# Physics 5C Lab Manual

UCLA Physics and Astronomy Department

Primary authors: Art Huffman, Ray Waung

# Introduction

## OVERVIEW

This lab series is very similar to the Physics 6A and 6B series. Please refer to those lab manuals for general information.

Important: This manual assumes that you have already taken the Physics 7A and 7B labs, and that you are familiar with Microsoft Excel. In addition, it assumes that you are able to perform all the operations associated with Pasco Capstone (particularly for Experiment 5); call up sensors; use them to take various measurements; produce, title, label, and vary the appearance of graphs; perform calculations on the measured variables in Capstone, and use the results to create graphs.

Note to TAs: You should have taught a Physics 7A lab section before teaching a 7C lab. If you have not, you should make sure that you have gone through all the Capstone operations for an experiment (particularly Experiment 5) before teaching it.

Note to Instructors: The thermodynamics experiment, Experiment 5, requires two lab sessions to complete. It consists of two parts: a measurement of absolute zero using the Ideal Gas Law, and an experiment with a heat engine. For the experiment to be assigned two sessions, you would have to make the request at the beginning of the quarter, and possibly omit the radioactivity or photoelectric experiment. If you take no action, the default option is that the experiment will be assigned one session, and the students will just do the absolute zero measurement. (Later in the quarter up to the week before the experiment, you could request that the students do the heat engine part of the experiment instead of the absolute zero measurement.

It is essential that you follow the general rules about taking care of equipment and reading the lab manual before coming to class.

As before:

| | |
|---|---|
| Lab grade = | (12.0 points) |
| | − (2.0 points each for any missing labs) |
| | + (up to 2.0 points earned in mills of “additional credit”) |
| | + (up to 1.0 point earned in “TA mills”) |
| Maximum score = | 15.0 points |

Typically, most students receive a lab grade between 13.5 and 14.5 points, with the few poorest students (who attend every lab) getting grades in the 12s and the few best students getting grades in the high 14s or 15.0. There may be a couple of students who miss one or two labs without excuse and receive grades lower than 12.0.

How the lab score is used in determining a student’s final course grade is at the discretion of the individual instructor. However, very roughly, for many instructors a lab score of 12.0 represents approximately B− work, and a score of 15.0 is A+ work, with 14.0 around the B+/A− borderline.

## POLICY ON MISSING EXPERIMENTS

1. In the Physics 6 series, each experiment is worth two points (out of 15 maximum points). If you miss an experiment without excuse, you will lose these two points.

2. The equipment for each experiment is set up only during the assigned week; you cannot complete an experiment later in the quarter. You may make up no more than one experiment per quarter by attending another section during the same week and receiving permission from the TA of the substitute section. If the TA agrees to let you complete the experiment in that section, have him or her sign off your lab work at the end of the section and record your score. Show this signature/note to your own TA.

3. (At your option) If you miss a lab but subsequently obtain the data from a partner who performed the experiment, and if you complete your own analysis with that data, then you will receive one of the two points. This option may be used only once per quarter.

4. A written, verifiable medical, athletic, or religious excuse may be used for only one experiment per quarter. Your other lab scores will be averaged without penalty, but you will lose any mills that might have been earned for the missed lab.

5. If you miss three or more lab sessions during the quarter for any reason, your course grade will be Incomplete, and you will need to make up these experiments in another quarter. (Note that certain experiments occupy two sessions. If you miss any three sessions, you get an Incomplete.)

# Electrostatics

## APPARATUS

- Heat lamp
- Timer
- Two Lucite rods
- Rough plastic rod
- Silk
- Cat fur
- Stand with stirrup holder
- Pith balls on hanger
- Electroscope
- Electrophorus
- Coulomb's Law (charging pads not needed)

## INTRODUCTION

This experiment consists of many short demonstrations in electrostatics. In most of the exercises, you do not take data, but record a short description of your observations. If high-humidity conditions prevent you from completing certain parts, you may try them again next week with the Van de Graaff experiments.

## THEORY

The fundamental concept in electrostatics is *electrical charge*. We are all familiar with the fact that rubbing two materials together — for example, a rubber comb on cat fur — produces a "static" charge. This process is called *charging by friction*. Surprisingly, the exact physics of the process of charging by friction is poorly understood. However, it is known that the making and breaking of contact between the two materials transfers the charge.

The charged particles which make up the universe come in three kinds: positive, negative, and neutral. Neutral particles do not interact with electrical forces. Charged particles exert electrical and magnetic forces on one another, but if the charges are <u>stationary</u>, the mutual force is very simple in form and is given by Coulomb's Law:

$$F_{\mathrm{E}} = kqQ/r^2, \tag{1}$$

where $F_{\mathrm{E}}$ is the electrical force between any two stationary charged particles with charges $q$ and $Q$ (measured in coulombs), $r$ is the separation between the charges (measured in meters), and $k$ is a constant of nature (equal to $9\times10^9$ Nm$^2$/C$^2$ in SI units).

The study of the Coulomb forces among arrangements of stationary charged particles is called *electrostatics*. Coulomb's Law describes three properties of the electrical force:

1. The force is inversely proportional to the square of the distance between the charges, and is directed along the straight line that connects their centers.

2. The force is proportional to the product of the magnitude of the charges.

3. Two particles of the same charge exert a repulsive force on each other, and two particles of opposite charge exert an attractive force on each other.

Most of the common objects we deal with in the macroscopic (human-sized) world are electrically neutral. They are composed of atoms that consist of negatively charged electrons moving in quantum motion around a positively charged nucleus. The total negative charge of the electrons is normally exactly equal to the total positive charge of the nuclei, so the atoms (and therefore the entire object) have no net electrical charge. When we charge a material by friction, we are transferring some of the electrons from one material to another.

Materials such as metals are *conductors*. Each metal atom contributes one or two electrons that can move relatively freely through the material. A conductor will carry an *electrical current*. Other materials such as glass are *insulators*. Their electrons are bound tightly and cannot move. Charge sticks on an insulator, but does not move freely through it.

A neutral particle is not affected by electrical forces. Nevertheless, a charged object will attract a neutral macroscopic object by the process of *electrical polarization*. For example, if a negatively charged rod is brought close to an isolated, neutral insulator, the electrons in the atoms of the insulator will be pushed slightly away from the negative rod, and the positive nuclei will be attracted slightly toward the negative rod. We say that the rod has *induced* polarization in the insulator, but its net charge is still zero. The polarization of charge in the insulator is small, but now its positive charge is a bit closer to the negative rod, and its negative charge is a bit farther away. Thus, the positive charge is attracted to the rod more strongly than the negative charge is repelled, and there is an overall net attraction. (Do not confuse electrical polarization with the polarization of light, which is an entirely different phenomenon.)

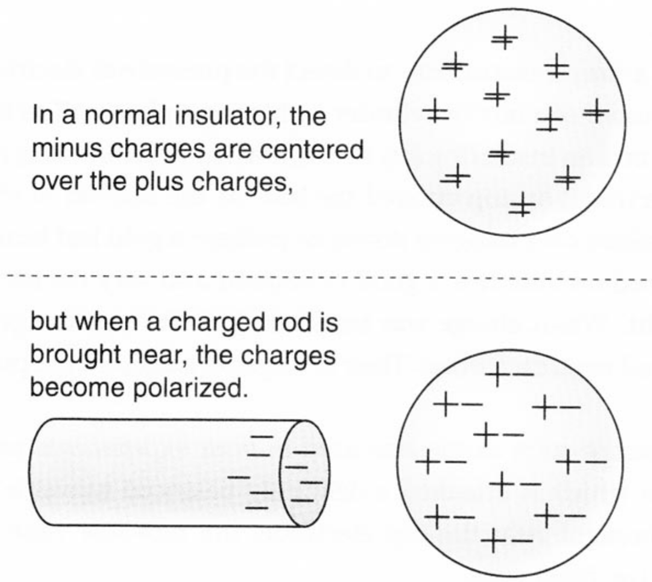



***Figure 1***

If the negative rod is brought near an isolated, neutral conductor, the conductor will also be polarized. In the conductor, electrons are free to move through the material, and some of them are repelled over to the opposite surface of the conductor, leaving the surface near the negative rod with a net positive charge. The conductor has been polarized, and will now be attracted to the charged rod.

Now if we connect a conducting wire or any other conducting material from the polarized conductor to the ground, we provide a "path" through which the electrons can move. Electrons will actually move along this path to the ground. If the wire or path is subsequently disconnected, the conductor as a whole is left with a net positive charge. The conductor has been charged without actually being touched with the charged rod, and its charge is opposite that of the rod. This procedure is called *charging by induction.*

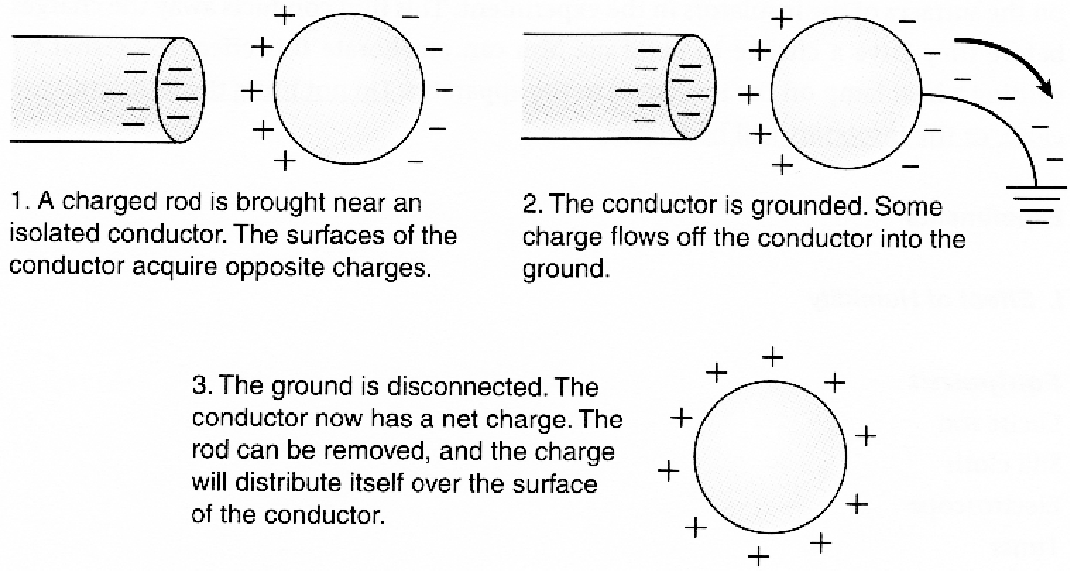



***Figure 2.*** *Charging by induction.*

## THE ELECTROSCOPE

An electroscope is a simple instrument to detect the presence of electric charge. The old electroscopes consisted of a box or cylinder with a front glass wall so the experimenter could look inside, and an insulating top through which a conducting rod with a ball or disk (called an electrode) on top entered the box. At the bottom of the rod, very thin gold leaves were folded over hanging down, or perhaps a gold leaf hung next to a fixed vane. Gold was used because it is a good conductor and very ductile; it can be made very thin and light. When charge was transferred to the top, the gold leaves would become charged and repel each other. Their divergence indicated the presence of charge.

A modern electroscope such as the one used in your experiments consists of a fixed insulated vane, to which is attached a delicately balanced movable vane or needle. When charge is brought near the top electrode, the movable vane moves outward, being repelled by the fixed vane.

## ELECTROSTATICS AND HUMIDITY

We are all familiar with the fact that cold, dry days are "hot" for electrostatics, and we get small shocks after walking across a rug and touching a door knob, or sliding across a car seat and touching the metal of the car door. If the humidity is fairly low on the day of your lab, the experiments will proceed easily. If the humidity is extremely low, as is often the case in Southern California, you will probably not escape the lab without a direct experience with electrostatics! If the humidity is high, as it is sometimes in the summer, the experiments are more difficult, and some may be impossible.

If the experiments are difficult on the first week of the electrostatics lab, they will be left up so you can try some of them with the Van de Graaff experiments in the following lab.

When the air is humid, a thin, invisible film of water forms on all surfaces, particularly on the surfaces of the insulators in the experiment. This film conducts away the charges before they have a chance to build up. You can ameliorate this effect somewhat by shining a heat lamp on the insulators in the apparatus. Do not bring the heat lamp too close, or the insulators will be melted.

