lines that will connect points at the center and at the ends of this “plate”.
2. Also, draw in the  $\vec{E}$ -field vectors tangent at several places to one of the field lines.

Questions: Describe the motion of a positive test charge released near the center of the plate? ... near the end of the plate? ...outside the plates?

### Part IV. Electric Potentials

1. Get out of “qplates.emf” by clicking the Source menu, and then select “3D point charge”. Add charge, +4.
2. Draw in several field lines.
3. Next select “Equipotentials with number” from “Field and Potential” menu. Draw the equipotential lines at several distances from the charge; say 1, 2, 4 and 8 units away. Note that a “number” is displayed next to each equipotential line.



Questions: What are the relative directions of the field lines and the equipotential lines?

4. Try “dragging” a  $\vec{E}$ -field vector along the equipotential line.

Questions: Did the magnitude of the  $\vec{E}$ -field change? Describe the direction of the  $\vec{E}$ -field as you moved along the equipotential line? Explain why no work would have been done on the charge as you moved it along this equipotential line?

5. Next place clicks a  $\vec{E}$ -field vector on each of the 4 equipotential lines.

Questions: Describe the relative magnitude of each  $\vec{E}$  vector? Is work required to move from one equipotential line to the next? Explain.

What do the “numbers” on the equipotential lines mean? Do an approximate numerical calculation to show how much work is done on moving a +1 charge from a large distance to four of your equipotential lines.

# **ELECTROSTATIC CHARGE, POTENTIAL AND CAPACITANCE**

## **OBJECTIVE:**

By doing this experiment, we want you to acquaint yourself with the following concepts:

- Electric charge
- Electric potential
- Capacitance

## **METHOD:**

In this experiment you'll use a glass rod and silk cloth to produce a positive charge on the rod. Then you will use a rubber or plastic rod and wool cloth to produce a negative charge on the second rod. You'll be able to demonstrate the forces of attraction and repulsion between charges.

We'll also show you how to use an electrometer to measure the electrical potential (measured in volts) between two conducting surfaces when electrical charges are produced on those surfaces.

You'll also investigate capacitance by adding charge to parallel plate capacitor and measuring the relationship between charge and potential.

## **THEORY and DEFINITIONS:**

Before starting the procedure, you should review the definitions of charge, electrical potential and capacitance given at the end of this write up.

## **APPARATUS:**

Rubber or Phenolic Rod and Wool Cloth, Glass Rod and Silk Cloth, String, Pith Ball, Lab Stand, Electrometer, Ceramic Spacer, Parallel Plate Capacitor, Ruler and Vernier Caliper.

## **PROCEDURE:**

### **Part 1.**

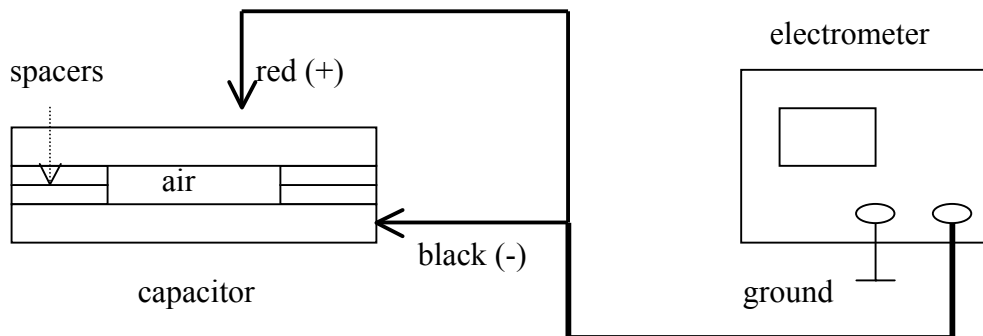
Note: Throughout this experiment, you'll need to remove excess charge from your body and the apparatus. Do this by touching the apparatus with one hand and the water pipe or other "ground" with the other hand.

1. Generate a charge by rubbing the rubber rod with the wool cloth. Then transfer this charge to the suspended pith ball by touching it with the rod. Describe what happened when you initially brought the rod close to the ball. Was it attracted or repelled?

- Now generate more charge on the rubber rod. This time slowly move it close to the ball. What happened? Why?
- Repeat steps 1-2 using the glass rod and silk cloth. [first discharge the ball by touching it and the water pipe or ground]
- After charging the ball with the glass rod, try bringing the charged rubber rod slowly toward the previously charged ball. Do the charges from the rubber rod appear to be different from those on the glass rod? Explain this.

## Part 2.

- Assemble a parallel plate capacitor. Use the two aluminum plates and separate them by the thickness of two ceramic spacers.
- Connect the wire from the electrometer to the capacitor as shown. Be sure to connect the connector with red marking to the top plate. Now any charge on the top plate will be indicated by the electrometer.



- Next, ground the plates with your hand to remove any excess charge. Transfer some charge from the rubber rod to the pith ball. Then suspend the ball over the top plate and observe the polarity (+ or -) of the electrometer reading. Actually touch the ball to the plate and record this reading. Was the charge on the rubber rod positive or negative? Explain your results.
- Repeat with glass and silk.
- Return to the rubber rod and wool. This time rub the two together but now touch the wool cloth to the top plate. How does this with your results in (3.)? Is this what you would expect? Why?

### Part 3.

In this part of the experiment, we want you to calculate the amount of charge (and number of electrons) that you generate and transfer to the capacitor.

You'll use the equation

$$Q = CV \quad (1)$$

where  $C$  = the capacitance in farads

and  $V$  = the electrical potential difference between the plates in volts

and  $Q$  = the charge in coulombs

What the above equation says is that for a given number of volts between the plates, with a larger the capacitance more charge can be stored on the plates!

So what value do you use for the capacitance of the plates? Use the equation,

$$C = \frac{\epsilon_0 A}{d} \quad (2)$$

where  $\epsilon_0$  = the permittivity of air =  $8.9 \times 10^{-12} \text{ F} / \text{m}$

$A$  = the area of one of the plates

and  $d$  = the separation of the plates.

This equation will give you capacitance of the parallel plates alone. The electrometer and its cable also can store some charge, so it has an effective capacitance, which happens to be 100 picofarads. That is,  $100 \times 10^{-12} \text{ F}$ . Just add the 100 picofarads to the value you calculate from equation (2). Then use this total capacitance when you're asked to use equation (1).

1. Make sure that the capacitor is assembled with two spacers. The thickness of a spacer is 1.6 mm, then  $d = 3.2 \text{ mm} = 3.2 \times 10^{-3} \text{ m}$ .
2. Connect the electrometer to the capacitor.
3. Generate some charge using the rubber rod and wool cloth and transfer this to the top plate.
4. Repeat as often as necessary to get approximately – 100 volts.
5. Now calculate
  - a. the capacitance of the parallel plates [equation (2)]
  - b. add 100 picofarads to this answer
  - c. calculate the total charge on the capacitor and electrometer [equation (1)]

- d. Using the value for the charge of one single electrons,  $1.6 \times 10^{-19} \text{ C}$ , calculate the number of electrons that you transferred to the capacitor and electrometer.

### **EXPLORATON: Electrical potential (volts) and work**

In this short exploration, we want you to observe what happens to the electrometer reading when the separation is varied between two charged parallel plates. Your instructor will assist you with this exploration when you're ready.

1. The electrometer should be already connected to the plates of the variable space capacitor.
2. Charge one plate with a rubber rod and note the electrometer reading. At this point, answer this question, will there be attraction or repulsion between the two plates?
3. Slowly increase the distance between the plates and note the electrometer reading. Did it increase, i.e. become more negative?
4. If the force between the plates was attractive, did you do work on the plates to overcome this attraction?
5. Push the plates closer together until you are at the original separation. Observe the electrometer reading.

This brief demonstration should help you later when you study the meaning of voltage and electrical potential. It is a demonstration of the work done when charges are moved.

### **Charge**

We now know that charge is a measure of the number of electrical pieces of matter. The unit of charge is "coulomb". Benjamin Franklin discovered that there were two types of electrical charges. He arbitrarily called one type of charge "positive" and the other type "negative". But it wasn't until over 100 years after Ben Franklin that physicists discovered that atomic matter consisted of electrons (negative charges), protons (positive charges) and neutrons (no charge). It became clear that practical applications of electricity usually involve either a surplus or a deficiency of electrons on a surface or the movement of electrons in metallic conductors. By the time the "electron" was discovered, theories and applications of electricity had already been developed for some time, so it was convenient to keep on using Franklin's conventions for positive and negative charges. *One such convention is about charge flow moving from positive to negative*

*potential*. Because the electron is a negative piece of matter, when you add electrons to a surface, it becomes negative. If you remove electrons, then the surface becomes positive. Both the proton and the electron have the same absolute value of charge; but the proton is positive and the electron is negative.

### **Electrical Potential**

Electrical potential is measured in units of volts. The potential difference or voltage between two points in space is proportional to the amount of work done in moving charges from one place to another. More precisely, voltage is the number of joules of work done in moving 1 coulomb of charge. Work has to be done because the attractive (or repulsive) force between charges must be overcome if the charges are moved.

### **Capacitance**

Capacitance is a measure of the ability of a surface to hold charge for a given electrical potential difference between them. An important equation is  $Q = CV$ .

## Suggest Data Sheet

### Part 3.

$$d = \text{_____ (m)} \quad A = \text{_____ (m}^2\text{)}$$

$$C = \frac{\epsilon_0 A}{d} = \text{_____ (F)}$$

$$\text{Total Capacitance} = C + 100 \times 10^{-12} = \text{_____ (F)}$$

$$\text{Total Charge } Q = CV = \text{_____ (C)}$$

$$\text{The number of electrons} = \frac{Q}{1.6 \times 10^{-19}} =$$

## CIRCUIT BASICS

### INTROGUCTION:

This activity is an exploration of the basic features of electrical circuits.

### OBJECTIVE:

As you do this exploration, you'll acquaint yourself with  
complete circuits      electrical resistance  
series connections      parallel connections

### METHOD:

In the experiment on electrostatics, we defined and discussed charge and potential. In this week's experiment the charge will move continuously through a complete circuit. This flow of charge past a point in circuit is called electrical current. Very often people will just speak of current when it is clear that they are talking about electricity.

The unit of [electrical] current is the ampere (A). An ampere is one coulomb of charge moving past a point in circuit each second. *The direction of the flow is in the direction taken by a positive charge. This is the convention originated by Benjamin Franklin.*

Another important concept to understand is that of [electrical] resistance. As the electrons move through a solid material, they will collide with atoms that make up the solid. As these collisions occur, energy is usually lost by the electrons. *[Note; the electrons only lose energy in this process. The same number of electrons still exists and continues on through the material.]* This energy lost by the electrons is converted to heating up the material. The material is said to resist the flow of charge, or have electrical resistance. Some materials like metals, e.g. gold, silver, copper, and aluminum are good conductors at normal temperatures. Others like carbon, tungsten, and certain alloys and ceramics offer more resistance to the electrical current and therefore heat up. This heating is useful, for example, if you want to heat water or light a bulb!

The unit of electrical resistance is the ohm ( $\Omega$ ). When 1 ampere flows in a circuit and the electrical potential between two points in the circuit is 1 volt, the resistance between those points is 1 ohm. In general, R is given by

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

### APPARATUS:

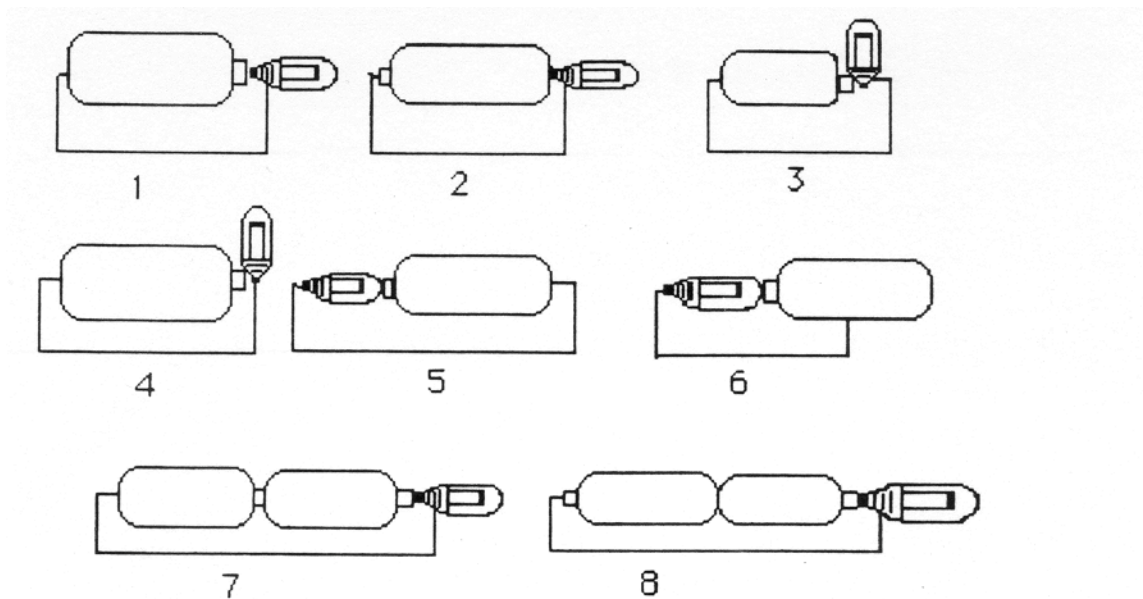
Bulbs, Bulb Socket, Battery, Resistor, Rheostat, Voltmeter, Ammeter, and Connect Wires.