## EXPERIMENTS

### I. *EFFECT OF HUMIDITY*

#### *Equipment*

- Lucite rod
- Silk cloth
- Electroscope
- Timer

#### *Procedure*

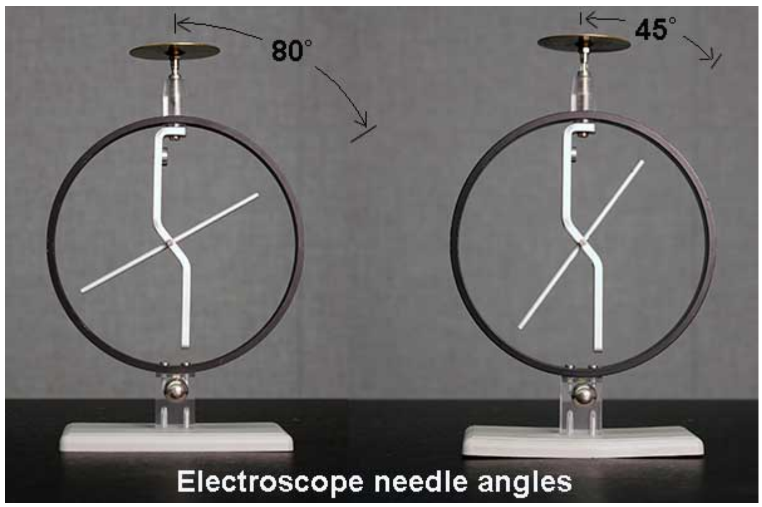
1. Record your observations in writing either on the computer (e.g., in Microsoft Word) or on your own paper. If writing by hand, write clearly, legibly, and neatly so that anyone, especially your TA, can read it easily. Start each observation with the section number and step number (e.g., I-2 for the step below). You do not need to repeat the question. Not all steps have observations to record.

2. Record in your notes the relative humidity in the room (from the wall meter) and the inside and outside temperature.

3. For this experiment, do not shine the flood lamp on the electroscope. Be prepared to start your timer. You may use the stopwatch function of your wristwatch.

4. Rub the lucite rod vigorously with the silk cloth. Use a little whipping motion at the end of the rubbing. Touch the lucite rod to the top of the electroscope. Move the rod along and around the top so you touch as much of its surface to the metal of the electroscope as possible. Since the rod is an insulator, charge will not flow from all parts of the rod onto the electroscope; you need to touch all parts (except where you are holding it) to the electroscope. Start your timer immediately after charging the electroscope.

5. Record the time it takes the electroscope needle to fall completely to 0°. Time up to five minutes, if necessary. If the needle has not fallen to 0° after five minutes, record an estimate of its angle at the five-minute mark. Typically, after charging, the needle might be at 80°.




6. If the electroscope needle falls to 0° in a few minutes, the heat lamp will help in the experiments below. If the needle falls to 0° in 15 seconds or so, as it does on some summer days, you will probably have difficulty completing the experiments, even with the help of the heat lamp. If this is the case, you can try again next week.

## *II.* ***ATTRACTION AND REPULSION OF CHARGES***

In this section, you will observe the characteristics of the two types of charges, and verify experimentally that opposite charges attract and like charges repel.

### ***Equipment***

- Two lucite rods
- One rough plastic rod
- Stand with stirrup holder
- Silk cloth
- Cat's fur

***Procedure***

1. Charge one lucite rod by rubbing it vigorously with silk. Place the rod into the stirrup holder as shown in Figure 7.

2. Rub the second lucite rod with silk, and bring it close to the first rod. What happens? Record the observations in your notes.

3. Rub the rough plastic rod with cat's fur, and bring this rod near the lucite rod in the stirrup. Record your observations.

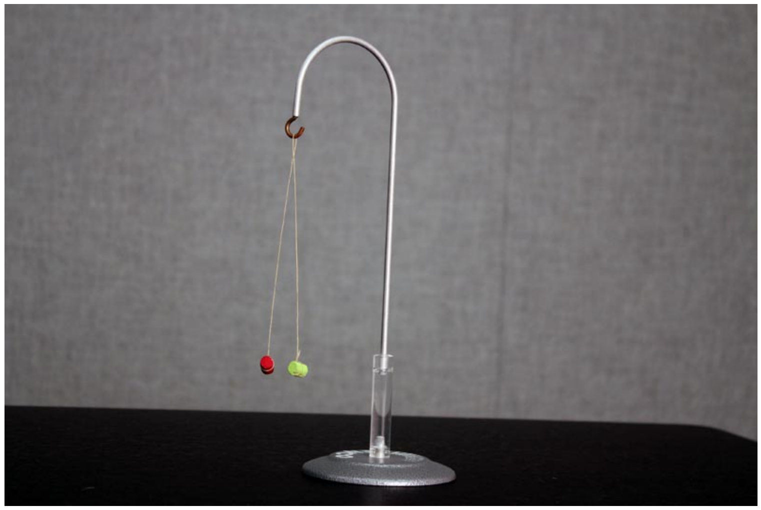
For reference purposes, according to the convention originally chosen by Benjamin Franklin, the lucite rods rubbed with silk become positively charged, and the rough plastic rods rubbed with cat's fur become negatively charged. Hard rubber rods, which are also commonly used, become negatively charged.

## *III.* ***PITH BALLS***

In this section, you will observe the induced polarization of a neutral insulator and the transfer of charge by contact.

***Equipment***

- Hanger with pith balls
- Lucite rod
- Rough plastic rod
- Silk cloth
- Cat's fur



***Procedure***

(The heat lamp may help to minimize humidity near the pith balls.)

1. Touch the pith balls with your fingers to neutralize any charge.

2. Charge the lucite rod by rubbing it with silk.

3. Bring the lucite rod close to (but not touching) the pith balls. Observe and record what happens to the balls. Explain your results. (Refer to the theory section, if necessary.)

4. Touch the pith balls with your finger to discharge them. Recharge the lucite rod with silk.

5. Touch the pith balls with the lucite rod. (Sometimes it is necessary to touch different parts of the rod to the balls.) Then bring the rod near one of the balls. What happens? Record and explain your results.

6. Charge the rough plastic rod with cat's fur. How does the plastic rod affect the pith balls after they have been charged with the lucite rod? Record your results.

## *IV.* ***CHARGING BY INDUCTION***

***Equipment***

- Electroscope
- Lucite rod
- Rough plastic rod
- Silk cloth
- Cat's fur

***Procedure***

1. Charge the lucite rod by rubbing it with silk.
2. Bring the lucite rod near (but not touching) the top of the electroscope, so that the electroscope is deflected.
3. Remove the lucite rod. What happens? Record the results your notes. Use several sentences and perhaps a diagram or two to explain the behavior of the charges in the electroscope.
4. Bring the lucite rod near the electroscope again so that it is deflected. Hold the rod in this position, and briefly touch the top of the electroscope with your other finger. Keep the rod in position. What happens? Record the results in your notes.
5. Now remove the lucite rod. If you have done everything correctly, the electroscope should have a permanent deflection. Diagram in your notes what happened with the charges. (Refer to the theory section, if necessary.)
6. With the electroscope deflected as a result of the operations above, bring the charged lucite rod near the electroscope again. Remove the lucite rod, and bring a charged rough plastic rod near the electroscope. What happens in each case? Record the results in your notes.

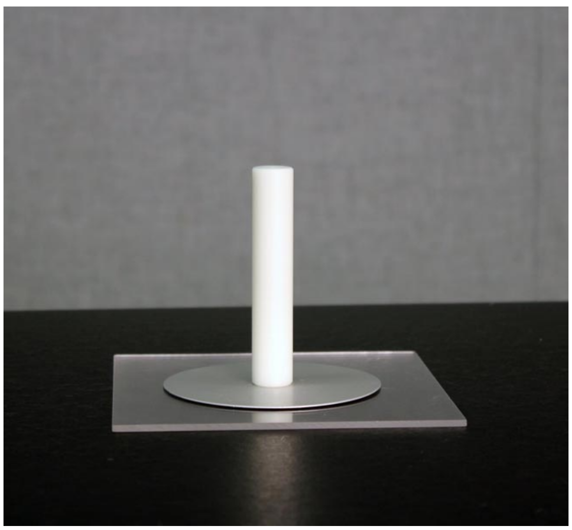
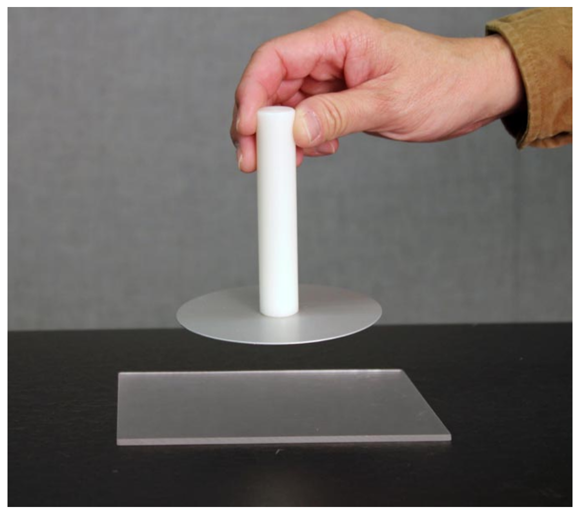
## *V.* ***ELECTROPHORUS***

The electrophorus is a simple electrostatic induction device invented by Alessandro Volta around 1770. Volta characterized it as “an inexhaustible source of charge”. In its present form, the electrophorus consists of a lucite plate on which rests a flat metal plate with an insulating handle.

The lucite plate is positively charged by being rubbed with silk. Because lucite is an insulator, it remains charged until the charge leaks off slowly. The metal plate does not pick up this positive charge, even though it rests on the lucite. The plate actually makes contact with the lucite in only a few places; and because lucite is an insulator, charge does not transfer easily from it. Instead, when you touch the metal plate, electrons from your body (attracted by the positive lucite plate) flow onto the metal plate. Your body thus acts as an “electrical ground”. The metal plate is negatively charged by induction. Because the positive charge is not “used up”, the metal plate can be charged repeatedly by induction.

***Equipment***

- Electrophorus
- Silk cloth
- Electroscope
- Neon tube

***Procedure***

(The heat lamp shining on the equipment may improve its operation.)

1. Charge the electrophorus lucite plate by rubbing it with silk. A whipping motion toward the end of the rubbing may help. Usually the lucite needs to be charged only once for the entire experiment.

2. Place the metal plate on the center of the lucite plate, and touch it with your finger. (You may feel a slight shock.)

3. Hold the metal plate by its insulating handle as far from the metal as possible. Bring the metal to within 2 cm of your knuckle, and then slowly closer until a (painless) spark jumps.

4. Recharge the metal plate by placing it back on the lucite, touching the lucite, and then lifting the plate off with its insulating handle. Bring it near your lab partner’s knuckle.

5. Repeat the procedure until you have experienced several sparks. What is the average distance a spark will jump? Record this distance in your notes.

6. Recharge the metal plate, and bring it slowly near the top of the electroscope. Observe what happens with the electroscope needle.

7. Move the plate away from the electroscope, and record what happens with the electroscope needle. Is it still deflected? Why or why not?

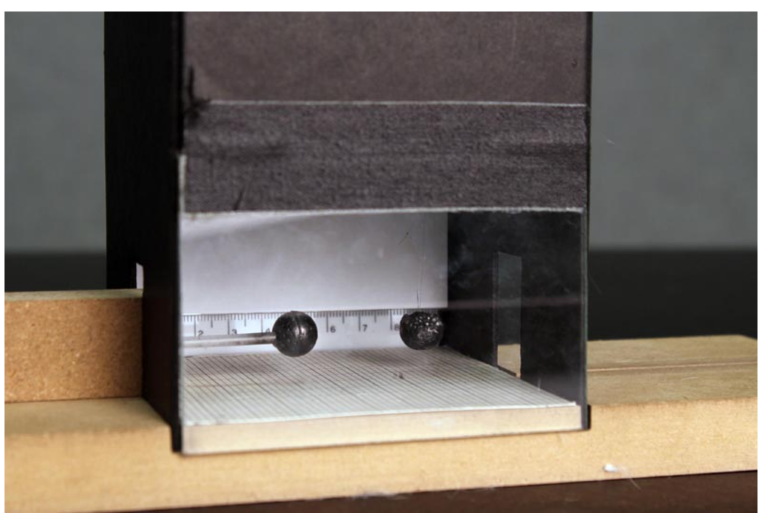
8. Recharge the metal plate, and actually touch it to the top of the electroscope. Set the metal plate aside. Observe what happens with the electroscope needle. Is there any difference in the behavior of the needle compared to the results in procedure 6? If so, how do you account for the difference? Record this explanation in your notes.