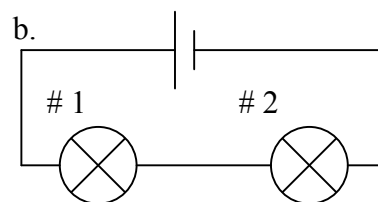
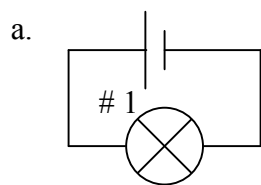
## PROCEDURE:

1. Take a battery, a light bulb, and one piece of wire. Can you make the bulb light up? When you have succeeded, write a sentence or two describing what is necessary to light a bulb. How many electrical connections are there on the light bulb?

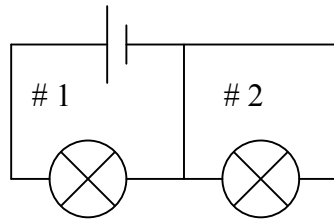
Here's a quiz: Predict which bulbs will light and record your predictions. (You can try the different arrangements if you are unsure.)



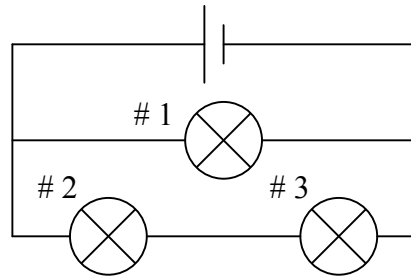
2. Now put 3 light bulbs in holders and assemble the following circuits, one after the other. (Notice that the holders make two different contacts with the bulbs.) In each case record whether each bulb is bright, dim, or out and explain why. Keep circuit (d) assembled for further use.



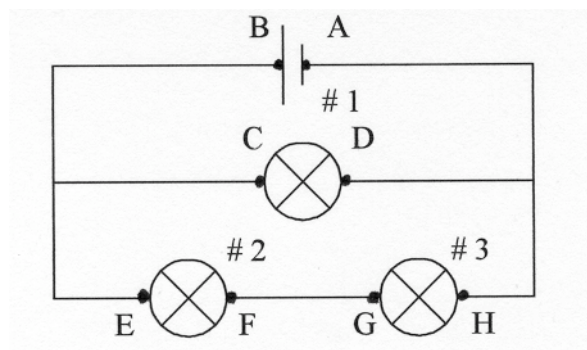
c.



d.



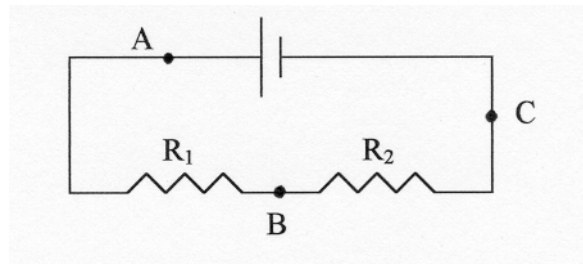
3. a) The wires that you are using are very good conductors and have very low resistance. Using circuit (d), replace a short wire by a very long wire. Do you see any difference in the brightness of the bulbs? Will changing the length of any of the connecting wires affect the current in the circuit? Explain.
- b) Change the shape of the circuit by gently bending or twisting the long wire without changing any of the connections. Do you see any difference in the brightness of the bulbs? Does the shape of the circuit affect the current in the circuit? Explain.
4. We'll continue working with circuit (d), which we've redrawn below with some additional labels.



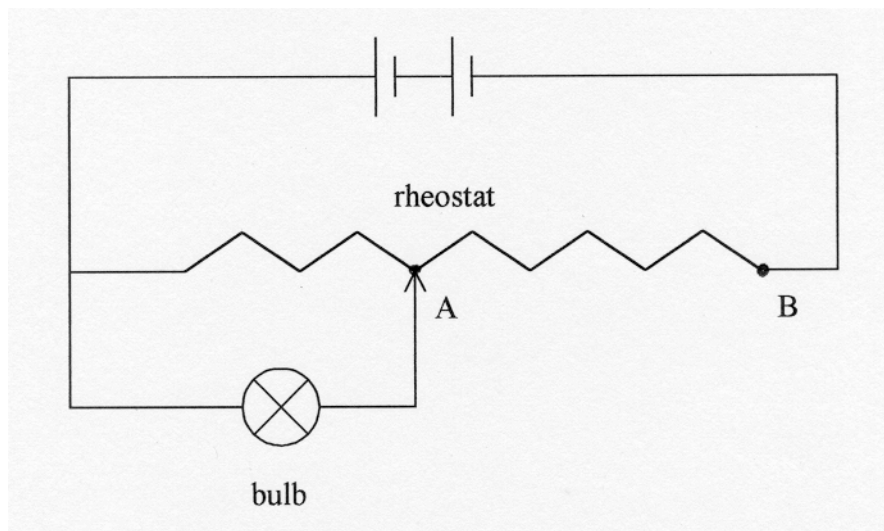
Connect one side of the voltmeter (black post) to point A. Measure and record the voltage difference between point A and points B, C, D, E, F, G, and H by connecting the other side of the voltmeter (red post) to each point in turn. At which points is the voltage the same? At which points is it zero? Explain your results.

5. Remove bulb # 1 from its holder. What happens to the other bulbs? Explain. Put bulb # 1 back in its holder and remove # 2. Explain what happens.
6. Short bulb # 2 out of the circuit by connecting a wire from E to F. What happens to bulb # 2 and # 3? Explain.

7. Make a circuit with 1 battery in series with 2 resistors,  $R_1$  and  $R_2$ . Place the ammeter in the circuit at point A. (To do this, open the circuit at point S, and connect one wire from the red post of ammeter to the positive end of the battery and connect black post of ammeter to the left side of  $R_1$ .) NOTE: In contrast to a voltmeter, an ammeter is always placed directly in the circuit. (why?) Measure and record the current through the ammeter (through point A). Repeat with points B and C. Compare the values at A, B, and C. Does the current vary from one place to another in a one-loop circuit? (Does current get “used up” in a resistor?)



8. Design a circuit that allows you to measure the values of  $R_1$  and  $R_2$  individually, then  $R_1$  and  $R_2$  in series and parallel. You know the voltage across a battery and you have ohm's law to help you! In lecture you learned that  $R_{\text{series}} = R_1 + R_2$  and  $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2}$ . Check your measured values with these relationships.
9. What would happen to the light bulb when point A is moved closer to point B? Explain.



# **ELECTRIC VOLTAGE, CURRENT, POWER and WORK**

## **OBJECTIVE:**

This experiment is to give you some insight into the meaning of the concept of electrical voltage and electrical current and how they relate to energy.

It also should reinforce your understanding about the distinction between power and work.

## **METHOD:**

You will connect a source of electricity to a resistor that is immersed in a water calorimeter. By measuring the amount of current that flows (number of amperes) and the voltage decrease (volts) as the current passes through the resistor, you will be able to calculate the amount of power being dissipated by the resistor.

(Remember that power is the rate of doing work, or in this case, the rate at which energy is being expended.)

You will also measure the temperature of the water over a known period of time. You will make a numerical comparison of the total electrical work done in 2 minutes intervals to the heat energy required to raise the water temperature in the same time intervals.

## **APPARATUS:**

Electrical Calorimeter, Ammeter, Voltmeter, Power Supply, Wires, DataStudio, Computer and Temperature Sensor, Balance and Masses.

## **THEORY:**

To perform this experiment and do the calculations, you'll need to know the following:

Thermal Energy - Recall that it takes 1 calorie to raise 1 gram of water 1 degree centigrade. The net energy increase is the total mass of the water times the number of degree increase,  $\Delta T$ , in water temperature:

$$Q = m\Delta T, \text{ where } Q \text{ is in calories} \quad (1)$$

Because the water is in a metal cup, this equation must be modified to include the mass and specific heat of the metal. That is:

$$Q = ( c_1 m_1 + c_2 m_2 ) \Delta T \quad (1a)$$

where the subscripts refer to the different materials.

Note that heat losses also happen and must be considered! You'll need to convert the energy to a different set of units, the joule. There are 4.185 joules in 1 calorie. Both the joule and calorie are units of energy or work. That is,

$$Q = 4.185 \text{ m}\Delta T, \text{ where } Q \text{ is in joules} \quad (1b)$$

## **ELECTRICAL UNITS:**

You also need to know what the electrical units mean in terms of the fundamental ideas of work and power.

### CURRENT:

One ampere of electrical current means that one coulomb of charge per second is flowing in the circuit;

$$1 \text{ Ampere} = 1 \text{ Coulomb/1 sec} \quad (2)$$

### VOLTAGE:

One volt means that one joule of energy has been expended on one coulomb of charge;

$$1 \text{ volt} = 1 \text{ joule/1 Coulomb} \quad (3)$$

If we multiply the terms in Eqs. (2) and (3), we get

$$1 \text{ Ampere} \times 1 \text{ volt} = 1 \text{ joule/sec}$$

### POWER:

You recognize that a joule per second is the rate of doing work. This is what we mean by power. Algebraically, we have

$$P = VI \quad (4)$$

where

V = voltage (volts)

I = current (amps)

P = power which is given the name watts;

(A watt is just a different name and means the same thing as a joule per second)

### ENERGY:

The total energy involved in this process is just the power multiplied by the time the power was on. That is

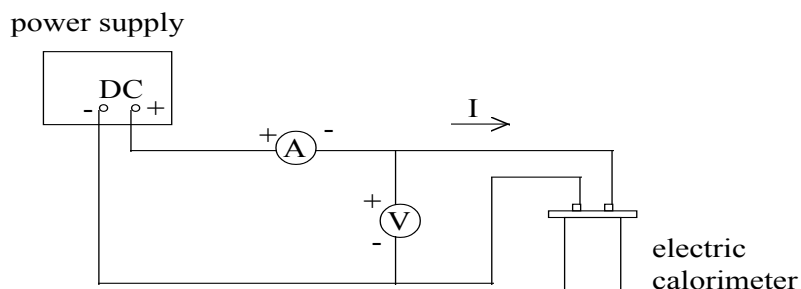
$$\text{Energy} = Pt \quad (5)$$

where  $(E) = \text{joule}, (P) = \text{watt}, (t) = \text{seconds}$

### **SUGGESTED PROCEDURE:**

In this experiment, you measure the temperature using temperature sensor with the DataStudio. Turn on the Interface and Computer and then double click DataStudio icon. At the “Experiment Setup” window drag the temperature sensor from Sensor List to analog channel A.

1. Determine the mass of the water you will add to the calorimeter. First weigh the empty cup and then the cup plus water. Fill 3/4ths full.
2. Connect the DC terminals of the power supply in series with the ammeter and the terminals on the electrical calorimeter. Also, connect the voltmeter to the terminals of the calorimeter.



\* Don't turn on the power supply until your instructor has checked your circuit!

3. Measure the initial water temperature with the DataStudio and temperature sensor.

Click the Start button, wait few second then click Stop button. Drag the recorded data from Data List to Table Display. Click “Statistics” button on

the displayed table window and then choice “Mean”. Manually record the mean value that is initial temperature of water and calorimeter.

4. Delete the data and table. Double click Temperature Sensor icon to open “Sensor Properties” window. In Sample Rate choose “Slow”, “30 second”, then click OK.
5. Click “Options” button to open “Sampling Option” window. Type 600 seconds for Automatic Stop.
6. Drag the Graph Display from Display List to analog channel A.
7. Turn on the DC power supply. Adjust the power supply so that 2 amperes is flowing in the circuit. Record the voltage and click Start button to begin data recording.
8. Continue automatically recording the temperature and continue gently stirring for 10 minutes. Turn off the power supply after stopped data recording.
9. Make graph display window active, click “Scale to fit” button and then click “Smart Tool” button. Move cross hair to determine the changes of temperature for every 2 minutes over a total 10 minutes.

### **CALCULATIONS:**

1. Use Eqs. (1a) to calculate the heat energy per time interval needed to raise the water temperature in your experiment. By using Eqs. (1b), this energy is expressed in joules.
2. Use Eqs. (4) and (5) to find the electrical power and electrical energy in the same time interval that was dissipated by the resistor in the water calorimeter.
3. Plot the thermal energy as a function of the electrical energy. [That is, electrical energy on the x - axis and the thermal energy on the y - axis.]