9. Once again, recharge the metal plate. Hold one end of the neon tube with your fingers, and bring the metal plate slowly closer to the other end. Observe what happens with the neon tube. The induced current should create a brief flash of light. By grounding the end of the tube with your fingers, you are providing a pathway for the charges to move.

10. In this section, you charged the lucite plate by rubbing it at the beginning, and were then able to charge the metal plate repeatedly. Where does the charge on the metal plate come from? Where does the energy that makes the sparks and lights the tube come from? Comment in your notes.

## *VI.* ***COULOMB'S LAW***

You will be testing the inverse $r$-squared dependence of Coulomb's Law with a very simple apparatus. There is a tall box containing a hanging pith ball covered with a conducting surface, and similar pith balls on sliding blocks. A mirrored scale permits you to determine the position of the balls. (The purpose of the closed box is to minimize the effects of air currents.)



The displacement $d$ of the hanging ball from its equilibrium position depends on the electrical force $F$ which repels it from the sliding ball. The force triangle of Figure 10 gives

$$\tan\phi = F/mg, \tag{2}$$

while the physical triangle of the hanging ball gives

$$\sin\phi = d/L. \tag{3}$$

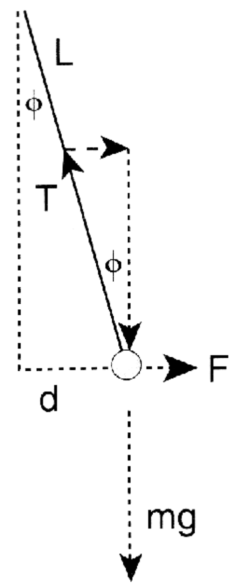
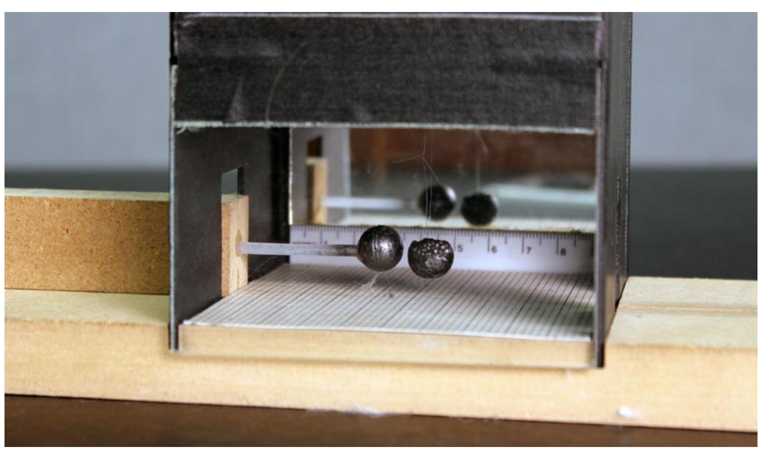



*Figure 10*

If the angle $\phi$ is small, then $\tan\phi = \sin\phi$, and $d$ is proportional to $F$. Therefore, to demonstrate the inverse $r$-squared dependence of Coulomb's Law, we need to measure the displacement as a function of the separation between the centers of the balls.

The purpose of the mirror is to minimize parallax errors in reading the scale. For example, to measure to position of the front of the hanging ball, line up the front edge of the ball with its image. Your eye is now perpendicular to the scale, and you can read off the position. Figure 11 below shows the situation where your eye is still too high and to the right.



***Equipment***

- Coulomb's Law apparatus
- Electrophorus
- Silk cloth

***Procedure***

1. Take a moment to check to position of the hanging ball in your Coulomb apparatus. Look in through the side plastic window. The hanging ball should be at the same height as the sliding ball (i.e., the top of the mirrored scale should pass behind the center of the hanging pith ball, as in Figure 12 below). Lift off the top cover and look down on the ball. The hanging ball should be centered on a line with the sliding balls. If necessary, adjust carefully the fine threads that hold the hanging ball to position it properly.

2. Charge the metal plate of the electrophorus in the usual way by rubbing the plastic base with silk, placing the metal plate on the base, and touching it with your finger.

3. Lift off the metal plate by its insulating handle, and touch it carefully to the ball on the left sliding block.

4. Slide the block into the Coulomb apparatus without touching the sides of the box with the ball. Slide the block in until it is close to the hanging ball. The hanging ball will be attracted by polarization, as in Section III of this lab. After it touches the sliding ball, the hanging ball will pick up half the charge and be repelled away. Repeat the procedure if necessary, pushing the sliding ball up until it touches the hanging ball.

5. Recharge the sliding ball so it produces the maximum force, and experiment with pushing it toward the hanging ball. The hanging ball should be repelled strongly.

6. You are going to measure the displacement of the hanging ball. You do not need to measure the position of its center, but will record the position of its inside edge. Remove the sliding ball and record the equilibrium position of its inside edge that faces the sliding ball, which you will subtract from all the other measurements to determine the displacement $d$.

7. Put the sliding ball in, and make trial measurements of the inside edge of the sliding ball and the inside edge of the hanging ball. The difference between these two measurements, plus the diameter of one of the balls, is the distance $r$ between their centers. Practice taking measurements and compare your readings with those of your lab partner until you are sure you can do them accurately. Try to estimate measurements to 0.2 mm.

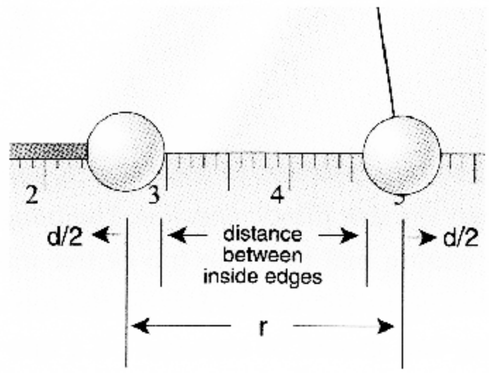



***Figure 12.*** *The positions of the inside edges are marked. The difference between these positions plus the diameter of one ball is the distance between the centers of the balls.*

8. Take measurements, and record the diameter of the balls (by sighting on the scale).

9. Remove the sliding ball, and recheck the equilibrium position of the inside edge of the hanging ball.

10. You can record and graph data in Excel or by hand (although if you work by hand, you will lose the opportunity for 2 mills of additional credit below). Recharge the balls as in steps 1 – 4, and record a series of measurements of the inside edges of the balls. Move the sliding ball in steps of 0.5 cm for each new measurement.

11. Compute columns of displacements $d$ (position of the hanging ball minus the equilibrium position) and the separations $r$ (difference between the two recorded measurements plus the diameter of one ball).

12. Plot (by hand or with Excel) $d$ versus $1/r^2$. Is Coulomb's Law verified?

13. For an additional credit of 2 mills, use Excel to fit a power-law curve to the data. What is the exponent of the $r$-dependence of the force? (Theoretically, it should be $-2.000$, but what does your curve fit produce?)

14. For your records, you may print out your Excel file with a table and graph of your numerical observations and any other electronic files you have generated.

## ADDITIONAL CREDIT (3 mills)

You can change the charge on the sliding ball by factors of two, by touching it to the other uncharged sliding ball (ground it with your finger first). The balls will share their charge, and half the charge will remain on the first ball (assuming the balls are the same size). This way, you can obtain charges on the first ball of $Q$, $Q/2$, $Q/4$, and so forth.

Devise and execute an experiment to verify the dependence of the Coulomb force on the value of one of the charges. (That is, we want to show that the force is proportional to one of the charges.) The method is up to you; explain your plan and results in your notes. What should you plot against what? Does anything need to be held constant?

# Van de Graaff

## APPARATUS

- Heat lamp
- Electroscope
- Lucite rod and silk
- Van de Graaff generator
- Grounding sphere
- Ungrounded sphere
- Faraday cage
- Faraday pail
- Plastic box to stand on

## INTRODUCTION

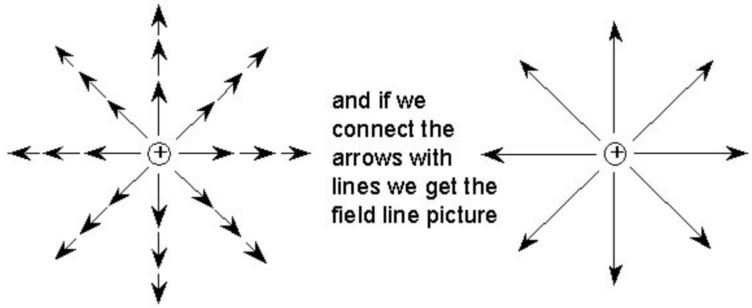
In this experiment, we will continue our study of electrostatics using a Van de Graaff electrostatic generator. If the electrostatics experiments were difficult because of humidity during the previous week, we will intersperse some of them with the experiments this week.

## ELECTRIC FIELD

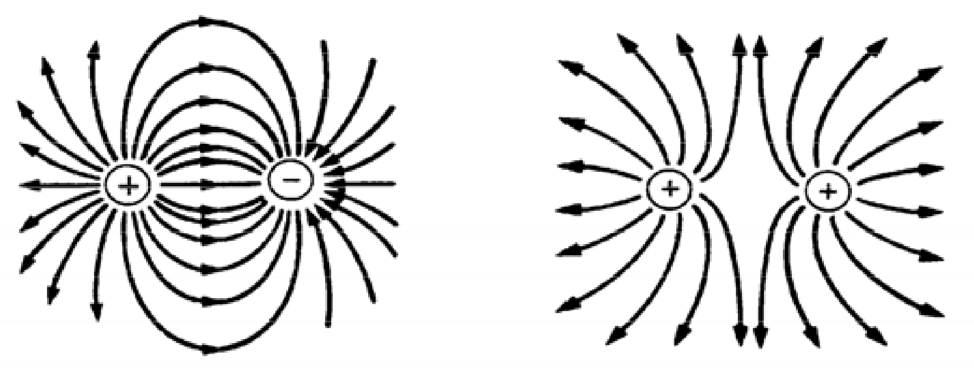
Consider an electric charge exerting forces on other charges which are separated in space from the first charge. How can one object exert a force on another object with which it is not in contact? How does the force move across empty space? Does it travel instantaneously at infinite speed or at some finite speed?

In the 19th century, physicists suggested the beginning of a solution to these questions. Instead of imagining that the charge produces forces on other charges directly, they imagined that the charge fills the surrounding space with an *electric field*. When other charges are inside the electric field, they experience electrical forces.

Electric fields can be visualized clearly by imagining that a small positive test charge is carried around, and the direction and strength of the force exerted on the charge are mapped. Think first about mapping the electric field of a single stationary positive charge. As we move the test charge around, the force is always directed radially outward from the stationary charge, and its strength decreases with distance from the stationary charge. If we draw arrows in the direction of the force, with lengths proportional to the strength of the force, we obtain a picture of the electric field similar to this:




These lines provide a very convincing picture of electric fields. Look at the fields surrounding two unlike charges (which attract each other) and two like charges (which repel each other):



The electric field itself is defined as the force exerted on a test charge divided by the value of test charge. By dividing out the charge, we are left with only the properties of space around the charge:

$$\text{(electric field)} = \text{(force on a test charge q)/q} \tag{1}$$

or

$$E = F/q. \tag{2}$$

The field lines begin on positive charges and end on negative charges (or at infinity if the system is not overall neutral). Keep in mind that the lines do not necessarily represent the path a test charge would follow if released, but rather, the direction and strength of the force on a stationary test charge. That is, the direction of the force is along the field line passing through the test charge, and the strength of the force is proportional to the density of field lines near the charge. (Actually, the electric field is proportional to the number of field lines penetrating a unit area centered on the point of interest. Lots of field lines indicate a strong force.)

Imagine several positive and negative charges situated in space. The space around the charges is filled with field lines. These field lines start on the positive charges; the positive charges are the "sources" of the lines. The field lines end on negative charges; negative charges are the "sinks" of the lines. If there are more positive than negative charges in the region of space we are examining, then some of the field lines leave the area completely, moving to infinity. If negative charges predominate, then some of the field lines come in from infinity. This is the picture: field lines filling space, starting on positive charges; or coming in from far away, ending on negative charges; or disappearing into the distance.

The introduction of the electric field concept seems to be an unnecessary complication at first, but physicists eventually discovered that the equations of electricity and magnetism are simpler when written in terms of fields than in terms of forces. The culmination of this process was reached around 1870 with the completion of Maxwell's equations.

## ELECTRIC POTENTIAL

Since an electric field exerts forces on charges in it, there is potential energy associated with the position of a charged particle in the electric field, just as a massive object has potential energy in the gravitational field of the Earth. Imagine that we hold a positive charge fixed in position, and we bring in a small positive test charge (different from the fixed positive charge) from afar. As we move the positive test charge in, it is repelled by the fixed charge, and we must exert a force on the test charge to bring it closer. A force exerted though some distance performs work: we must do work on the test charge to move it closer. This work goes into increasing the electric potential energy of the test charge, just as the work done in lifting an object goes into increasing its gravitational potential energy. The electric potential energy can be converted into kinetic energy by releasing the test charge. The test charge flies away, gaining kinetic energy in the process.

We would like to introduce a quantity related to potential energy which depends only on the properties of the charge, so we divide out the test charge and write

$$\text{(potential)} = \text{(potential energy)}/\text{(charge)} \tag{3}$$

or

$$V = U/q. \tag{4}$$

This relationship defines a new quantity: the *electric potential* $V$. Potential is energy per charge and is measured in joules per coulomb (also known as *volts*, with unit symbol V). These are the same volts used in measuring the voltage of a battery. Understanding how the potential energy of an electric field is related to the voltage of a 6-V battery is one of the difficult conceptual leaps of electricity and magnetism. While you are trying to assimilate it, remember that as you learn new concepts in physics, it is important to keep the basic definitions in mind. If a battery is rated at 6 volts, then it is prepared to give 6 joules of energy to every coulomb of charge that is moved from one of its terminals to the other. For example, if we wire the filament of a small light bulb to the battery so that charge is moved through the filament, the energy goes into heating the filament "white hot".

## GAUSS' LAW

Certain results in this lab can be understood most easily on the basis of Gauss' Law. Gauss' Law is an important reformulation of Coulomb's Law, which makes easier the derivation of some interesting consequences of electrostatics, such as the fact that all charge placed on a conductor moves to its outside surface. Gauss' Law can be expressed as a surface integral of the electric field:

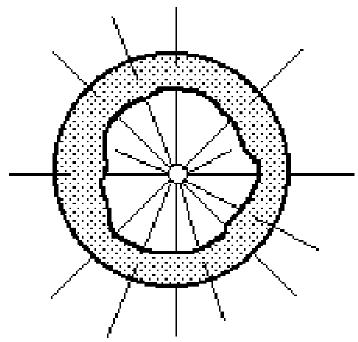
$$\int \mathbf{E} \cdot \mathrm{d}\mathbf{A} = q_{\mathrm{in}}/\epsilon_0. \tag{5}$$

The surface integral is called the *flux* of the electric field, and is evaluated over any closed surface. The charge $q_{\text{in}}$ is the total charge enclosed <u>within</u> the surface, and $\epsilon_0$ is the constant in Coulomb's Law:

$$F = kqQ/r^2 = qQ/4\pi\epsilon_0 r^2 \tag{6}$$

with $k = 1/4\pi\epsilon_0$.

We now derive Coulomb's Law from Gauss' Law. Let's start with an isolated charge $q$, and draw an imaginary sphere of radius $r$ centered on the charge. This sphere is an example of a *Gaussian surface.*



Here the electric field is always perpendicular to the imaginary sphere, and has the same constant value $E$ at all points on the surface. Thus, the surface integral is simply the electric field $E$ multiplied by the surface area $4\pi r^2$ of the sphere:

$$\int \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \mathbf{E} \cdot \int \mathrm{d}\mathbf{A} = E(4\pi r^2) = q_{\text{in}}/\epsilon_0 = q/\epsilon_0. \tag{7}$$

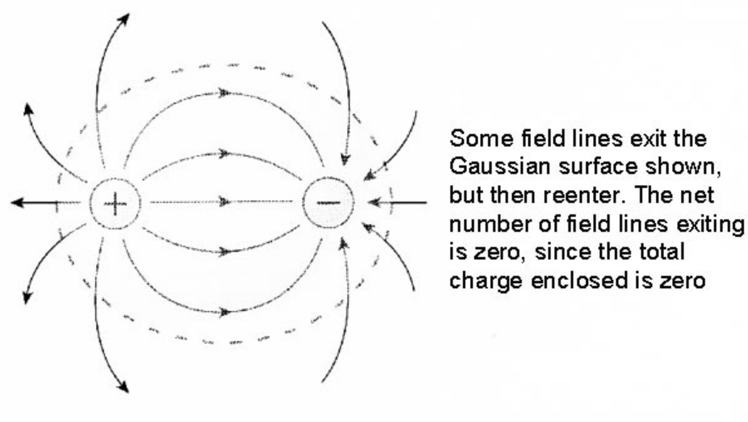
This gives us the electric field of the charge $q$ at a distance $r$:

$$E = q/4\pi\epsilon_0 r^2. \tag{8}$$

Since the force on a test charge $Q$ due to this electric field is $F = QE$, we have $F = qQ/4\pi\epsilon_0 r^2$ — which is Coulomb's Law! In this sense, Gauss' Law is a reformulation of Coulomb's Law in terms of the electric field. It seems unnecessarily complicated, but you will see that we can immediately derive some interesting results with Gauss' ideas.

You can conceptualize Gauss' Law in terms of field lines by noting that the integral $\int \mathbf{E} \cdot \mathrm{d}\mathbf{A}$ over a surface is proportional to the number of field lines penetrating the surface (regardless of the angle between these lines and the surface). If field lines are entering and exiting the surface, then the flux integral is proportional to the number of lines exiting minus the number of field lines entering.

Here is an example. Imagine a closed surface of any shape (a Gaussian surface) enclosing a volume of space with possibly some charges inside. Let us find the net flux $\int \mathbf{E} \cdot \mathrm{d}\mathbf{A}$ through this surface. If the surface encloses a positive charge and an equal negative charge, then some of the field lines from the positive charge may leave and then reenter the surface, heading for the negative charge. The contribution to the net flux from the field lines exiting and then reentering is zero.

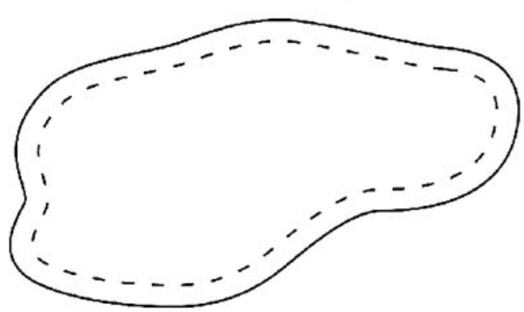



For this situation of equal positive and negative charges, the net flux is zero, because every field line that leaves later reenters. (Note that this is true no matter how the Gaussian surface is shaped or positioned, as long as it encloses both charges. If there are charges outside the surface, then their field lines will enter and later exit the surface, so the contribution from these charges is zero.)

$$\int \mathbf{E} \cdot \mathrm{d}\mathbf{A} = 0 \quad \text{for no } \underline{\text{net}} \text{ enclosed charge.} \tag{9}$$

In fact, if the imaginary Gaussian surface encloses an unknown amount of charge, we can calculate the net flux $\int \mathbf{E} \cdot \mathrm{d}\mathbf{A}$ and multiply by $\epsilon_0$ to obtain the charge inside: $q = \epsilon_0 \int \mathbf{E} \cdot \mathrm{d}\mathbf{A}$. (If there is a net entry of field lines, then $\int \mathbf{E} \cdot \mathrm{d}\mathbf{A}$ will be negative, and the equation above shows how much negative charge is enclosed by the surface.) Our first conclusion from Gauss' Law is that if we draw an imaginary closed surface, measure or compute the flux through the surface, and multiply by $\epsilon_0$, we obtain the net charge (positive minus negative) enclosed by the surface. If the total charge inside the Gaussian surface is zero, then no field lines can exit (that do not reenter later).

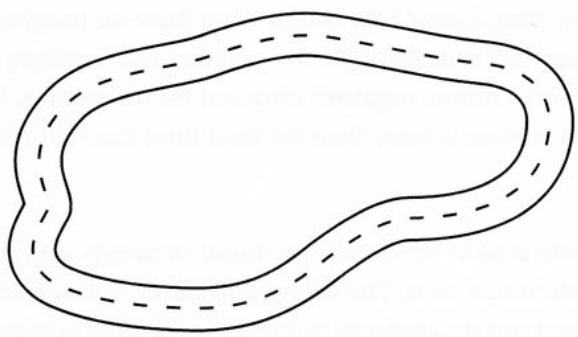
Now suppose we take a solid conductor — a chunk of metal — and dump some charge (say, a few billion electrons) on it. The charge will spread out over the conductor until equilibrium is reached and the electrons no longer move. (The movement of the charges takes place in a tiny fraction of a second.)



A Gaussian surface just inside a solid conductor has no field lines in it.

First, note that there are no field lines anywhere inside the conductor. Why? Field lines represent forces on charges. If there were a field line inside the conductor, then charge would move. By definition, charge is always free to move in a conductor. But the charge has stopped moving; it must have arranged itself so that there are no field lines inside the conductor. Now draw a Gaussian surface just inside the surface of the conductor. No field lines penetrate this surface, so according to Gauss' Law, there is no net charge inside the surface (that is, inside the conductor). Under static conditions, all of the (excess) charge resides on the outer surface of the conductor. This is our second conclusion from Gauss' Law. Of course, it is not too surprising. Loosely speaking, the bits of charge repel one another, and they move as far away from each other as possible to the outer surface. We will see this effect in one of the following experiments.

Now consider a hollow conductor of any shape. A hollow metal sphere is an example, although the shape need not be regular. Again, if charge is placed on the conductor, all of it will move to the outside surface.



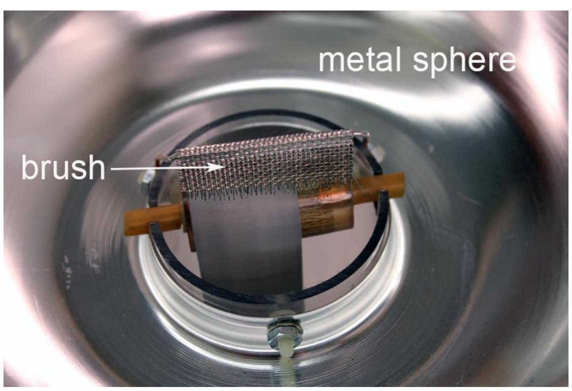
A conductor with a cavity inside and a Gaussian surface within the conductor.

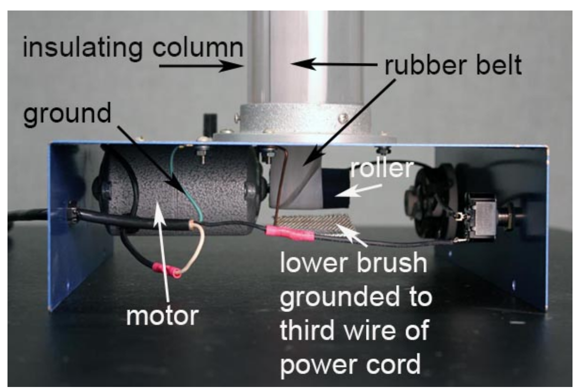
A Gaussian surface inside the metal, between its outside and inside surface and entirely in the conductor, has no field lines penetrating it; thus, there is no field in the conductor. Any surface inside the cavity has no net field lines exiting it, so no charge is enclosed. Thus, there is no electric field inside the cavity. (Strictly speaking, you need another law of electrostatics in addition to Gauss' Law to complete the proof that there is no electric field inside a cavity, devoid of charges, in a conductor. See The Feynman Lectures, Volume II, Section 5 – 10.)