### Suggest Data Sheet and Calculations

#### (1). Heat Energy

$m_1$  (mass of water) = \_\_\_\_\_ (g)     $c_1$  (specific heat of water) = \_\_\_\_\_

$m_2$  ( mass of inner cup & stirrer) = \_\_\_\_\_ (g)

$c_2$  (specific heat of aluminum) = \_\_\_\_\_

t (second)	0	120	240	360	480	600
T ( $^{\circ}C$ )						
$\Delta T$ ( $^{\circ}C$ )						
$Q = 4.18(c_1 m_1 + c_2 m_2) \Delta T$ (joule)						

#### (2). Electrical Energy

$V$  = \_\_\_\_\_ (V)                       $I$  = \_\_\_\_\_ (A)

Electrical power  $P = VI$  = \_\_\_\_\_ (j)

t (second)	120	240	360	480	600
$E = Pt$ (joule)					





# MAGNETIC FIELD

## INTRODUCTION:

This lab activity is designed to help you visualize and understand the strength and orientation of the magnetic fields that occur around current carrying wires. You'll use the EM Field Software Program to simulate and draw the magnetic field lines and the field vectors around:

- a single wire [carrying current both into and out of the display],
- a pair of wires,
- a loosely coupled solenoid, and
- a tighter solenoid.

## CONCEPTS:

This activity will allow you to practice with and learn about:  
magnetic field lines  
magnetic field vector,  $\vec{B}$ , and the  
right hand rule

**Magnetic Field lines...**when a current flows through a wire, a magnetic field surrounds the wire. The direction of the magnetic field is closed loop around the wire. How do you know that such a magnetic field exists? Because it exerts a torque on iron filings, on permanent magnets, and on small magnetic compasses causing them to all line up with the direction of the field. The magnetic field can also exert forces on any moving electrical charges.

**Magnetic Field Vector,  $\vec{B}$ ...**this is a vector that is tangent to the field lines, i.e. it indicates a particular direction of the field. The stronger the field, the longer the vector,  $\vec{B}$ . By convention, the field vector direction is given by the “right-hand rule”.

**Right-hand Rule...**if you point the thumb of your right hand in the direction of the positive current flow through a straight wire, the direction of the magnetic field points in the same direction that your fingers curl.

You might ask, is this an arbitrary rule? Could we rewrite the rule? Not really! Once we defined what “positive charges and positive current flow” meant, that magnetic field direction is chosen by another arbitrary choice; the direction of the field from a permanent magnet is said to originate at its N pole and circulate back to its S pole. Because wires and coils of wire behave like permanent magnets and vice versa, then we stuck with the “right-hand rule” to make the forces and torque be consistent. To do this experiment and understand electromagnetism, you can just “remember” and “learn how to apply” the right-hand rule.

**About The Program, EM Fields...**one of the menu selections is 2D line currents (magnetism). This menu option allows you to build an arrangement of current-carrying wires. The wires are to be imagined as very long and perpendicular to the screen. Positive currents are those flowing out of the screen toward you. Negative currents carry current into the screen, away from you. The program can then draw in the field lines and magnetic field vectors for these wires.

## **PROCEDURE:**

### **Part 1. Single Wire(s)**

1. Under the Display menu, choose “show grid”. Then from Sources menu choose “2D line currents (magnetism)” and place a single, positive current near the center of the display. Draw field lines at 4 equally spaced distances. Also put field vectors,  $\vec{B}$  tangent to the field lines.
2. Replace the positive current with a negative one.
3. Try changing the increasing the magnitude of the current.

Questions: (a) explain, using the right-hand rule, why the field points in the directions that it does. (b) Does the magnitude of  $\vec{B}$  decrease as  $\frac{1}{r^2}$  or as  $\frac{1}{r}$ ? (c) What effect does the magnitude of the current have on the field...does the field increase linearly with I?

### **Part 2. Two Wires**

4. Now place two wires on the screen, one carrying current in the (+) direction, the other in the (-) direction. Separate by two units. Draw field lines and field vectors.

Questions: (d) Where is the field the strongest? The weakest? (e) Using the right hand rule, explain why?

### **Part 3. Coils of Wire**

5. Place eight wires on the screen in two rows; 4 positive on the top row, and 4 negative carrying wires on the bottom row. Separate the two rows by three units. Separate the individual wires by just two units for now. Draw the field lines, clicking in the space between the two rows. Also draw the field vectors in  
the space between the rows of wires,  
the space near the ends, and  
the regions exterior to the two rows.

6. Add in eight more wires by filling the spaces between the wires so now they are separated by just 1 unit. Keep the space between the rows the same. Redraw the field lines and field vectors.

Questions: (f) Where is field the strongest now? (g) Compare the strongest  $\vec{B}$  vector to the case of just a single pair. (h) Explain, again using the right-hand rule, why the field gets stronger in some regions and almost goes to zero in others?

## MAGNETISM and THE TANGENT GALVANOMETER

### INTRODUCTION:

This activity is a combined exploration and experiment about the interaction of magnets and electric currents.

### OBJECTIVE:

The purpose of this experiment is to study the effects of an electric current on a magnet. You will also measure the magnetic field of the Earth.

### METHOD:

You'll use a coil of wire and place a compass at the center of this coil. You'll observe that as an electric current passes through the coil, the compass is deflected from its original north-south alignment. This apparatus can be used to measure the ratio of two fields; one produced by the current and the other by the earth's magnetic field.

### THEORY and DEFINITIONS:

The strength of a magnetic field,  $\vec{B}$ , at the center of a circular loop of wire is given by the following equation:

$$B = \mu_0 \frac{NI}{2R} \quad (1)$$

where  $N$  = the number of turns in the coil,

$R$  = the radius of the coil in meters,

$I$  = the current through the coil (amperes),

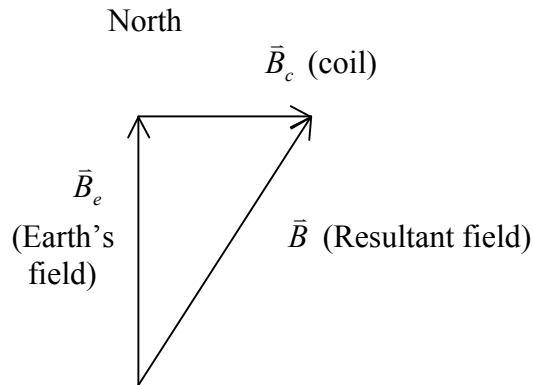
$\mu_0 = 4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$ , the permeability of free space,

and  $B$  is the magnetic field intensity, the unit of  $B$  is tesla (T).

A compass needle points in the direction of the magnetic field at the location where the compass is placed. Consider what would happen if you were to place a compass at the center of the circular coil with  $I = 0$  and the entire apparatus were oriented so the compass needle was in the plane of the coil. If a current were now passed through the coil, the compass needle would deflect through an angle  $\theta$ . The compass needle will have rotated until it is parallel with the new magnetic field vector. This new magnetic field is the vector sum of adding the earth's  $\vec{B}$  field and the  $\vec{B}$  field from the coil.

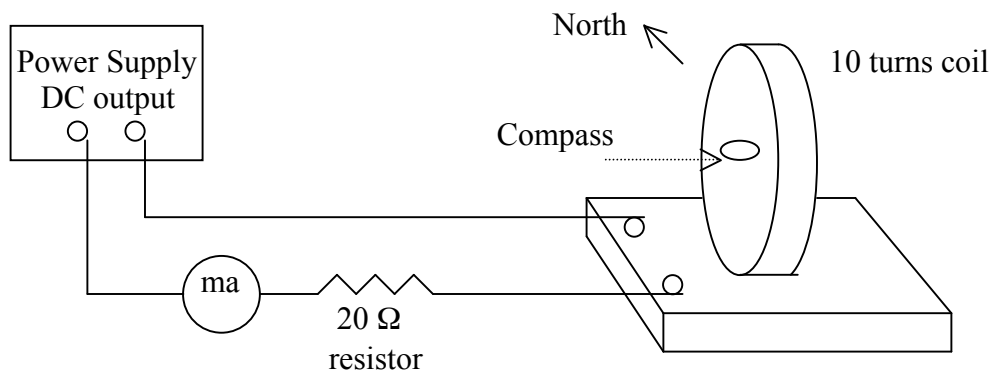
If you know either one of these two magnetic fields and the angle between them, you can calculate the other one. From the diagram you can see that the relationship is just,

$$\tan \theta = \frac{B_{coil}}{B_{earth}} \quad (2)$$



### PROCEDURE:

1. Examine the compass needle and determine the direction of magnetic north. Also measure the outside diameter of the form on which the coil was wound. Your coil has 10 turns on it.
2. Position the circular coil on the lab table so that its vertical plane is north and south. Then support the meter stick through the center of the coil so that it runs east and west.
3. Put the compass on the meter stick at the center of the coil, and arrange it so that it reads zero degrees.
4. Connect the coil to the DC output of the power supply and milliammeter as shown in the figure below. Use the 400 mA range of the meter. With no current flowing, note and record the angle of the compass needle. It should be zero.



5. Increase the current to 50 ma (0.05 a) and record needle deflection (Attempt to this as accurately as you can. 2 to 2.5 degrees should be your goal.)
6. Repeat for current settings of 100, 200, 300, and 400 ma.
7. Reduce current to zero and reverse the connections to the coil so the current will pass through in the opposite direction.
8. Take another set of data for the reversed current and needle deflections. Note the direction of needle deflection obtained in step 5 & 6 to those step 8.

### **CALCULATIONS:**

1. Calculate the absolute average of the pair of angular deflections for equal but reversed currents.
2. From your electrical current data and the radius of the coil, use equation (1) to calculate the B field at the center of the coil for each current,  $B_c$ .
3. Plot  $\tan \theta$  as function of  $B_c$ .
4. Calculate a value for the horizontal component of the earth's magnetic field. Use equation (2) and recognize that the slope of the curve you plotted in step 3 is  $\frac{1}{B_e}$ .

### **QUESTION:**

Suppose the magnetic compass was replaced by a very strong, fixed magnet and the coil were suspended by a weak spring that allowed some rotation against a restoring torque. Describe the action when a current is passed through the coil. (This moving coil configuration is commonly used in electrical meters and galvanometers.)

### Suggested Data Sheet

Radius of Coil,  $R = \underline{\hspace{2cm}}$  (m);

Number of turns,  $N = \underline{\hspace{2cm}}$

CURRENT		COMPASS DEFLECTION			B FIELD at the CENTER...	
I (ma)	reverse I (ma)	Right	Left	Aver.	Tan $\theta$	$B_c$
+50	-50					
+100	-100					
+200	-200					
+300	-300					
+400	-400					

Slope of Tan  $\theta$  vs.  $B_c = \underline{\hspace{2cm}} = \frac{1}{Be}$

$B_c = \underline{\hspace{2cm}}$  (Tesla)



# INDUCED EMF

## INTRODUCTION:

This activity is combined **exploration and experiment about induced electromotive force (EMF).**

## OBJECTIVE:

The purpose of this experiment is to examine how a changing magnetic field can be used to induce a voltage and cause a current to flow in circuit. You'll also explore the concept of what a transformer does and how it works.

## METHOD:

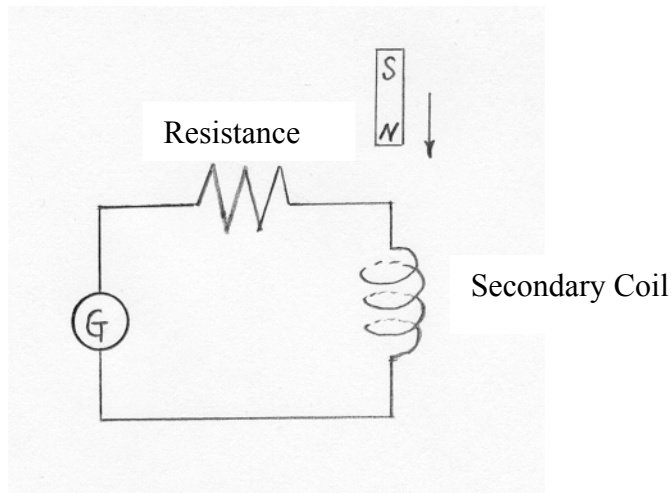
In summary you'll

1. Use a permanent magnet to induce a transient current to flow in long coil of wire.
2. Induce a current to flow in a secondary coil by changing the current flow in a primary coil of wire.
3. As an additional exploration, you'll use a kit to make a lab step-up and a step down voltage transformer.

## PROCEDURE:

### Part 1: EMF induced by a moving permanent magnet.

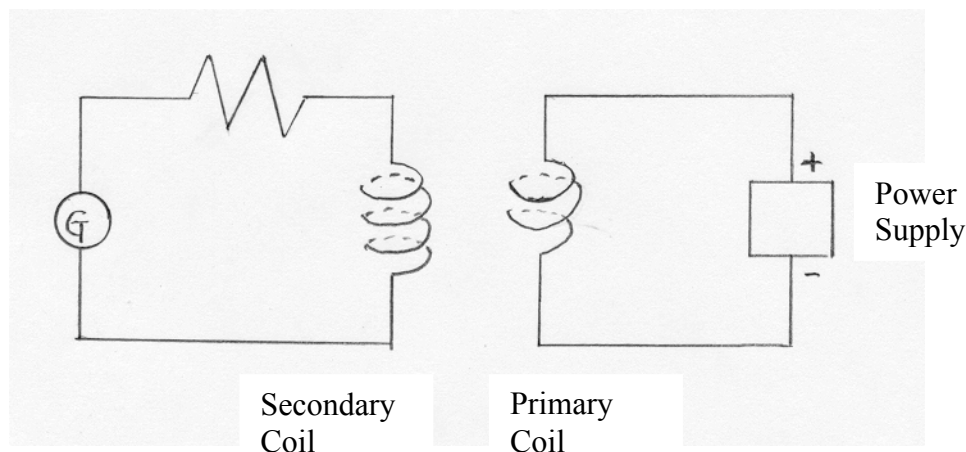
1. Connect the secondary coil, resistance box, and galvanometer in series. [The secondary coil is the outer coil and has the most number of turns; just set the inner, primary coil aside temporarily. You'll need it later.]