When a volume of space is enclosed by a conductor, there is no static electric field penetrating it from the outside. The conductor shields the inner space. This is a very practical example of the standard advice about remaining inside an automobile during a lightning storm. The automobile encloses its occupants with metal. Even if the automobile is itself struck by lightning and the occupants are touching its inner surface, the occupants will not be harmed or even shocked. It does not matter that the metal surface of the automobile is broken by the non-conducting windows. A small electric field may penetrate a short distance at the windows, but the nearly complete metal surface of the automobile shields the interior very well. A wire mesh cage will effectively shield its interior, as long as the mesh hole size in not particularly large compared to the size of the whole cage. We will try a shielding experiment below. Gauss' Law has other interesting consequences, but we now move to a description of the experimental apparatus.

## THE VAN DE GRAAFF GENERATOR

The Van de Graaff Generator is a common electrostatic machine which produces voltages of 100,000 V or more on its sphere. Voltage is a measure of energy per unit charge. High voltages can be estimated roughly by how far they will make a spark jump in air. Static charges that jump a centimeter or so, as with the electrophorus, involve 10,000 – 30,000 V. With the Van de Graaff machine, sparks may jump as far as 15 cm. Even though the voltage is high, the total charge transferred is so small that little pain is felt if one of these sparks reaches your body.




The Generator consists of a vertical rubber belt revolving around two rollers. The belt delivers charge to a large insulated metal sphere. One roller is typically covered with wool, and the other with neoprene. The making and breaking of contact between the rubber belt and the rollers generates a static charge, which imparts to the roller and belt opposite signs of charge. The two different roller materials are chosen so that one roller becomes positively charged and the other negatively charged. Let us imagine that the lower roller becomes positively charged. The right side of the belt will become negatively charged as a consequence, and some negative charges will be carried up the belt. This is not where the majority of the negative charges come from, however. Instead, the negative charges are induced from the brush onto the belt.

Near both rollers are brushes. The brushes are comb-like arrangements of metal points near, but not in contact with, the rubber belt near the rollers. The lower brush is connected to the electrical ground through the third wire of the power cord. The ground — planet Earth — is a gigantic reservoir of electrical charge, both positive and negative. Small amounts of charge can be transferred to and from the Earth without significantly "charging it up". The positive roller attracts negative charges (electrons) from the ground by induction; these charges flow onto the belt and stick there, since the belt is an insulator. The belt then carries the negative charges to the upper roller, which has been negatively charged by the friction of the belt. The negative charges are thus repelled onto the upper brush, where they are conducted out to the Van de Graaff dome.

You might initially think that negative charge would not continue to build up on the dome as it is repelled by the additional charge. But Gauss' Law guarantees that any charge delivered to the inside of the sphere moves to its outer surface. Thus, the upper brush does not charge up, and the belt can continue to deliver charge up to the sphere, where it accumulates until the air around the sphere starts to "break down" and the charge leaks off into the surrounding air.

## CAUTIONS IN THE USE OF THE VAN DER GRAAFF GENERATOR

If the Generator sparks directly to your body, it produces a slightly painful sting, but not a dangerous shock. Anyone who has worked with these machines has received several of these shocks. To reduce the number of shocks you receive, keep all parts of your body a meter away from the sphere. When turning the machine on or off, touch the grounding sphere to the Generator sphere, or hold the grounding sphere or wire with the hand that you reach up to the switch. Be sure the Generator sphere has been touched with the grounding sphere after you turn it off; the sphere may stay charged for many minutes.

On a cold dry day when electrostatics is powerful, charge will actually flow through the air and get on you and any equipment nearby. If you get charged up, sparks will jump from you to the ground when you came near various objects. Continually hold a grounding wire to prevent this from happening. You may need to ground carefully the other equipment to prevent spurious results in your experiments. On a good day, you are almost certain to receive some small shocks.

## EXPERIMENTS

### I. *TEST THE EFFECT OF HUMIDITY AGAIN*

#### *Equipment*

- Lucite rod
- Silk cloth
- Electroscope
- Timer

***Procedure***

1. Record below the readings of the relative humidity in the room (from the wall meter) and the inside and outside temperature.

   Humidity = ______________________________

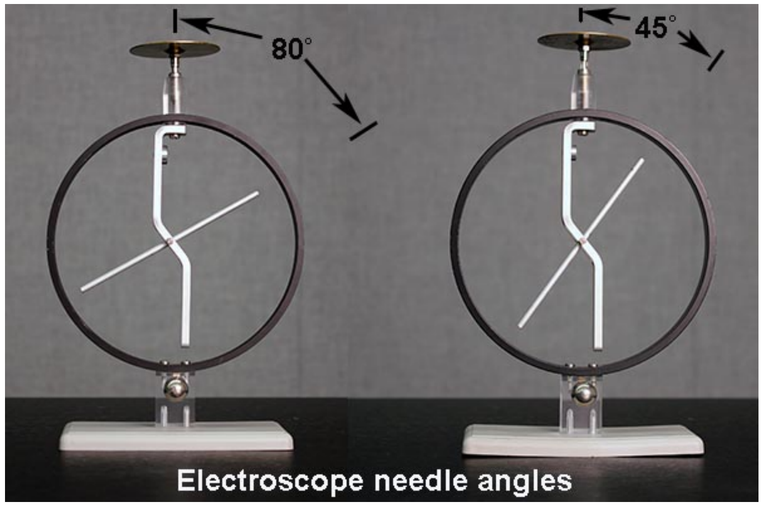
   Inside temperature = ______________________________

   Outside temperature = ______________________________

2. For this experiment, do not shine the flood lamp on the electroscope. Be prepared to start your timer. You may use the stopwatch function of your wristwatch.

3. Rub the lucite rod vigorously with the silk cloth. Use a little whipping motion at the end of the rubbing. Touch the lucite rod to the top of the electroscope. Move the rod along and around the top so you touch as much of its surface to the metal of the electroscope as possible. Since the rod is an insulator, charge will not flow from all parts of the rod onto the electroscope; you will need to touch all parts (except where you are holding it) to the electroscope. Start your timer immediately after charging the electroscope.

4. Record the time it takes the electroscope needle to fall completely to 0°. Time up to five minutes, if necessary. If the needle has not fallen to 0° after five minutes, record an estimate of its angle at the five-minute mark. Typically, after charging, the needle might be at 80°.

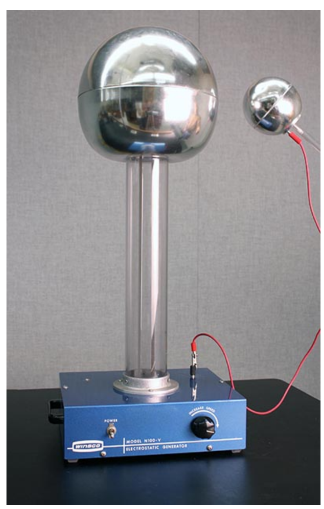



## *II.* ***VAN DE GRAAFF PARAMETERS***

The 10-cm spheres on insulating rods are surprisingly expensive and easily dented. Please take care that they do not roll off the table and fall on the floor.

### ***Equipment***

- Van de Graaff Generator
- Grounded discharge sphere
- Wire ring with "lightning rod"
- Insulating stand



### ***Procedure***

1. Devise a way to measure the radius ($r$) of the Van de Graaff sphere.

   $r =$ ______________________________

2. Hold the grounded sphere (the one attached to the Van de Graaff Generator base by

a wire) by its insulating handle, and bring it into contact with the metal dome of the Generator. Turn on the machine with your other hand, and draw the grounded sphere away until sparks are jumping to it from the Generator dome. Experiment with the motor control speed of the Generator.

Devise a way to measure the maximum spark length to the discharge ball. How will you do this, since you cannot simply hold up a meter stick while the Van de Graaff is sparking?

maximum spark length = ______________________________

Hold the discharge sphere at the maximum distance for continuous sparking, and estimate the spark frequency. (That is, how many sparks are emitted per second? Use you watch, the computer, or the Capstone clock to make a time estimate.)

spark frequency = ______________________________

3. The "breakdown" electric field is $3{\times}10^6$ V/m for dry air. This is the field necessary to make a spark jump through air — for example, between two metal plates with an electric field in the air gap.

   The Van de Graaff belt delivers charge continuously to the sphere. If there is no discharge sphere nearby, the potential of the Van de Graaff sphere (its voltage) rises until the electric field at the surface reaches the breakdown value. Then charge begins to leak into the air (through a corona discharge, with many small sparks). An equilibrium potential for the sphere is reached when the leakage rate from the sphere is equal to the delivery rate from the belt.

   The electric field $E$ at a distance $r$ from a charged sphere (calculated from Gauss' Law) is

$$E = Q/4\pi\epsilon_0 r^2, \tag{10}$$

   where $Q$ is the charge on the sphere. To find the potential V of the sphere, we integrate $E$ from $r = \infty$ to $r = R$ (the radius of the sphere):

$$V = -\int E\,\mathrm{d}r = Q/4\pi\epsilon_0 R. \tag{11}$$

   (We suggest, for purposes of midterm preparation in the lecture part of the course, that you know how do derive the result above. Getting all the signs correct is somewhat tedious.) Using the electric field at the surface of the sphere and eliminating $Q$, we find

$$V = ER. \tag{12}$$

   Using $E =$ breakdown electric field, and your measured value of $R$, calculate the potential $V$ of the sphere.

   $V =$ ______________________________

   Advertisements for this type of Van de Graaff Generator typically state that it will produce voltages as high as 400,000 V. Is this a reasonable value, taking into account various leakages? What factors might cause the actual potential to be smaller than calculated?

4. Use your measured maximum spark length and the breakdown electric field to estimate the potential difference necessary to make a spark jump this distance between two parallel metal plates.

   $V =$ ______________________________

   Is this potential in agreement with your calculated value? How about the advertised potential?

5. Using your calculated potential, calculate the charge stored on the sphere from

$$V = Q/4\pi\epsilon_0 R. \tag{13}$$

   Express your answer as a number between 1 and 999 in coulombs (C) with the appropriate prefix, such as m $= 10^{-3}$, µ $= 10^{-6}$, n $= 10^{-9}$, p $= 10^{-12}$, etc. (It may help to remember that $1/4\pi\epsilon_0 = 9 \times 10^9$ in SI units.)

   $Q =$ ______________________________

6. The capacitance of a configuration of conductors is defined as $C = Q/V$. The equation above can be manipulated to give the capacitance of an isolated sphere as

$$C = 4\pi\epsilon_0 R. \tag{14}$$

   Calculate the capacitance of your Van de Graaff sphere. Express your answer as a number between 1 and 999 in farads (F) with the appropriate prefix, such as m $= 10^{-3}$, µ $= 10^{-6}$, n $= 10^{-9}$, p $= 10^{-12}$, etc.

   $C =$ ______________________________

7. Assume the sphere discharges completely with each spark, and use your measured spark frequency to calculate the average discharge current ($i$) while sparking.

   $i =$ ______________________________

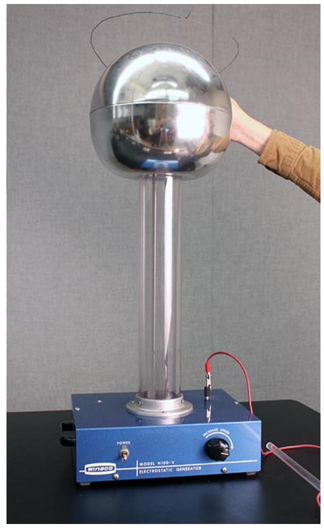
   Evidently, the discharge rate must be equal to the rate at which the belt is delivering charge to the sphere. A current of 3 mA is considered the minimum dangerous (possibly fatal) current. How does your measured current above compare? Would you rate this Van de Graaff as "safe for student use"? The manufacturer states that the current delivered by the belt is 10 µA. Does this agree with your estimates? Did we make any poor assumptions above?

## *III.* ***LIGHTNING ROD***

### *Equipment*

- Van de Graaff Generator
- Grounded discharge sphere
- Wire ring with "lightning rod"

- Insulating stand



***Procedure***

1. Place the wire ring on top of the Van de Graaff metal dome. Put the grounded sphere into contact with the dome, turn on the machine, pull the grounded sphere several centimeters away from the dome, and observe whether any sparks are created.

2. While the machine is still running, use the grounded sphere to slide the wire ring off the dome. (Don't bring your hands near or you will be shocked.) Then hold the grounded sphere several centimeters away from the dome, and observe whether any sparks are created.

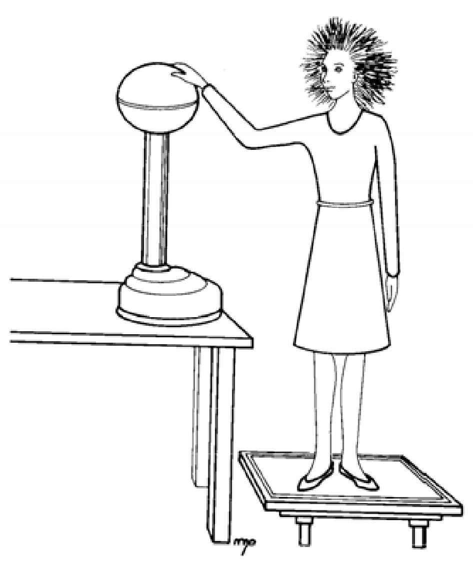
3. Bring the grounded sphere into contact with the dome again, and turn off the machine.

4. Based on your results, give a clear explanation below of how and why a lightning rod works.

***To Try Hair-Raising (optional)***

1. Start with a key or other pointed metal object in your pocket (not absolutely necessary).

2. Stand on the insulating stand so that you can easily reach over to place your hand on the Van de Graaff dome, but all other parts of your body are one-half meter away from the benches or other persons.



3. Place your hand firmly on the dome. Have your partner turn on the machine carefully while not getting too close to you. When the machine is running, you will feel a slight tingling sensation, but no pain, as the hairs on your arms and legs are raised. Do not pull your hand away from the dome while the machine is running, or sparks will jump to your hand as you pull back.

4. After the machine has run for 30 seconds or so, shake your head to loosen your hair, but do not remove your hand from the dome.

5. When finished, have your partner turn off the machine carefully.

6. Pull your hand away from the dome. Have your partner discharge the dome. If you step down immediately, you will get a slight shock (usually not painful). Wait a few moments until the charge leaks away. Or, take the key or pointed metal object out of your pocket and hold it up. You will probably hear the charge hissing off it. Bring the point slowly toward the Van de Graaff base box until you finally touch it with the point. Now all the charge has been grounded, and you can step down without being shocked.

   Hair raising produces widely varying results on different persons and also depends strongly on the humidity present during the demonstration. It seems to work best on persons with light, fluffy hair that has been washed recently. Persons with coarse, highly curly, or oily hair, or hair that has been treated with sprays or gels, do not produce the more spectacular results.

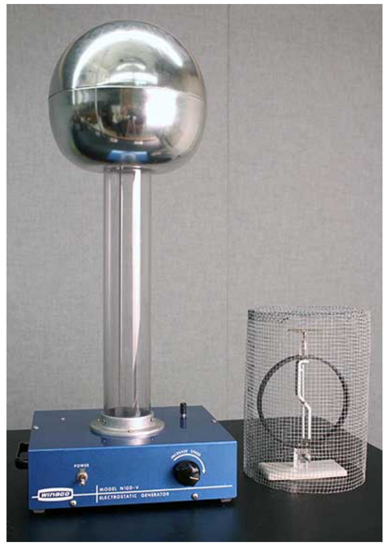
## *IV.* ***FARADAY CAGE***

This experiment demonstrates the electric-field shielding characteristic of conductors.

***Equipment***

- Electroscope
- Metal wire cage

- Van de Graaff Generator
- Grounding sphere



***Procedure***

1. Set the electroscope within approximately half a meter of the Van de Graaff Generator. Turn on the machine, and observe and record the results.

2. Turn off the machine. Ground its dome and the electroscope so that they are completely discharged.

3. Cover the electroscope with the metal wire cage, and repeat step 1. Try moving the cage even closer to the dome (with an insulated rod!). Is there any deflection? How do you explain the results?

## V. ***FARADAY ICE PAIL***

In the experiments last week, we have shown that a charged rod can induce an opposite charge on a conductor. In this section, we will show that the induced charge is not only opposite in sign, but also equal in magnitude, to the inducing charge.

***Equipment***

- Van de Graaff Generator
- Two conducting spheres, one grounded
- Electroscope with Faraday pail

***Procedure***

1. Position the electroscope with Faraday pail away from the Van de Graaff Generator. (When the metal dome of the Generator is charged, an electroscope nearby may deflect from the electric field of the dome, as you found in the last experiment. This deflection will end when the dome is discharged. However, on some days charge will actually move through the air and get on the electroscope, and the electroscope will remain deflected even after the dome is discharged. In this case, you will need to discharge the electroscope with your finger, or perhaps you may need to touch both the top electrode (or pail) and the guard ring of the electroscope with the grounded sphere, to get it completely discharged before performing the remaining steps.)

2. Run the Van de Graaff Generator for a few moments until its sphere is charged.

3. Hold the ungrounded conducting sphere by its insulating handle, and charge it by momentarily touching it to the Van de Graaff dome. Discharge the dome. Make sure the electroscope is discharged, and lower the small sphere into the pail without touching the side of the pail with the sphere. The goal is to get the charged sphere into the pail without a spark jumping between them. If you find this step difficult, start again as follows: Discharge the insulated sphere and the Van de Graaff dome. Turn the Van de Graaff motor control down and run it very briefly so when you touch the insulated sphere to it, the sphere picks up a smaller charge.

4. When you can get the charged sphere into and out of the pail without a spark jumping, record answers to the following: Is there any deflection while the charged sphere is inside the pail? When the sphere is removed, is there still any deflection?

5. With the sphere charged, lower it all the way into the pail so that no sparks jump (sphere completely inside but not touching the bottom). Touch the pail momentarily with your finger. What happens to the deflection? Remove the sphere, still holding it in your hand. Record any changes to the deflection.

6. The pail and electroscope are now charged by induction. Lower the sphere into the pail, let it touch the bottom, and remove it without touching it to the edges as it goes out.

What happens to the deflection? Explain your results.

## *VI.* ***GAUSS' LAW***

A consequence of Gauss' Law is that all charge on a conductor moves to the outside surface. This experiment is very similar to the previous one. You will need two electroscopes, so borrow one from another group, or work together.

***Equipment***

- Van de Graaff Generator
- Two conducting spheres, one grounded
- Two electroscopes, one with Faraday pail

***Procedure***

1. Position the electroscope with the Faraday pail and the other electroscope away from the Van de Graaff Generator, and somewhat separated from each other. In the procedures below, recall the cautions and advice in steps 1 and 3 of the previous experiment.

2. Run the Van de Graaff Generator momentarily until its sphere is charged.

3. Hold the ungrounded sphere by its insulating handle, and momentarily touch it the Van de Graaff dome. Discharge the dome. Check that both electroscopes show zero deflection.

4. Bring the charged sphere near, but not touching, the electroscope without the pail. It should deflect, indicating the presence of charge.

5. Lower the sphere into the pail on the other electroscope until it touches the bottom. Carefully lift it out <u>without touching the edge of the pail</u>.

6. Bring the sphere near, and into gentle contact with, the top of the other electroscope. Is there any deflection? What is your conclusion?

7. Now touch the ungrounded sphere to the outside of the pail, and then bring it into gentle contact with the other electroscope. Can you remove charge from the outside of the pail?

***Additional Credit (3 mills)***

When you can perform this experiment well and explain the results clearly, call your TA over and demonstrate and explain the experiment. He or she will award you 3 mills if you can do it without significant assistance.

Note: If the previous week was bad for electrostatics, some experiments may be carried over to this week.

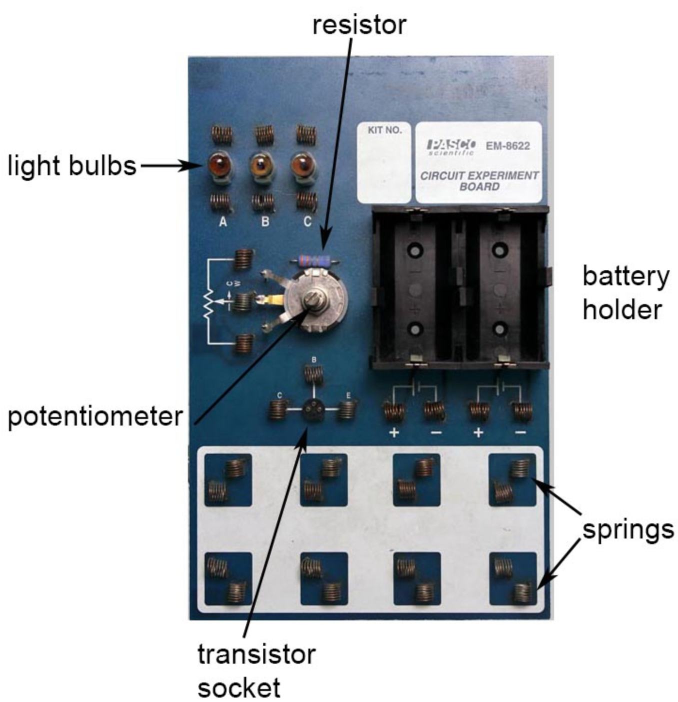
# Electrical Circuits

## APPARATUS

- Computer and interface
- Voltage sensor
- Fluke 8010A multimeter
- Pasco circuit board with two D-cells
- Box with hook-up leads and components

## INTRODUCTION

This experiment is an introduction to the wiring of simple electrical circuits, the use of ammeters and voltmeters, series and parallel circuits, and RC circuits. The circuits will be wired up on the Pasco circuit board.




## BRIEF REVIEW OF DC CIRCUIT THEORY

In a metal conductor, each atom contributes one or two electrons that can move freely through the metal. An electric current in a wire represents a flow of these electrons. The flow is quite chaotic since the electrons have a large thermal component to their motion; they are always “jittering” around randomly. When a current flows, however, there is a general drift velocity of the electrons in one direction superimposed on the random motion.

The total charge (which is proportional to the number of electrons) that passes one point in the circuit per unit time is the *current*. Current is measured in units of coulombs per second, which is also known as *amperes* (with unit symbol A).

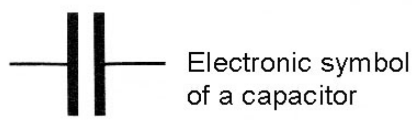
An electric field is needed to keep the electrons flowing in the metal (unless the metal is a superconductor). This field is normally provided by the chemical action of a cell or battery, or by a DC power supply. The electric field is the change in the *voltage* per unit distance. The unit of *volt* (V) is also energy per unit charge, or joules per coulomb. Voltage can be viewed as a pressure pushing the charges through the circuit, and current can be viewed as a measure of the charge that passes one point in the circuit per unit time.

Normal metals have a *resistance* to this flow of charges, and thus voltage is needed to maintain the current. It is found experimentally that for many materials over a wide range of conditions, the current is proportional to the voltage: $i = kV$. The symbols $i$ for current and $V$ for voltage are standard notation. However, we can write $k = 1/R$ and define a new quantity — the *resistance* $R$ — measured in *ohms* ($\Omega$). Ohm's Law, $i = V/R$, is not a fundamental law of physics in the same manner as Coulomb's Law, but is found to be approximately true in many circumstances. We will test Ohm's Law below.

Oftentimes in circuits, we want to reduce or limit the current with *resistors*. A typical resistor is a small carbon cylinder with two wire leads. The cylinder is encircled with colored rings which code its value of resistance. Figure 8 below shows the color code.

## RC CIRCUIT THEORY

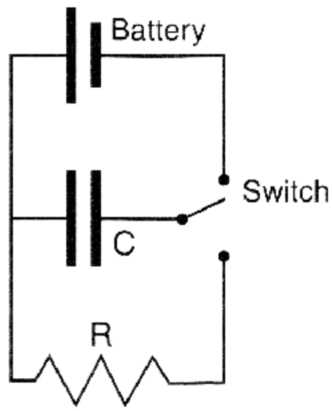
A capacitor consists of two conductors separated by an insulator (e.g., two parallel metal plates separated by an air gap).