2. Set the resistance box to 10,000 ohms.
3. Now thrust the magnet inside the coil. Observe what happens to the galvanometer needle! When the galvanometer needle moves, what does that indicate? Change the resistance setting until you get a near full-scale galvanometer deflection when you insert and then withdraw the magnet.
4. Try varying the speed with which you insert and remove the magnet. Also try reversing the polarity of the magnet; that is, put the South Pole in first instead of the North Pole. Record what happens and discuss.
5. Move the magnet up and down with an oscillatory motion and watch the galvanometer. Vary the frequency of the motion. What kind of current are you generating with this oscillatory motion?

## Part 2. EMF Induced by a Changing Current.

6. Next, connect the primary or inner coil to the dc power supply. Set the primary coil on the table and adjust the current to 2 Amperes.



7. Pick up the primary coil and insert it (quickly) into the secondary coil. Record what happens to the galvanometer needle. Explain. Next, place the primary coil inside the secondary coil with 2 amperes still flowing. Does the galvanometer show a steady or a transient (temporary) deflection when you inserted the coil? Explain.
8. Now, open the circuit by removing one of the connecting leads from the power supply. Record what happens as you open and close the circuit in the primary coil. Explain.

9. With 2 A current through the primary coil and the primary coil sitting inside the secondary coil, insert the iron rod into the primary coil. Record what happens to the galvanometer. Explain. Now remove the iron rod and replace it, this time noting if you can feel any force on the iron rod as you move it in and out of the coil. Is the force attractive or repulsive?

### EXPLORATION: a Simple Transformer Circuit

We've set-up a kit that illustrates the major components of transformer. We want you to see how this transformer can be used to set-up (increase) or set-down (decrease)

an alternating voltage. There are two different coils; one with 200 turns, the other with 800 turns. Both can be placed on a laminated iron core.

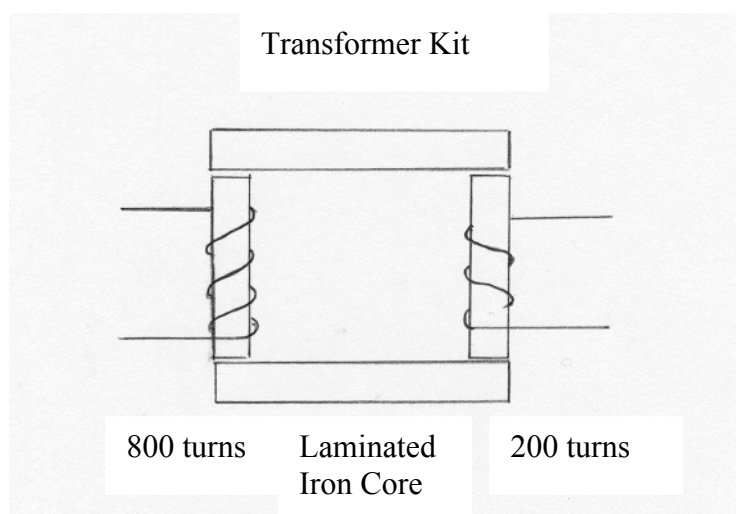
We've set up an alternating source of voltage that can be connected to either one of the coils. We want you to measure the voltage on both coils when the oscillator is connected to one of them. The object is for you to determine how to get the maximum voltage induced into the second coil!

You can [and should] try:

- using the coils off the iron core...just move them close to one another,
- slip the coils on the iron core...leave the cross piece open and,
- both coils on the closed iron core.

Do these twice: once with the 200 turns coil as input and again with the 800 turns coil as input.

Describe what you did. Explain how this demonstrates, how a step-up transformer works.



# REFLECTION AND REFRACTION OF LIGHT

## OBJECTIVE:

The purpose of this experiment is to study the laws of geometric optics through a series of hands-on demonstrations. Specifically, you are

1. To trace a laser beam as it reflects from a plane surface,
2. To trace a laser beam as it bends when it enters or leaves a plastic block,
3. To trace a laser beam when total internal reflection occurs, and
4. To determine the focal lengths of mirrors and lenses.

## METHOD:

You will have a low power, Helium-Neon laser to use as a light source. The bright pencil-like beam of the Helium-Neon laser will allow you easily to trace the path of light rays through various optical components such as prisms, lenses, etc. In this experiment, the dimensions of the apparatus are large in comparison with the wavelength of the light. Therefore, the approximation that light travels in straight lines is valid.

## APPARATUS:

Helium-Neon Laser, Optical Kit.

## THEORY:

### A. Reflection

The law of reflection states that when a ray of light is reflected from a smooth surface the angle  $\theta_i$  between the incident ray and the normal to the surface is equal to the angle  $\theta_r$  between the reflected ray and the normal, as shown in Fig. 1.

$$\theta_i = \theta_r \quad (1)$$

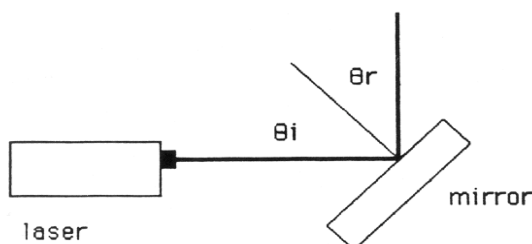


figure 1.

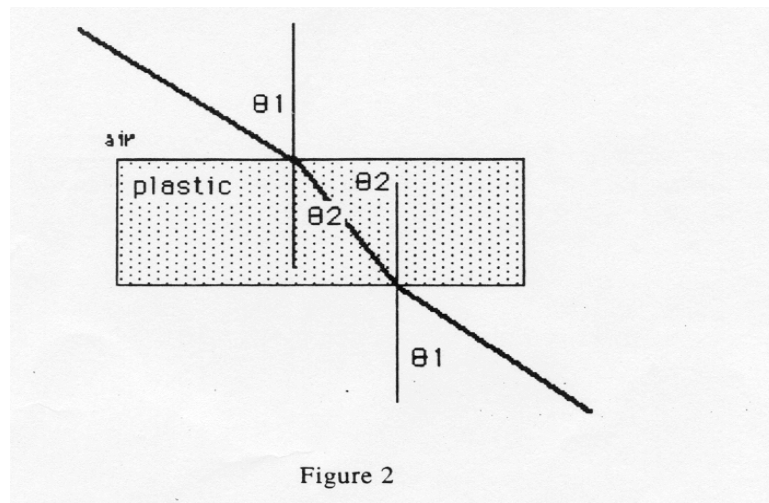
## B. Refraction

If the light crosses the surface and enters another medium, the beam will be bent at the surface. The law of refraction, called Snell's Law, specifies the manner in which the bending occurs:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (2)$$

where  $\theta_1$  and  $\theta_2$  are the angles between the normal to the surface and light ray in medium 1 and 2. The quantities  $n_1$  and  $n_2$  are the indices of refraction of the media.

In air,  $n = 1.0003$ . In glass,  $n$  is in the range  $1.4 - 2.0$ .



As indicated in Fig. 2, Snell's Law tells us that light is bent toward the normal when passing into a medium with a greater index of refraction and is bent away from the normal when passing into a medium with a smaller index of refraction.

### PROCEDURE:

#### CAUTION:

The laser should be handled with caution. Avoid looking directly into the beam. This is a class II laser and is safe for general lab use. Its power output [less than 1 mw] is low enough to cause no harm to the skin. You should not look directly into the beam and do not direct the beam into anyone's eyes.

### Experimental Techniques:

You will trace the rays on sheets of computer paper laid on a board. Place the laser at one end of the board and turn it on. The beam should skim 1-2 mm above the

paper. The idea is to keep the beam low so that some of the scattered light will be seen on the paper, and at the same time high enough so that wrinkles in the paper do not block the beam.

To take data in this experiment, the following techniques may be helpful.

#### A. Ray Tracing

1. Put the element where you want it on the paper. Trace its outline and then don't move it around on the paper.
2. Each ray is traced by marking two points along each leg of its path (circle the points - they are data points). After a path is marked, the paper (with the element fixed on it) is moved to reposition the element with respect to the laser. This creates a new path, which can then be marked, the paper moved, etc.
3. When marking is complete, lift the element off the paper and trace the rays by connecting the dots.

#### B. Back Reflection

This is a method for aligning a surface perpendicular to the laser beam, and is handy for drawing normal lines. Position the surface approximately perpendicular to the beam and look at the reflection of the beam off the end of the laser. When the beam reflects directly back at the laser, it is perpendicular to the surface.

#### C. Snell's Wheel

We have furnished you a device called a Snell's Wheel. It's a complete circular protractor made of plastic. Notice that one-half of the circular disk is solid plastic, while the other half is open. This design will help you trace and measure the angle of reflection and angle of refraction of a beam entering or leaving the plastic. It also easily allows you to see the phenomenon of total internal reflection.

#### D. Beam Multiplier

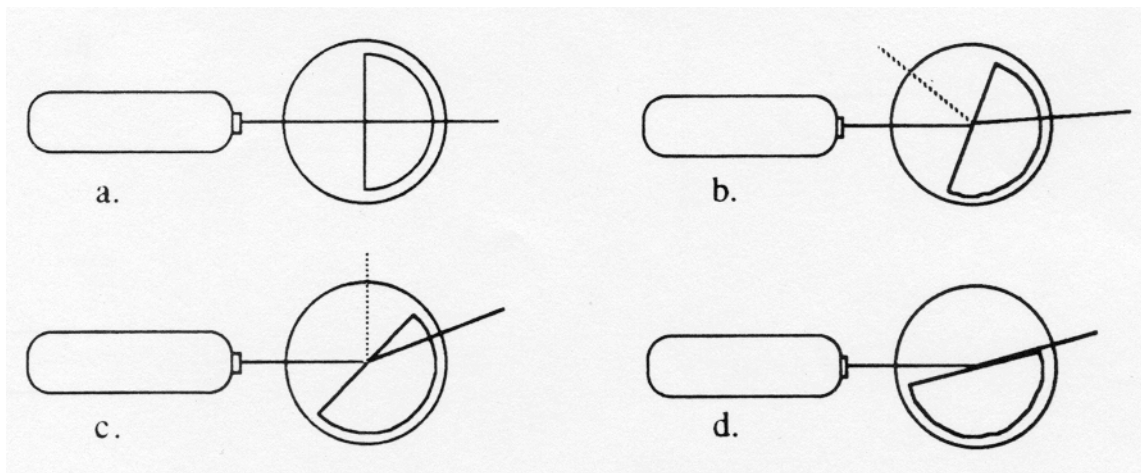
Another useful device you'll use is called a beam multiplier. It's a block of glass with parallel face, totally coated with a reflecting material on one side and partially on the other. When you shine a laser beam a small clear opening, you can get a series of parallel beam coming out of the partially coated side. This is a practical application of reflection and refraction phenomena and is very interesting device to study

### **Experimental Procedure:**

Become familiar with the plastic elements and the techniques listed above. Then do the experimental procedures A, B, C, and D. Procedures A, B, C, and D should each

be done on a separate sheet of computer paper. All calculations, results, and conclusions should be there too.

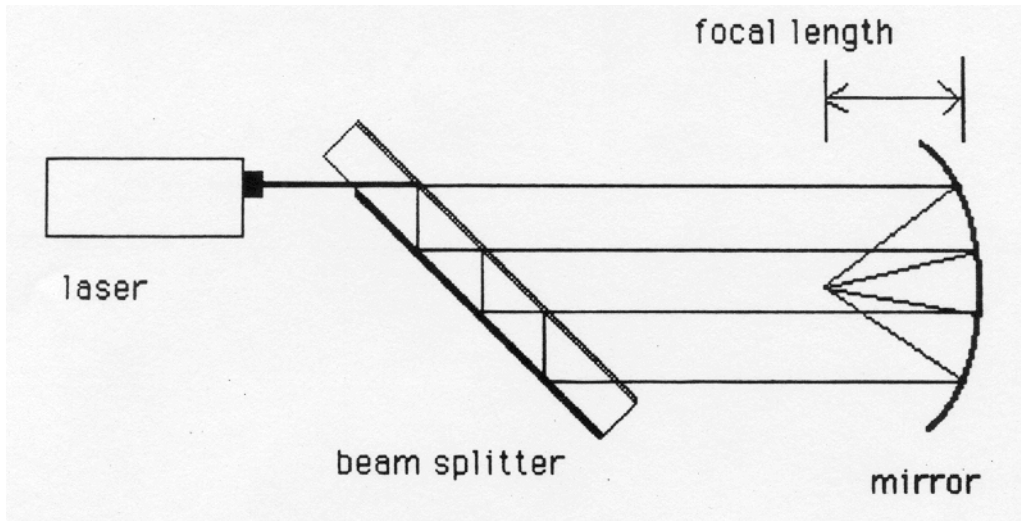
- A. Verify the law of reflection. Using several different angles. You may use a mirrored surface or a block with a plane face.
  - B. Determine the index of refraction of a glass cube, using several different angles.
  - C. Now use the Snell's Wheel to examine the phenomenon of total internal reflection, which occurs when the beam of light does not emerge from the plastic, but rather totally reflects inside.
1. First set up the laser and the wheel as shown in the figures below. Note that you want the beam to enter the wheel on solid side. Then the beam will emerge from the plastic into the air.



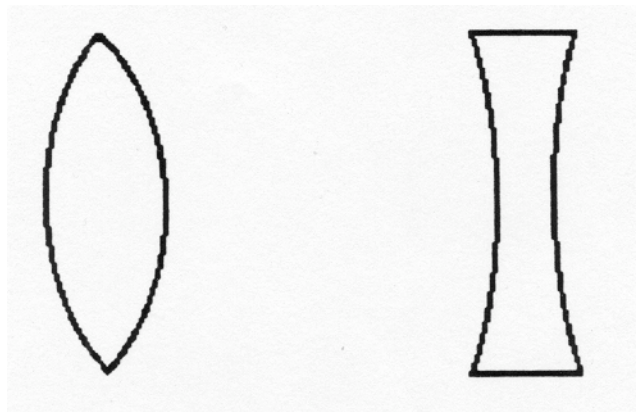
2. Rotate the wheel as shown in figures (b) and (c). Note what happens to the reflected beam and the refracted beam. Are the angles of reflection the same as the angles of incidence? Are the angles of reflection equal to the angles of refraction? Why not?
3. Continue rotating the wheel until the beam is totally reflected inside the plastic. [Complete figure (d) above by sketching in the direction of the reflected beam.] How could you know that total internal reflection happened by looking at the reflected beam alone? How does the brightness of the reflected beam change when the refracted beam disappears? Where is the refracted beam at the onset of total internal reflection?
4. Find the critical angle  $\theta_c$  ( $\sin \theta_c = 1/n$ ) where total internal reflection just begins. Since you can measure the angle, then you can calculate the index of refraction of the plastic used in the Snell's Wheel.



- D. Examine the effect of a curved mirror on parallel light rays that hit the mirror. Do both sides of the mirror. Summarize your results, using equation (1). Determine the focal length of the mirror (the distance from the mirror to the focal point, the point where parallel rays reflected off the mirror come together or appear to come from).



- E. Replace the mirror in part D with the curved plastic lenses, and determine the focal lengths of these lenses using the same approach as in D.





## LENSES and OPTICAL INSTRUMENTS

### OBJECTIVE:

This experiment is to allow you to study the formation of images formed by single lens and by lenses used in combination.

### METHOD:

You'll assemble the optical bench with a light source, lens and an imaging screen. By measuring the distances from source to the lens and from lens to the image you can calculate the focal lengths of three lenses.

You'll also combine two lenses on the optical bench to make an "astronomical telescope".

### THEORY:

The main ideas you'll need to understand include:

1. The difference between a real and virtual image
2. The thin lens formula

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \quad \text{where } d_o = \text{the object distance and } d_i = \text{the image distance}$$

3. The magnification formula

$$m = \frac{h'}{h} = -\frac{d_i}{d_o} \quad \text{where } h' = \text{image height, } h = \text{object height and negative sign signifies that the image is inverted.}$$

4. How to draw a ray diagram

### APPARATUS:

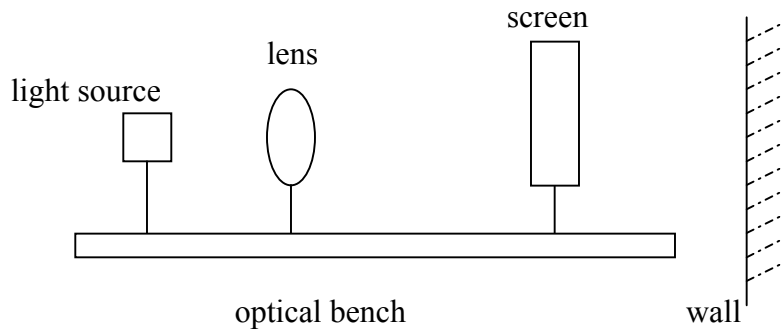
Optical bench, light source, image plate, lens holders and 3 lenses (approximate focal lengths of 5, 18 and 37 cm).

NOTE: Please handle lenses at the edges to avoid smudging or scratching.

## PROCEDURE:

### Part 1. Focal length of single lenses and real images.

1. In this part, test one lens at a time. Set up the optical bench as shown in the figure. Begin with the 18 cm focal length lens.



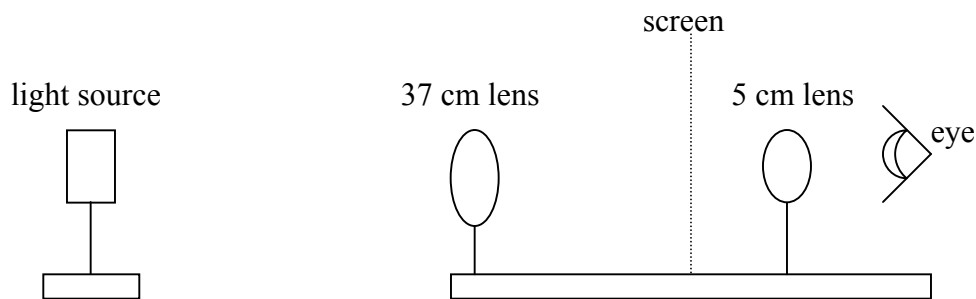
(So how do you know which lens is which? You can get a rough idea of the approximate focal length by either of two methods. Look through the lens at a distant object (at least 3 meters away). Vary the distance between your eye and the lens. There will be a transition zone where the object is neither inverted nor erect, but seems to fill the entire lens. At that point, your eye is in the approximate focal plane of the lens. Another way is to form a real, inverted image of a distant object on any reflecting surface. The distance from the lens to the surface is the approximate focal length. The more distant the object, the better these methods are.)

2. Now, back to the optical bench! Adjust the distance from the source (the object) to the screen to 1 meter. Put the 18 cm lens in the holder and adjust its position until you get a sharp image of the light source. Measure the object and image distances from the lens. Also measure the object and image sizes. Calculate the focal length of the lens using the thin lens formula. Compare the measured magnification with the calculated value. Draw a ray diagram that shows the situation you just observed. Try to make it roughly to scale.
3. Repeat using the 18 cm lens, but this time find a different position for the lens that gives another sharp image on the screen. Explain why the image size is different now than it was in step 2. Draw a ray diagram for this arrangement.
4. Place the light source 10 cm from the lens. Can you get an image on the screen? Look through the lens at the object. What do you see? Explain with words and a ray diagram.

5. Repeat step 2 for the 37 cm and 5 cm lenses. (The image for the 37 cm lenses will be off the end of the optical bench. Using the white laboratory wall as a screen. Adjust the bench to a convenient distance from the bench to the wall to make it easy for you to measure the image distance.)

## Part 2. Astronomical Telescope.

1. In this part of the experiment, you'll assemble an astronomical telescope using two lenses, a 37 cm and a 5 cm lens. Use the 37 cm lens for the objective and the 5 cm as the eyepiece.
2. Place a light source on the far side of the lab, at least 3 meters away. Form a real image on the screen using the 37 cm lens. (Record the distance from the lens to the screen.) Now place the eyepiece, 5 cm lens, behind the screen at a distance approximately equal to its focal length. Remove the screen. Look through the eyepiece and adjust the lens to get a sharp image of the distant object. Record the distances. Turn on the room lights and look through your "telescope". Describe what you see. Alternately, take your telescope into the hallway and look at distant objects at the far end.



## PHYSICAL OPTICS

### OBJECTIVE:

The purpose of this experiment is to study the phenomena of physical optics through a series of hands-on demonstrations of optical interference and diffraction phenomena.

### METHOD:

You will use a low power, Helium-Neon laser as a light source. The coherent and monochromatic beam of the Helium-Neon laser will allow you to easily observe interference and diffraction through slits and diffraction gratings. In this experiment, certain dimensions of the apparatus are small in comparison with the wavelength of light. Therefore, you will be able observe the effects of the wave nature of light.

### APPARATUS:

Helium-Neon Laser, Optical Kits.

### THEORY:

Important equations are:

$$a \sin \theta = m\lambda \quad \text{for maxima for double slits and diffraction grating}$$

$$D \sin \theta = m\lambda \quad \text{for minima for single slit}$$

### DETAILED PROCEDURE:

#### CAUTION

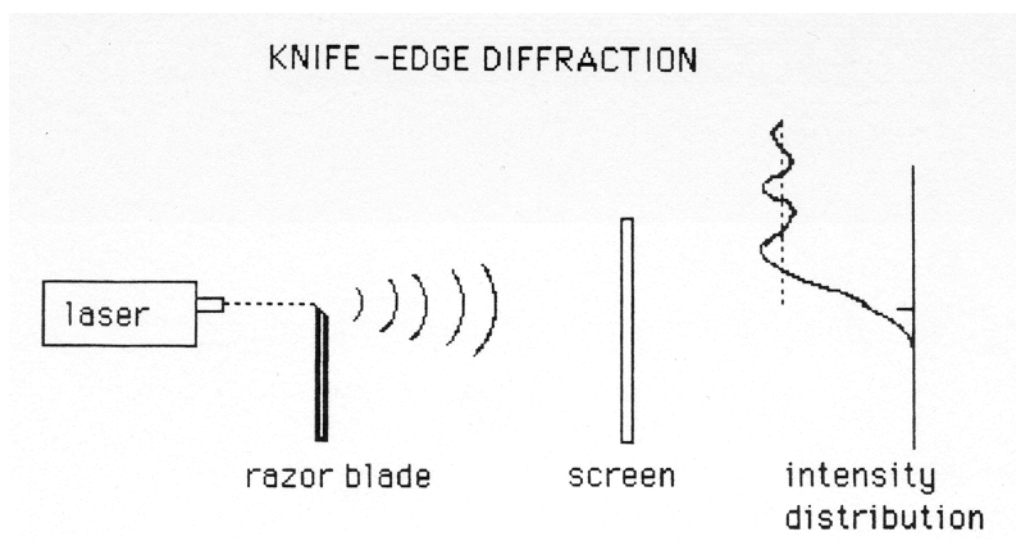
Avoid looking directly into the laser beam. This laser is safe for general lab and industrial use. Its power is low enough to cause no harm to the skin. You should prevent the direct beam from striking your retina, as you would avoid any intense source of light.

#### **Part 1. Diffraction: knife-edge**

Although at one time, people believed that light traveled in perfectly straight lines, we can use the laser to see that light actually bends, or is diffracted, around small objects.

1. Set up the laser so that it is aimed at a screen about two meters away.

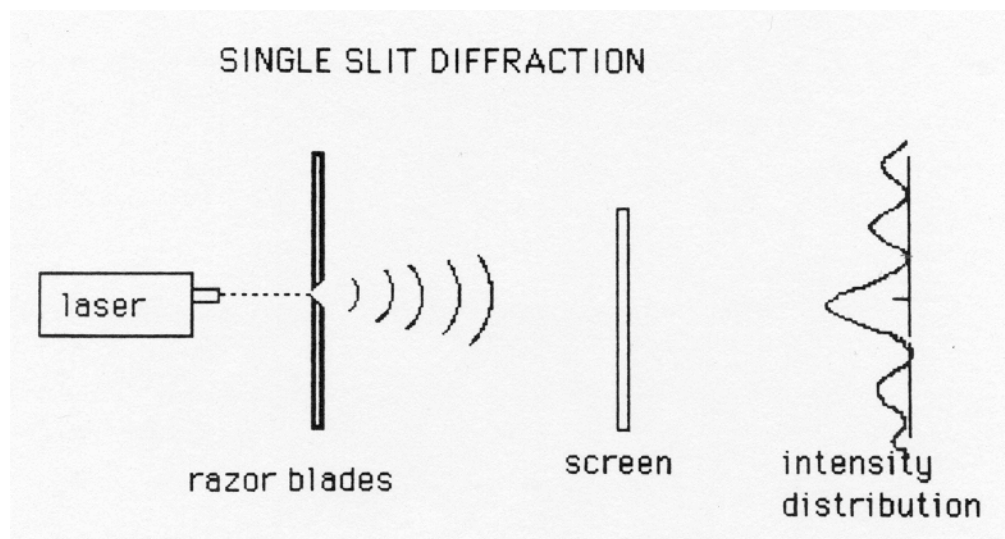
- Slide the edge of a razor blade part way into the laser beam using the magnetized razor blade holder and observe the interference patterns on the screen.
- Make a sketch of the pattern you see. Close observation will show that there is not a sharp shadow of the edge of the razor blade on the screen, but instead there is a diffraction pattern consisting of a series of bright and dark fringes parallel to the edge of the razor blade.
- Why does this pattern appear the way it does? What physical phenomenon is responsible for this pattern? Is light acting as a wave or as a particle now? Explain.



## Part 2. Single Slit

In this section of the experiment we will use a single slit which is nothing more than two knife-edges placed close to each other. We will observe how slit width affects the diffraction pattern and we will measure the thickness of a sheet of paper using our newfound knowledge of diffraction through slits.