It is found that when the two plates are connected to a source of DC voltage, the plates "charge up", with one becoming negative and the other becoming positive. If the DC voltage is now disconnected, the charge remains on the plates, but drains off slowly through the air. If the plates are now shorted by a wire, the charge will neutralize — with a spark and a bang, if the stored energy is large. A capacitor therefore stores charge and energy. For a given voltage, the capacitor will store more charge if the area of the plates is larger and/or if the plates are positioned closer together.

The equation for the charge in a capacitor is $Q = CV$: the stored charge $Q$ is proportional to the voltage $V$ and the capacitance $C$. Capacitance is a quantity determined by the physical characteristics of the capacitor, the area and separation of the plates, and the type of insulator. Capacitance is measured in farads (with unit symbol F): a one-farad capacitor stores one coulomb of charge at a potential of one volt. The farad is a large unit; most capacitors used in electrical circuits have capacitances measured in millionths of a farad (microfarads, or µF), billionths of a farad (nanofarads, or nF), or even trillionths of a farad (picofarads, or pF).

The circuit below would permit charging of the capacitor C by the battery and discharging of the capacitor through the resistor R.




Let us study the discharging process. When discharging through the resistor, the voltage across the capacitor is $V = -iR$. (The negative sign indicates that the capacitor voltage is opposite the resistor voltage.) However,

$$i = \mathrm{d}Q/\mathrm{d}t = C\,\mathrm{d}V/\mathrm{d}t \quad \text{(from } Q = CV\text{)}, \tag{1}$$

so we have

$$V = -iR = -RC\mathrm{d}V/\mathrm{d}t, \tag{2}$$

or

$$\mathrm{d}V/V = -\mathrm{d}t/RC. \tag{3}$$

The equation above integrates to $V = V_0 e^{-t/RC}$, where $V_0$ is the voltage at $t = 0$. The voltage on the discharging capacitor decreases exponentially with time, and its exponential slope is $1/RC$. We will find the exponential slope for an $RC$ circuit below by using the curve fitting features of Capstone.

## MULTIMETER

A multimeter is an important tool for anyone working with electrical circuits. A typical multimeter has different scales and ranges for voltage, current, and resistance. Some multimeters will also measure other quantities such as frequency and capacitance. In this experiment, we will be using the Fluke 8010A digital multimeter.

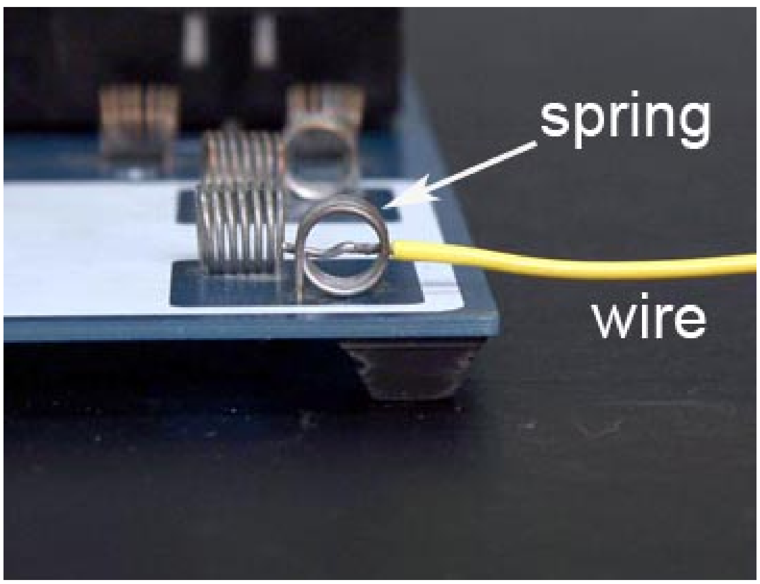
Take a moment to study this instrument. The green push-button power switch is at the lower right. The left-most button changes the measurements between AC and DC (alternating and direct current). This button should be out, as all of our measurements for this experiment are in DC.

To measure voltages, press the "V" button, and connect your test leads to the "common" and V/kΩ/S sockets. Push in a button for the appropriate scale: 2 V or 20 V in this experiment. To measure resistances, use the "kΩ" button and an appropriate scale. (Here kΩ represents thousands of ohms.)

You must be careful when measuring currents. Double-check your circuit when using the current meter. The meter must be hooked into the circuit so the current flows through the meter. The test leads are connected to the mA (milliampere) and common sockets. Before hooking the meter into the circuit, estimate first whether you expect the current to exceed 2 A. The meter has a 2-A fuse which will "blow" if this current is exceeded. All of our circuits below use smaller currents, provided they are wired correctly.

## HOOKING UP WIRES

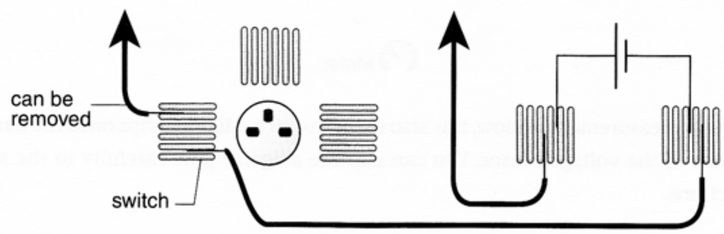
Connections are made on the circuit board by pushing a stripped wire or lead to a component into a spring. For maximum effect, the striped part of the wire should extend in such a way that it passes completely across the spring, making contact with the spring at four points. This extension produces the most secure electrical and mechanical connection.




If the spring is too loose, press the coils firmly together to tighten it up. The coils of the spring should not be too tight, as this may result in the bending or breaking of the component leads when they are inserted or removed. If a spring is pushed over, light pressure will straighten it back up.

## MAKING A SWITCH

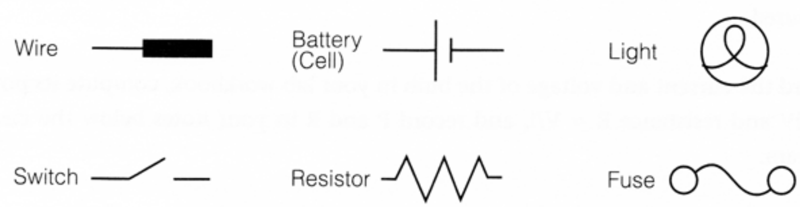
Use a vacant spring connection (such as one of the three around the transistor socket, as shown below) for a switch.




Connect one lead from the battery to this spring, and take a third wire from the spring to the light. You can now switch the power "on" and "off" by connecting or disconnecting the third wire.

## PROCEDURE

For each of the circuits below (except the first), discuss the circuit with you lab partner and agree upon a design. Then sketch the circuit neatly on a blank piece of paper using standard electrical symbols. Finally, hook up the circuit on the circuit board.




To be checked off as completing this experiment, your TA will glance at all your circuits, notes, and data, and look closely at the graphs of circuits 7 and 8.

- **CIRCUIT 1: CHECK YOUR COMPUTER VOLTAGE SENSOR**

  Plug a voltage sensor (just a pair of leads connected to a multi-pin socket) into the Science Workshop interface, turn on the interface and computer, call up Capstone and choose "Graph & Digits". Under "Hardware Setup", click on channel A and select "Voltage Sensor". Click the "Select Measurement" button in the digits box and select "Voltage (V)".

  In certain applications below, it is useful to have an analog meter on the computer screen linked to the voltage sensor. This permits you to determine quickly whether a voltage is present and what its approximate size is. This can be found at the right of the screen.

  For certain measurements below, it is also useful to stick alligator clips onto the banana plug ends of the voltage sensor. You can clip the alligator jaws carefully to the spring connections.

Check the voltage of one D-cell with both the voltage sensor and the digital multimeter to make sure the readings are in reasonable agreement. Record these readings. (Label your notes and circuit diagrams with the circuit number, 1 in this case.)

- **CIRCUIT 2: SINGLE BULB WITH VOLTMETER AND AMMETER**

  Design a circuit that will light a single light bulb with a single D-cell through a switch. (See "Making a Switch" above.) Try out the circuit and check that it works.

  Use the digital multimeter on a milliammeter scale, and wire it in series with the light bulb to measure the current flowing through the bulb. An ammeter must always be in series with the component whose current is being measured.

  Connect the leads of the voltage sensor across the light bulb to measure its voltage. A voltmeter must always be in parallel with the component whose voltage is being measured.

  Record the current and voltage of the bulb, compute its power $P = Vi$ and resistance $R = V/i$, and record $P$ and $R$ in your notes below the circuit diagram.

- **CIRCUIT 3: ADD A POTENTIOMETER**

  Rearrange your circuit so that you add a potentiometer in series with the light bulb whose current and voltage are still being measured. First, sketch the circuit in your notes. The potentiometer is the circular component with the screwdriver slot control (see Figure 1). Use the middle lead of the potentiometer and one of the end leads.

  Experiment with controlling the brightness of the bulb while observing the ammeter and voltmeter readings. (No data need be taken.)

- **CIRCUIT 4: BULBS IN PARALLEL**

  Design and wire up a circuit that will light all three bulbs in parallel. You may use one or both D-cells. Measure and record the battery voltage and the voltage across each bulb.

  Measure and record the current to each bulb separately, as well as the total current output of the battery. (Although the bulbs are labeled identically as #14 bulbs, their electrical characteristics may vary up to 30%, owing to relatively large variations allowed by the manufacturer.) One consequence of Kirchhoff's Current Law is that the sum of the currents of several components in parallel must be equal to the total current. Compare the sum of the three individual currents with the total current. <u>Enter the comparison clearly in your notes below the data and circuit for this part.</u> Upon what fundamental law of physics is Kirchhoff's Current Law based?

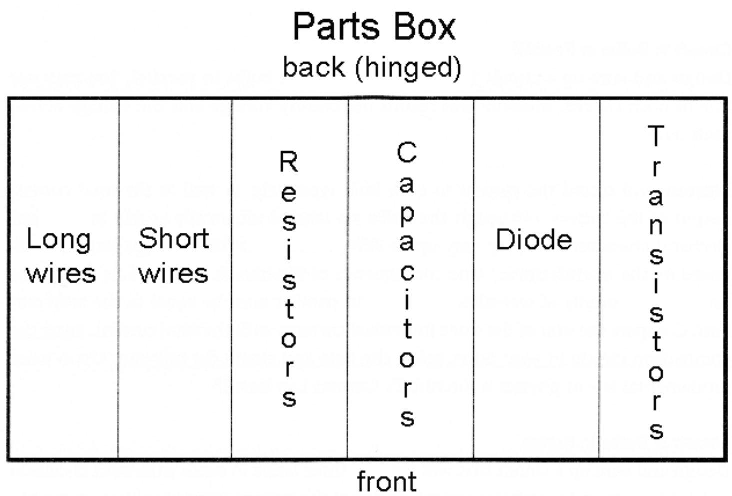
- **CIRCUIT 5: BULBS IN SERIES**

  Design and wire up a circuit that will light all three bulbs in series with both D-cells in series. Measure and record the current output of the battery. What would you expect to obtain if you measured the current to each bulb?

  Measure and record the voltage across each bulb separately, as well as the total voltage of the battery. One consequence of Kirchhoff's Voltage Law is that the sum of the voltages of several components in series must be equal to the total voltage. Compare the sum of the three individual voltages with the total voltage. Enter the comparison clearly in your notes. Upon what fundamental law of physics is Kirchhoff's Voltage Law based?

For Circuit 4, you should have entered in your notes the measured individual currents to each bulb and the measured total battery current; and for Circuit 5, similar entries for the voltages. Your current comparison may show a difference of 10% or more. Some meters on the current setting have significant internal resistance of their own (partly because of the fuse), so they actually reduce the current to the component when wired into the circuit. On the voltage settings, however, the meters do not change the circuit voltages significantly when they are wired in, so your voltage comparison should agree quite closely.

Keep your parts in the order shown. After finishing the experiments, put all parts back in their proper slots.