- Use the same set-up as for part one above, but now attach a second razor blade into the magnetized holder so that the two blade edges are parallel and facing each other. Observe the diffraction pattern as you push the blades together.
- How does the diffraction pattern change as the blades are moved together or apart?



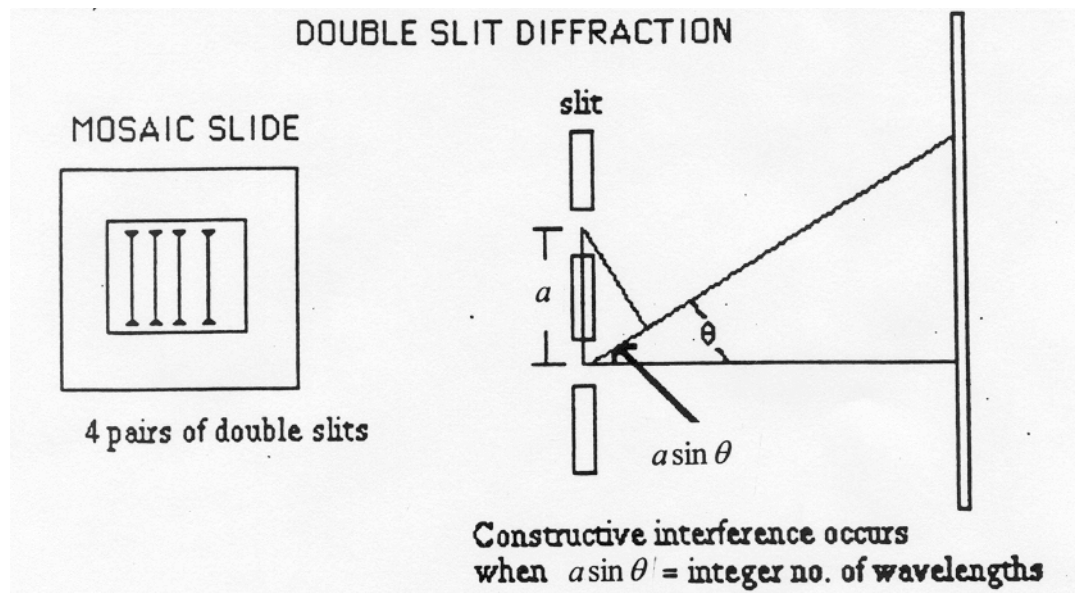
3. You will now measure the thickness of a sheet of paper
  - a. Insert a stack of two sheets of paper in between the razor blades and press the blades together.
  - b. Carefully slide the paper out from between the blades while holding the blades together.
  - c. Put this razor blade slit in the path of the laser beam and measure the distance from the slit to the screen (it should be about two meters). Call this distance  $L$ .
  - d. Measure the distance from the center of the central bright fringe to the center of the first black minimum on the left side. Call this distance  $X_L$ .
  - e. Measure the distance from the center of the central bright fringe to the center of the first black minimum on the right side. Call this distance  $X_R$ .
4. Calculate the values for width of the slit,  $D_1$  and  $D_2$  by using the equation given above. Remember that  $\theta$  is measured from the center of the central maximum to the first minimum. Since angles are small, you can use:  $\sin \theta = \tan \theta = X/L$ .  $\lambda$  is the wavelength of the laser.  $\lambda = 6.328 \times 10^{-7}$  meter.
5. Calculate the mean value of  $D_1$  and  $D_2$ . What is the thickness of a sheet of paper? (Remember the double thickness of a sheet of paper is equal the width of slit,  $D$ .)

Suggested data table:

$L$	$X_L$	$X_R$	$D_1$	$D_2$	$D$

### Part 3. Interference: Double Slits

When the laser beam is sent through two equal, narrow, parallel slits, each slit produces an identical diffraction pattern. If the slits are close enough together, the diffraction patterns overlap and interference occurs. In this part of the experiment we will observe double-slit diffraction and examine the characteristic diffraction and interference patterns produced as the slit widths and spacing are varied. You will use a diffraction slide, which has 4 pairs of double slits on the lower half of the slide. (It also has 3 diffraction gratings on the upper half of the slide.)

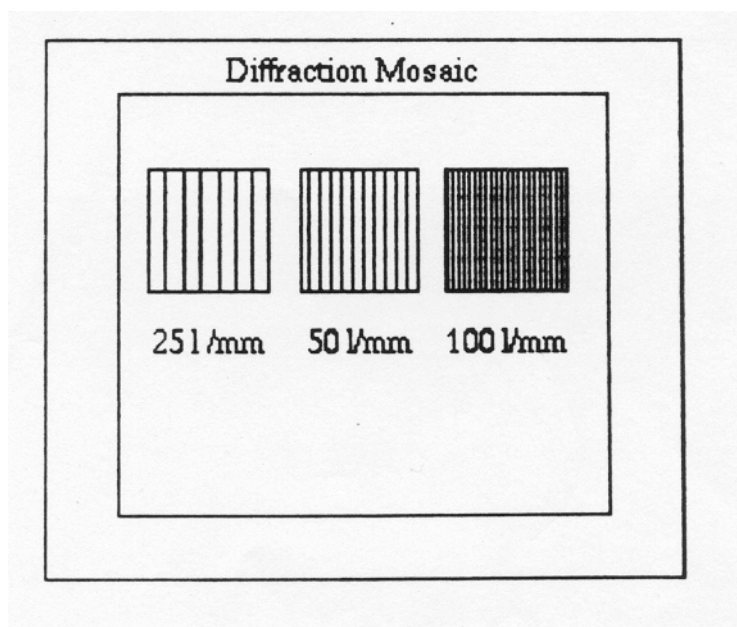


1. Place the diffraction slide mosaic in front of the laser so that the beam is transmitted through the first of the four sets of double slits. The first set of double slits is labeled  $25_u \times 25_u$ . The distance between the slits,  $a$ , is approximately  $4.5 \times 10^{-5}$  meter.
2. Observe the diffraction pattern that appears on a screen two meters from the slits. Sketch the diffraction pattern. And measure the distance ( $X_L$ ) from center of the central maximum to the center of first maximum on the left side. Measure the distance ( $X_R$ ) from center of the central maximum to the center of first maximum on the right side.
3. Repeat step 1-2 above, but this time using the second set of slits (labeled  $25_u \times 35_u$ ). These slits have same width as the first set but their separation,  $a$ , is approximately  $5.8 \times 10^{-5}$  meter. Compare this diffraction pattern with the diffraction pattern due to the first set of slits.

4. Repeat step 1-2 above, but this time using third set of slits (labeled  $25_u \times 50_u$ ). The separation,  $a$ , is approximately  $7.5 \times 10^{-5}$  meter. Compare this pattern with those produced by the first and second sets of slits.
5. Considering the findings and observations you made in steps 1-4, predict the resultant diffraction pattern of the fourth pair of slits (labeled  $50_u \times 50_u$ ). Slit width is twice that of the others and separation,  $a$ , is approximately  $10.0 \times 10^{-5}$  meter. Write your prediction.
6. Use the laser to see how accurate your guess was. Explain what happened (How close was your guess? What went wrong? Did you see anything unexpected?).
7. Calculate the exact separations,  $a$ , for each set. To do this you will use the equation:  $a \sin \theta = m\lambda$ , where  $m=1$ ,  $\sin \theta = \tan \theta = X/L$ .  $X$  is the mean value of  $X_L$  and  $X_R$ .  $L$  is 2 meters.

#### Part 4. Diffraction Gratings

When the laser beam is transmitted through a series of narrow evenly spaced parallel slits that are spaced close together, a much brighter pattern of fringes is observed than those due to a double-slit set-up. *An extended series of slits is called a diffraction grating.* In this part of the experiment, the diffraction and interference patterns produced by three diffraction gratings will be investigated. The diffraction gratings are on the upper part of the mosaic slide. Because photographic film shrinks during processing, all of the line spaces given in the instructions below are to be taken as approximate values.





1. Attach the diffraction grating to the magnetic holder at two meters away from screen. Align it so that the laser beam does through the diffraction grating with 25 lines/mm. Walk close to the screen and observe the diffraction pattern.
2. Make a sketch of the diffraction pattern and compare this pattern with the patterns for double-slits. Measure the distance ( $X_L$ ) from center of the central maximum to the center of first maximum on the left side. Measure the distance ( $X_R$ ) from center of the central maximum to the center of first maximum on the right side. Calculate the mean value,  $X$ , for  $X_L$  and  $X_R$ .
3. Repeat steps 1-2 for the diffraction grating with 50 lines/mm.
4. Repeat steps 1-2 for the diffraction grating with 100 lines/mm.
5. Calculate the actual number of lines per mm for each grating. To do this we will again use the following equation,  $a \sin \theta = m\lambda$ . Now  $a$  is the separation between the lines on the grating. Remember that  $[\text{\#lines/mm}] = [1/a]$  for  $a$  measured in mm.

# ATOMIC SPECTRA

## OBJECTIVE:

The basic objective of this experiment is to observe and measure the wavelength of discrete lines in the Hydrogen and Mercury spectrum. You'll also observe a continuous spectrum from an incandescent light source. To do this, you will assemble and use a simple grating spectroscope.

Another objective of this experiment is to understand how the Bohr theory of the atom is related to the Hydrogen spectrum.

## METHOD:

The grating constant must be obtained from a calibration using a spectral line of known wavelength. Satisfactory results can be obtained by using a Helium Neon laser, 632.8 nm, as a known calibration source.

You will do the following:

- a. Calibrate the grating using a Helium-Neon laser
- b. Measure three lines in the hydrogen spectrum
- c. Observe the mercury spectrum and measure the green line
- d. Observe a spectrum from a hot, incandescent body

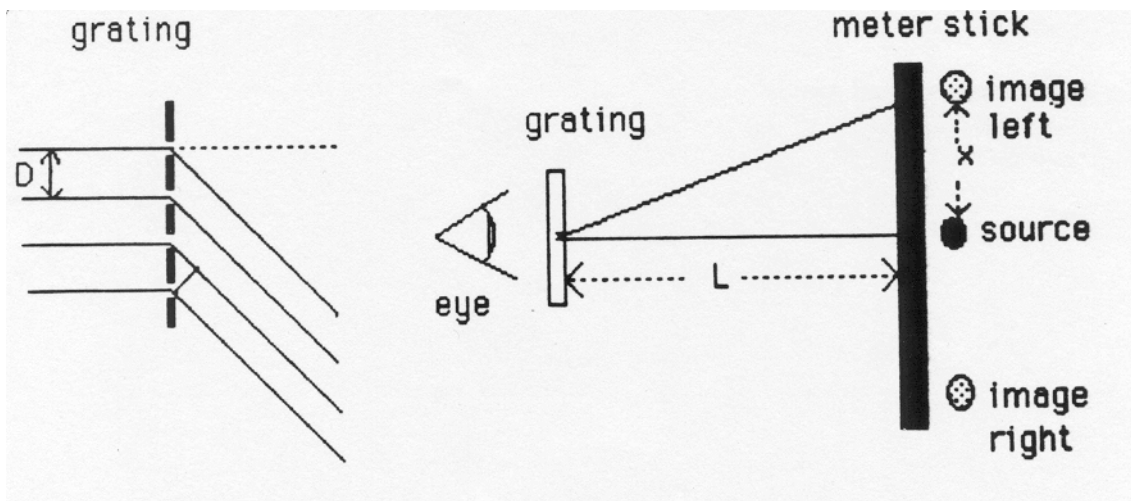
## APPARATUS:

Transmission diffraction grating, grating holder, mercury discharge tube, hydrogen discharge tube, power supplies and He-Ne laser.

## THEORY OF THE SPECTROMETER:

A simple grating spectrometer.

The diffraction grating can be used to disperse light from a source into its wavelength components. The simple apparatus you'll use today will allow you to see the entire spectrum at once. With some care and assistance from your lab partner you'll be able to measure the angle each color is diffracted. *Professional and research instruments are constructed that work on this same general principle. They measure the angles far more accurately than you will today.*



The wavelength can be calculated from the angle of diffraction. The grating needs to be approximately perpendicular to the incident beam. Then

$$n\lambda = d \sin \theta \quad (1)$$

where  $n$  = the order,  $\lambda$  = wavelength,  $d$  = grating constant, and  $\theta$  = the left or right angular deflection.

Measuring the angle can be done as shown in the illustration. When you look through the grating in the direction of the light source, several things can be seen. First, of course will be the source itself. You'll also be able to see a series of images of the source to the right [and left]. Notice that these images are of different colors. Your partner will need to help you locate the apparent positions of these images along the meter stick. Then the diffraction angle is found from the equation

$$\tan \theta = X/L \quad (2)$$

where  $X$  = the distance between the image and source [along the meter stick] and  $L$  = the distance from the source to the image.

[Note:  $\theta$  is not small, so the small angle approximation won't work!]

## ATOMIC SPECTRA AND BOHR THEORY OF THE ELECTRON

Another objective of this experiment is to compare your measured spectrum for hydrogen to the prediction of the Bohr theory of the hydrogen atom.

Neils Bohr developed a planetary-type model of the hydrogen atom to explain its spectrum. In this model electrons move in circular orbits around the nucleus (proton). He postulated that only orbits with special radii were allowed, each orbit having a different value for the electron energy. The lines that were observed in the spectrum of hydrogen atom were assumed to be light (photons) emitted by electrons changing from one discrete energy level to another. The energy of the levels in Bohr's model is:

$$E_1 = -\frac{13.6}{1^2} \text{ eV}, \quad E_2 = -\frac{13.6}{2^2} \text{ eV}, \quad E_3 = -\frac{13.6}{3^2} \text{ eV}, \quad E_n = -\frac{13.6}{n^2} \text{ eV, etc.}$$

Bohr postulated that when an electron goes from a higher energy orbit to a lower energy orbit, it emits a photon. To conserve energy, the change in the electron's energy,  $\Delta E_{\text{electron}} = E_{\text{photon}}$ . The energy of a photon is related to its wavelength by  $E_{\text{photon}} = hf = hc/\lambda_{\text{photon}}$ . Therefore, when an electron goes from its 3<sup>rd</sup> energy level to its 2<sup>nd</sup> energy level,

$$E_3 - E_2 = E_{\text{photon}}$$

$$\text{or} \quad -\frac{13.6}{3^2} \text{ eV} - \left(-\frac{13.6}{2^2} \text{ eV}\right) = 6.242 \times 10^{18} (hc/\lambda_{\text{photon}}) \text{ eV} \quad (3)$$

Electrons that end up in the 2nd energy level emit all of the lines of the hydrogen spectrum that you can see directly with your eyes.

## DETAILED PROCEDURE:

### Part 1. Grating Calibration

1. Shine the red laser light through the grating so that it lands on the center of the meter stick, and observe the series of red spots that are both to the right and left of the central image. [Don't look directly into the laser beam!]
2. Carefully measure the diffraction angle for the first spot to the right. Do this by measuring the distance to the screen and the distance from the central image. You will have to work with a partner to accomplish this. Use equation 2 to determine  $\theta$ .
3. After you've found the angle, then use this angle and the wavelength of the laser in equation 1 to calculate the value for the grating constant,  $d$ . Repeat this measurement for the first spot on the left. Take an average value of your results and use this in the rest of the experiment.

### Part 2. Measurement of the Hydrogen Spectra

1. Position the hydrogen source at the 50 cm mark of the meter stick. Look through the grating and observe the series of images. Describe what you see to the right and left of the source.
2. Locate three different color images along the meter stick and record their positions as accurately as you can. Also, carefully measure the distance,  $L$ , from the grating to the meter stick. Now use equation 2 to calculate the three angles of diffraction for each color image.

3. Use equation 1 to calculate the wavelengths. Use the value of  $d$ , the grating constant you found in part 1. Repeat your measurement using the spectral lines on the other side.
4. Compare the average values of each of your sets of measurements with the accepted value of 435.05, 486.13, and 656.28 nm. How accurate were your measurements? What is the main source of any discrepancy?
5. Calculate the energy of the photons in the red light. Compare this to  $E_3 - E_2$  for the electron. Repeat for the photons in the other colored lines. Compare with  $E_4 - E_2$  and  $E_5 - E_2$ . Does Bohr's theory work?

### **Part 3. Measurement of a Mercury Green Line**

1. Replace the hydrogen source with a mercury discharge lamp. Describe what you see when you look through the grating. Are the colors the same? Do you think that you could determine the type of atom by looking at its spectrum?
2. Measure the wavelength of the green line of mercury using the same technique you used for hydrogen.

### **Part 4. Observe a Continuous Spectrum**

1. Replace the mercury source with an incandescent lamp. Recall that tungsten or other incandescent lamp has a small filament of wire, which is electrically heated until it is hot enough to emit light. The light that you see is emitted from a solid material rather than individual atoms.
2. Describe what you see now. How does it differ from your previous results? What do you think cause the difference?

## Suggested Data Sheet

### Part 1. Grating Calibration

$$L = \text{_____ (cm)} \quad X = \text{_____ (cm)}$$

$$\tan\theta = X/L = \text{_____} \quad \theta = \text{_____}$$

$$\text{grating constant } d = \frac{\lambda}{\sin\theta} =$$

### Part 2. Hydrogen Spectra

Violet Line

$$L = \text{_____ (cm)} \quad X = \text{_____ (cm)}$$

$$\tan\theta = \quad \theta =$$

Blue Line

$$L = \text{_____ (cm)} \quad X = \text{_____ (cm)}$$

$$\tan\theta = \quad \theta =$$

Red Line

$$L = \text{_____ (cm)} \quad X = \text{_____ (cm)}$$

$$\tan\theta = \quad \theta =$$

# PHOTOELECTRIC EFFECT

## OBJECTIVE:

The major objective is for you to understand how the quantization of light explains the photoelectric effect.

## METHOD:

1. You will look the changes of current that flows through a vacuum phototube as the changes of the voltage applied between the anode and cathode. This will be done for two different light levels using the same color light. Also you will see they have same voltage needed to stop the photocurrent.
2. You will illuminate the phototube with different colors of monochromatic light and measure the amount of voltage needed to stop the photocurrent. From this information you will calculate a value of Planck's constant.

## APPARATUS:

Photoelectric Effect Module, digital voltmeter, mercury arc light, laser and three spectral filters.

The Photoelectric Effect Module consists of a 1P39 vacuum photodiode, a variable voltage supply that is applied to phototube, and a high gain amplifier and meter to read the current that flows through the phototube. Measurements are made of the photocurrent as a function of voltage that is applied across the photodiode. When light falls on the phototube surface, electrons are emitted and current can flow depending on the magnitude and polarity of the applied voltage.

## THEORY:

In the latter part of the 19<sup>th</sup> century, experiments showed that, when light is incident on certain metallic surfaces, electrons are emitted from the surfaces. This phenomenon is known as the **photoelectric effect**, and the emitted electrons are called **photoelectrons**.

Several features of the photoelectric effect could not be explained with classical physics or with the wave theory of light. The major observations that were not understood are as follows:

1. No electrons are emitted if the incident light frequency falls below some **cutoff frequency**,  $f_c$ , which is characteristic of the material being illuminated. This is inconsistent with the wave theory, which predicts that the photoelectric effect should occur at any frequency, provided the light intensity is high enough.
2. If the light frequency exceeds the cutoff frequency, a photoelectric effect is observed and the number of photoelectrons emitted is proportional to the light

intensity. However, the maximum kinetic energy of the photoelectrons is independent of light intensity, a fact that cannot be explained by the concepts of classical physics.

3. The maximum kinetic energy of the photoelectrons increases with increasing light frequency.
4. Electrons are emitted from the surface almost instantaneously, even at low light intensity.

A successful explanation of the photoelectric effect was given by Einstein in 1905. He assumed that light (or any electromagnetic wave) of frequency  $f$  can be considered a stream of photons. Each photon has an energy  $E$ , given by  $E = hf$ , where  $h$  is Planck's constant.

Einstein showed that the maximum kinetic energy,  $K_{\max}$ , of the electrons emitted from a surface is

$$K_{\max} = hf - \Phi, \quad (1)$$

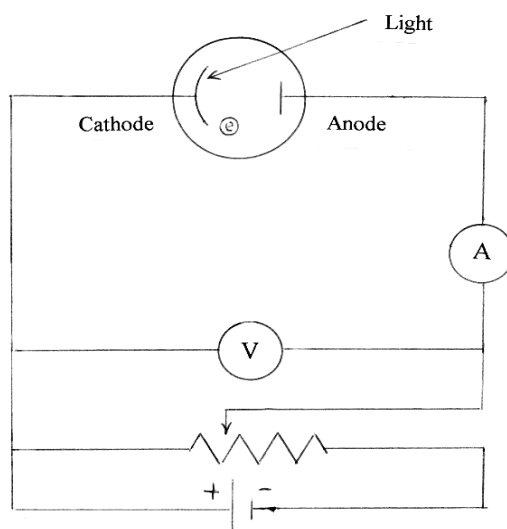
Where  $\Phi$  is the work function of surface,  $h$  is Planck's constant ( $h = 6.63 \times 10^{-34}$  Js),  $f$  is frequency of the light and  $K_{\max} = eV_s$ , where  $V_s$  is stopping voltage and  $e$  is the charge of the electron.

Equation 1 can be rearranged to

$$eV_s = hf - \Phi. \quad (2)$$

## METHOD:

The apparatus that you'll use to study the photoelectric effect and measure Planck's constant is shown in simplified form in the drawing below:





Light strikes the curved surface of the vacuum tube photocathode. If the wavelength is short enough, electrons are emitted from the surface of the cathode. If the anode post were made positive, then the electrons would be attracted to the positive terminal and current would flow in the circuit shown.

In this apparatus, we want to stop the flow of electrons, so the anode is made negative to stop the electron flow. The apparatus allows you to adjust the magnitude of the voltage that will just stop the photocurrent from flowing. The current detector internal to this apparatus has a sensitivity of approximately 1 nanoampere. When the photocurrent has been stopped, then the stopping voltage is measured with an external voltmeter.

## PROCEDURE:

1. Cover the aperture of the photoelectric module with an opaque card. Then adjust the zero control for zero meter reading. Also adjust the voltage adjustment to read zero on the DVM.
2. Replace the opaque card with a blue filter. Turn on the mercury lamp and position it 4 to 6 inches from the phototube. **CAUTION! DO NOT** look directly into the mercury lamp! Get the maximum reading you can on the meter.
3. Without disturbing the position of the lamp, increase the anode voltage. Record the voltage when the photocurrent reaches zero. That is stopping voltage. **NOTE:** Once the photocurrent reaches a zero value, further increases in the anode voltage have no effect on the current because it has all been stopped...so don't "pass" the voltage that corresponds to the zero current!...Note also that you can check the zero point by placing the opaque card in front of the detector opening, if the reading on the meter does not drop, then you are at the zero point.
4. Set the anode voltage to zero. Reposition the lamp further away so that the photocurrent is \_ of what it was in step 2. Then repeat step 3.
5. Repeat steps 2-3 using mercury lamp with green filter.
6. Repeat steps 2-3 using laser with red filter.

The colored filters are used to isolate the spectral lines and help stray room light. The filter-source combinations you'll be using are:

Mercury with blue filter	$f = 7.1 \times 10^{14} \text{ Hz}$
Mercury with green filter	$f = 5.5 \times 10^{14} \text{ Hz}$
Laser with red filter	$f = 4.7 \times 10^{14} \text{ Hz}$

## QUESTIONS:

1. How does your data for two levels of blue light show that the stopping voltage is independent of the intensity of the light? Discuss.
2. Explain why the blue light required a larger negative stopping voltage than the green light, and the green light required more stopping voltage than the red light.

## CALCULATIONS:

1. Plot the stopping voltage vs. frequency using three data points of blue light, green light and red light, and draw the best straight line you can through the points. (Plot  $V_s$  on the y-axis and  $f$  on the x-axis. Don't connect the dots – your best-fit line may not touch any of the three data points).
2. Find slope from your graph. The slope should equal  $\frac{h}{e}$ . Calculate a value for Planck's constant,  $h$ . ( $e = 1.6 \times 10^{-19}$  C is electron charge).
3. Compare your result to the accepted value for Planck's constant.
4. Calculate an approximate value for  $\Phi$ , the work function of the metal. Hint: just extend the line on your graph and find the approximate x-intercept. The x-intercept should equal  $\Phi/e$ .

## **APPENDICES**

**A-1 Graphical Presentation of Data**

**A-2 Summary of Error Analysis**

# GRAPHICAL PRESENTATION OF DATA

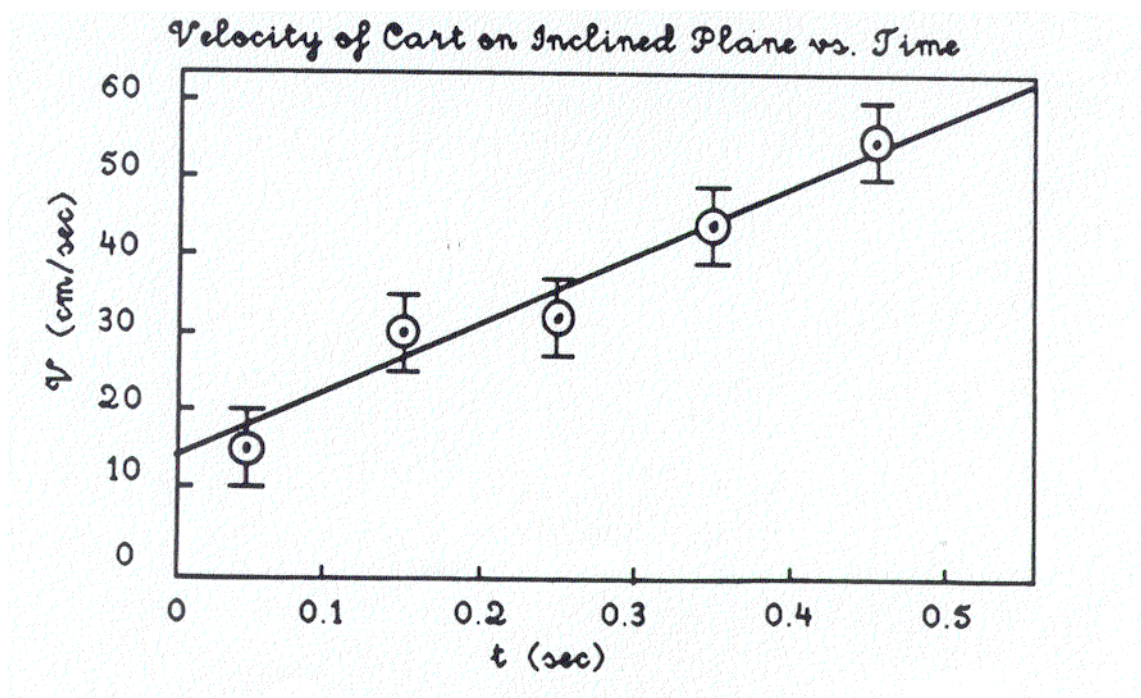
## INTRODUCTION

Good graphs often convey the essence and meaning of an experiment. One of the most important skills you will use in your physics labs is plotting and interpreting graphs.

## RULES for GRAPHING

The basic rules for graphing are summarized here and illustrated in the graph shown below. With a little practice, these rules will become automatic when you graph your data in lab.

1. Use words to title every graph.
2. Label the axes to show what is being plotted and what the units are.
3. Graphs should cover as much of a page in your notebook as possible.
4. Convenient scales should be selected to make it easy to plot and read numbers on the graphs. For example, scale divisions of 0.1 sec. are better than 0.15 sec.
5. By convention, the variable that you control is usually plotted on the x-axis.
6. If the points on the graph appear to lie on a straight line, draw the best straight line through the points (the one that passes as close to as many points as possible). If the points do not appear to lie on a straight line, draw a smooth curve that passes as close to as many data points as possible.
7. If the data points being plotted has an associated error or uncertainty this can be graphically represented by error bars. An error bar is a line through the data point with a length corresponding to the value.
8. Always place borders (small circle or square) around the data points.

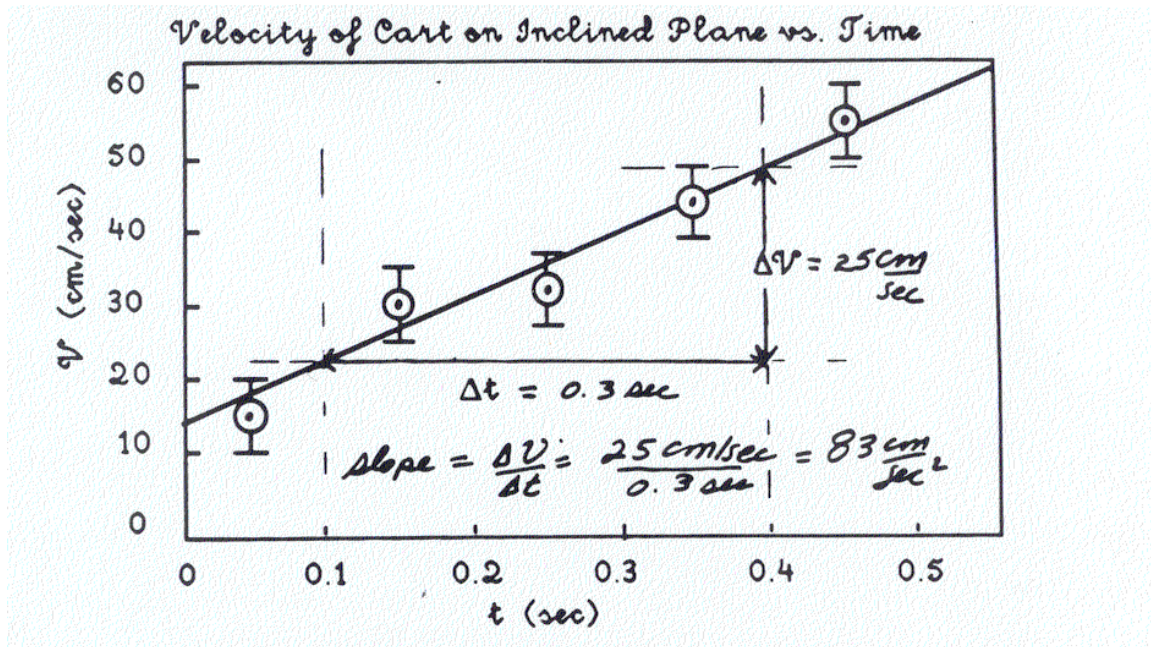


## GRAPHICAL ANALYSIS

If a graph yields a straight line, the quantities graphed have a linear relationship. This means that one variable is directly proportional to the other variable, and a simple equation for this can be written:  $y = mx + b$ . Graphs of this type are very useful: it is easy to find the values between data points (interpolation), and the line can be extended to find points outside the data range (extrapolation).

A linear graph has a constant slope (steepness). In the general equation for such a line ( $y = mx + b$ ), the slope is  $m$ . The slope can be either a positive or a negative number. If  $m$  is positive, the line slopes uphill. That is,  $y$  increases as  $x$  increases. If  $m$  is negative, the line slopes downhill, and  $y$  decreases as  $x$  increases. The quantity  $b$  is called the  $y$ -intercept. This is the value of  $y$  where the line intersects the  $y$ -axis. That is,  $b$  is the value of  $y$  when  $x = 0$ .

Applying this discussion to the above graph of velocity vs. time, we note that the graph is linear and the slope is positive. The equation that relates velocity to time ( $y$ -axis to the  $x$ -axis) is  $v = at + v_0$ . The slope,  $a$ , can be calculated from the graph, and the  $y$ -intercept,  $v_0$ , can be taken from the graph. This is illustrated below. For good accuracy, always measure the slope over as wide a range of  $\Delta x$  and  $\Delta y$  as possible. It is best to do the slope calculation on the graph as shown.



Many of the experiments will use this kind of graphical analysis to determine physical quantities. As you will learn in class, the slope of this line,  $a$ , corresponds to the acceleration of the cart, and the  $y$ -intercept,  $v_0$ , is the initial velocity of the cart.

## SUMMARY OF ERROR ANALYSIS

Every experimental quantity has an uncertainty: an estimate of how much you might reasonably expect the measured value to differ from the true value. This can be due to inaccuracy of the measuring instruments, difficulty in reading between scale divisions, human errors such as inconsistent reaction times, and many other causes. When comparing two numbers or determining an unknown, it is important to consider the degree of uncertainty, or error, that you think exists. You should always estimate and record the uncertainty in every measurement you make. Some rules for estimating uncertainty are summarized here.

Unfortunately, in data analysis the terms uncertainty and error are practically synonymous. Although “uncertainty” is less ambiguous, “error” is more commonly used in the literature. In this lab, we will largely conform to the accepted usage, but you should remind yourself now and again that “error” does not mean “mistake” -- it means “uncertainty”. The uncertainty can be expressed in two ways: Absolute Error and Relative Error.

### A. Absolute Error

This is an estimate of how much a measured quantity may differ from the true value, expressed in the same units.

For example, if you measure a length  $\ell$  as 50.0 cm and you think it is accurate within 2 mm ( $\Delta\ell = 0.2$  cm), then the length is expressed with the absolute error as

$$\ell = 50.0 \pm 0.2 \text{ cm}$$

### B. Relative Error

This is the ratio of the absolute error to the measured quantity, often expressed as a percentage:

$$\text{R. E.} = \frac{\Delta x}{x} \times 100\%$$

In the example above,

$$\text{R. E.} = \frac{\Delta\ell}{\ell} \times 100\% = \frac{0.2\text{cm}}{50.0\text{cm}} \times 100\% = 0.4\%$$

and the length is then expressed as

$$\ell = 50.0 \pm 0.4\%$$

### C. Significant Figures

After an uncertainty has been assigned to quantity, it is important that the quantity itself be specified only to this limit of accuracy. This is accomplished in writing  $\ell = 50.0 \pm 0.2$  cm since both the length and the uncertainty are given to tenths of a centimeter. It would be meaningless to specify  $\ell$  more exactly, such as  $\ell = 50.003 \pm 0.2$  cm, because the uncertainty is in the lengths place and thus nothing is known about the thousandths place. On the other hand, if the length is written as  $\ell = 50 \pm 0.2$  cm, accuracy is lost because you can't assume that 50 cm is the same as 50.0 cm (49.6 cm would round off to 50 cm, as would 50.4 cm). Thus, the three figures 50.0 are significant and are kept; all others are insignificant and are dropped.

### D. Accuracy of Repeated Measurements

Sometimes it is difficult to determine the best value of a quantity from one measurement, as in measuring a time interval with a stop clock when your reaction time can introduce an error. In these cases, it is useful to make several measurements and apply the following rules:

#### RULES FOR ACCURACY OF REPEATED MEASUREMENTS

1. The average value is the best answer.
2. The uncertainty is estimated by finding a range that contains most or all of the readings.

For example, if the time of an event is measured repeatedly:

<u>time (sec)</u>
2.02
2.14
1.92
1.82
2.08
1.92
2.18
2.00
2.06
1.96

The average of these times is

$$\bar{t} = 2.01 \text{ sec.}$$

The standard deviation,  $\sigma_N$ , is given by

$$\sigma_N = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N}}$$

and for this data  $\sigma = 0.10$  sec. So that, 70 % of the readings fall within the range  $(2.01 - 0.10) < t < (2.01 + 0.10)$ . The time is then expressed as

$$t = 2.01 \pm 0.10 \text{ sec.}$$

or, as a relative error,

$$t = 2.01 \text{ sec.} \pm 5\%$$

### E. Uncertainty in Scale Readings

If a measurement does not line up exactly with a scale marking, it is necessary to interpolate: estimate the position between scale markings. When using scales with marking close together, like mm markings on a meter stick, it is common to read to the nearest division and estimate the uncertainty as  $\frac{1}{2}$  of the scale division, such as  $36.0 \pm 0.5$  mm. On scales with wider markings, it may be possible to interpolate more accurately, such as measuring  $t = 23.6 \pm 0.2$  sec. with the stop clock.

Different observers might disagree on the precise size of the uncertainty; determine for yourself what you consider a reasonable estimate of this range.

As with other techniques of error analysis, this must be used with judgement. For example, in section D above where the range is  $\pm 0.02$  sec., then this uncertainty can be ignored since it is much smaller than the uncertainty due to repeated measurements.

### F. Accuracy of Graphical Results

When you construct a graph you make a judgement as to what constitutes the best-fit line through the data points, since all the points are not on the line. Thus, there is a question of accuracy since you probably don't draw the "absolute" best line. An estimate of the uncertainty is obtained from one of these two methods:



## RULES FOR ACCURACY OF GRAPHICAL RESULTS

- 1a. Have you and your partner make independent graphs of the same data. Take the difference between the slope values as the absolute error.

OR

- 1b. If you're working by yourself, draw another "best-fit" line that differs from the first. But still fits the data. Again, take the difference in the slopes as the uncertainty.

### G. Discrepancy

Experiments often conclude with a comparison of experimental and theoretical results. The two are rarely exactly the same, so you have to decide if they are in reasonable agreement. To do this, find the discrepancy (the difference between the two numbers) and compare it to the uncertainty of both numbers.

This is a general method of determining the validity of experimental results and can be used in all experiments, in physics and elsewhere that involves the comparison of two numbers.

The discrepancy is expressed as an absolute number or a percentage. For example, if two accelerations are:

$$a_{\text{ex}} = 42.5 \text{ cm/sec}^2$$

and

$$a_{\text{th}} = 42.8 \text{ cm/sec}^2$$

then the absolute discrepancy is

$$0.3 \text{ cm/ sec}^2$$

or, expressing it as a percentage, the relative discrepancy is

$$\frac{|a_{\text{th}} - a_{\text{ex}}|}{a_{\text{th}}} \times 100\% = 0.7\%$$

Without further analysis, the discrepancy tells you a lot about your experiment. If it is very small, like 0.1%, then the agreement is very good and you also are lucky, since this is about the limit of accuracy of most of the measuring equipment. If it is around 1%, you can probably find an explanation by carefully looking at the uncertainties that randomly appear in the experiment. If it is large, like 10%, then you can strongly suspect a gross error, which is almost always human (i. e., yours).

## H. Putting It All Together

Which is bigger, your discrepancy or your uncertainties? If your uncertainties are larger, you can say with some confidence that the theory is justified.

If the discrepancy is larger, then you cannot claim that the theory is verified. However, don't jump to a rash conclusion that the theory is wrong. Instead, first check your work to make sure you didn't make a mistake. If not, then consider systematic errors that could affect the results. Remember, the uncertainties that you determine are estimates of random errors. Uncertainties do not reflect systematic errors such as friction or a consistent mismeasurement of a quantity.

If you suspect a particular systematic error is present, relate it to the experimental findings. For example, in an air track experiment, if the measured acceleration  $a_{\text{ex}}$  is lower than predicted by theory, you could hypothesize that this was due to friction. On the other hand if  $a_{\text{ex}}$  is higher than  $a_{\text{th}}$ , friction would not be a reasonable explanation, but a recheck of the levelness of the track or the value of the mass might lead to something. Your results are always meaningful if you think about the physics of the experiments.