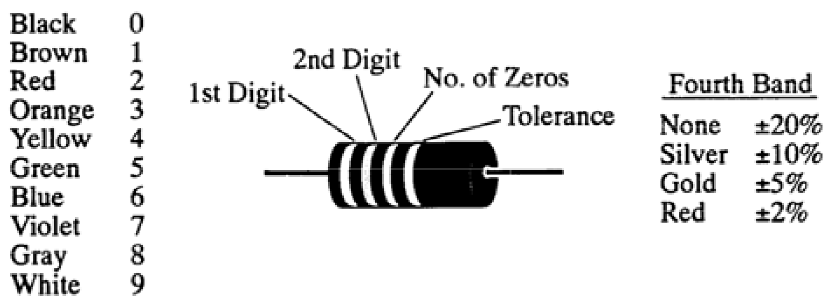


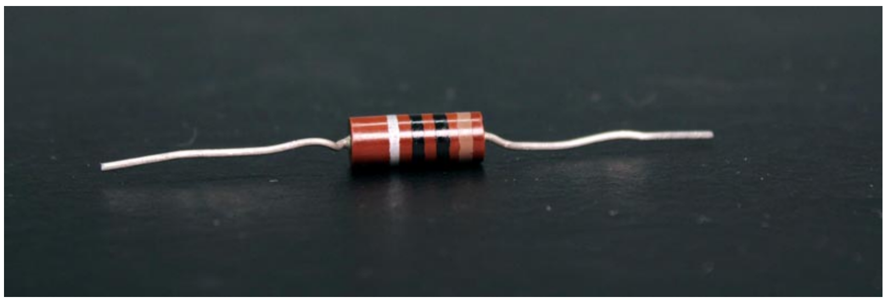

- **CIRCUIT 6: ADDITIONAL CREDIT (1 mill)**

Devise a circuit that will light two bulbs at the same intensity, but a third bulb at a different intensity. Try it. If one lab partner has been doing all the wiring on the circuit board, change tasks now so that both partners gain experience in wiring a circuit. When successful, draw the circuit diagram in your notes. Indicate what happens when you unscrew each bulb, one at a time. Your TA will award the mill when he or she checks your notes at the end of the lab.

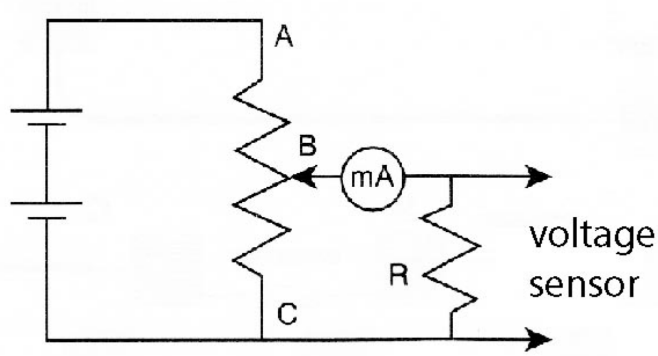
- **CIRCUIT 7: OHM'S LAW**

Choose one of the three resistors. Using the chart below, decode the values of the resistance and tolerance range of the resistor, and record them. Measure and record the resistance directly with your multimeter. Is the measured value within the tolerance range of the coded value?



Wire up the voltage divider circuit shown below on your circuit board with your chosen resistor in position R.




The element R is the resistor to be tested, the element mA is the multimeter on the milliampere scale, and the element ABC is the potentiometer, with B the middle connection (i.e., the sliding contact of the potentiometer). For the position of the potentiometer on your circuit board, see Figure 1. As you turn the potentiometer knob, the sliding contact B moves along the resistance of the potentiometer, allowing you to pick any voltage from zero to the full battery voltage $V$. This circuit permits you vary the voltage to the chosen resistor with the potentiometer, and to measure the voltage and current to it. Does it make any difference if its resistance $R$ is much larger or much smaller than that of the potentiometer? Your TA may award you a mill or two for a well-reasoned discussion of this point.

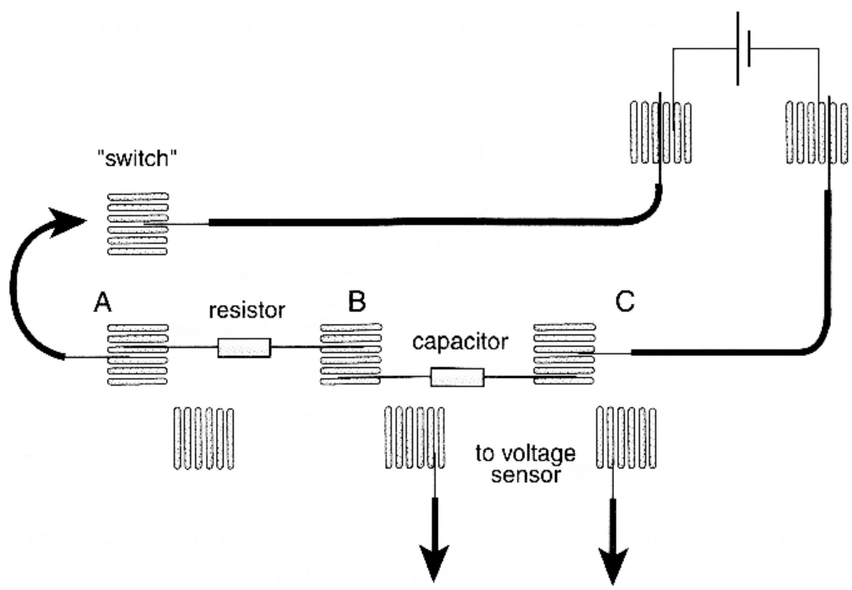
Set your computer to take data in a table of voltage from the voltage sensor while you input the current reading of the ammeter as a keyboard entry. To do this, Click on "Continuous

Mode" at the bottom of the screen and change this to "Keep Mode". Drag a new table over from the right side of the screen. select "Voltage (V)" for the first column. For the second column, click on "Select Measurement". Under "Create New", Choose "User-Entered Data" and then change the title to "current". Take data every 0.5 V between 0 V and 3 V by clicking the "Keep Sample" button. Remember to record the current (with units) for each voltage data point you keep.

Graph the data of $V$ as a function of $i$ in Capstone or Excel. Create a best-fit line and record the slope. Compare the slope ($R = V/i$) with your previously measured value of $R$. (You should have three entries of resistance compared in your notes: the "nominal" value read from the color code, the value measured by the multimeter, and the value determined from the slope of your graph.)

- **CIRCUIT 8: RC CIRCUIT**

Use the color-code chart above to locate a 100-kΩ (100,000-ohm) resistor. Measure and record its resistance with the ohmmeter scale of the multimeter. Wire (all in series) a D-cell, a switch, the 100-kΩ resistor, and the 100-µF capacitor, as in Figure 10 below. Connect the leads of the voltage sensor across the capacitor. Call up a meter scale linked to the voltage sensor on the computer screen, and set its limits to ± 2 V (to do this, click the "properties" button and then adjust "Meter Scale"). Make sure you are in "Continuous Mode" and not "Keep Mode".




With the switch open, briefly short the terminals of the capacitor to drain any residual charge. (Touch the capacitor leads simultaneously with the two leads of a loose wire.)

Click "Record", close the switch, and observe the charging of the capacitor on the screen meter. When the capacitor is charged up to nearly the full battery voltage, open the switch. The capacitor should remain at its present voltage, with a very slow drop over time. This indicates that the charge you placed on one of the capacitor plates has no way to move over and neutralize the opposite charge on the other plate.

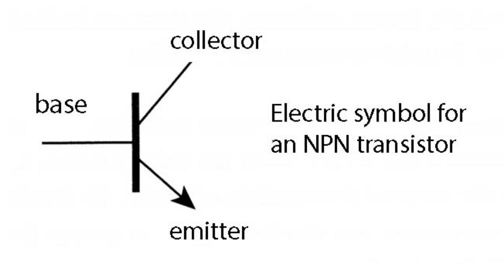
Click “Stop”. Prepare the computer to take data in a table of voltage as a function of time. At the bottom of the screen, set the sampling rate at 2 Hz. (The interface will then take a voltage reading every 0.5 second.) Close the switch, charge the capacitor to about 1.5 V, and switch the battery “off”. Click “Record”, and connect points A and C with a lead so the capacitor discharges through the resistor. Take data until the voltage of the capacitor drops below 0.05 V. Graph this data in Capstone or Excel. There may be a short section of curve at the beginning, before you completed the $RC$ circuit, where the charge is decreasing very slowly, and then a more rapid decrease as the capacitor discharges through the resistor.

We now want to determine the exponential slope of the curve: that is, to find the parameter “a” in a curve fit of $e^{-at}$. Click the “Highlight range of points...” button on top of the graph. A selection box will appear. Drag this box over the data of interest and then click inside the box to highlight the data. Click the “Apply selected curve fits...” button and choose “Natural Exponential”. the inverse of “a” should be $RC$. Make sure your graph is titled and the axes are labeled. <u>Beneath the graph, compare the experimentally determined value of RC with that obtained from the product of the measured resistance and the nominal capacitance.</u>

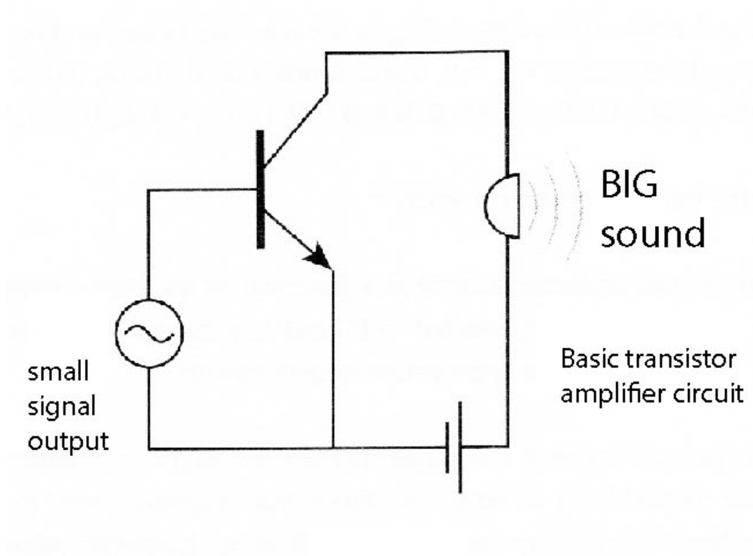
- **CIRCUIT 9: TRANSISTOR (additional credit up to 5 mills)**

This is a complicated additional credit assignment. Get yourself checked off on the rest of the experiment before starting it.

Transistors were probably not covered in class, so here is a brief introduction. A junction transistor has three connections: emitter, base, and collector.




Basically, a small current at the base controls a large current flowing in the emitter-collector circuit. For example, a small signal from a microphone input at the base can control a large current to a speaker. The transistor can therefore operate as an *amplifier*.




You don't get something for nothing; the large working current in the collector circuit must be supplied by an external source (in this case, the battery). The circuit above is barely functional. Normally, there would be resistors in the circuit to set the operating voltages of the transistor, capacitors to isolate the DC of the battery, and so forth. A stereo amplifier would have many amplification stages, with feedback and other arrangements to ensure that the amplification is linear (i.e., that the output is a faithful copy of the input, only larger).

A transistor can also operate as a switch. A small current at the base can switch on or off a larger current flowing in the emitter-collector circuit. A computer has thousands, perhaps millions, of transistors printed microscopically small on tiny circuit boards enclosed in the "chips" performing this function.

In this additional credit assignment, we will study the amplification property of a transistor. (Refer to the instructions below and the diagram on the following page.)

1. Wire up the circuit of Figure 13 on your circuit board. Use $R_1 = 1000\ \Omega$ and $R_2 = 100\ \Omega$. <u>Be sure your transistor is oriented as shown in the picture and connected properly. Also, double check the battery polarities; the short bar in the battery symbol is the negative terminal. Transistors are easy to burn out.</u>

2. Wire your multimeter on the millivolt scale to measure the voltage across $R_1$, and the computer voltage sensor to measure the voltage across $R_2$ on a digital scale to two places after the decimal (hundredths of a volt). By dividing these voltages by their respective resistances, you can determine the current flowing in the base circuit and the collector circuit.

3. Prepare a data table in your notes (or use Excel) with at least four columns and 20 rows. We will take data for $V_{\text{AB}}$ and $V_{\text{CD}}$, and compute their respective currents.

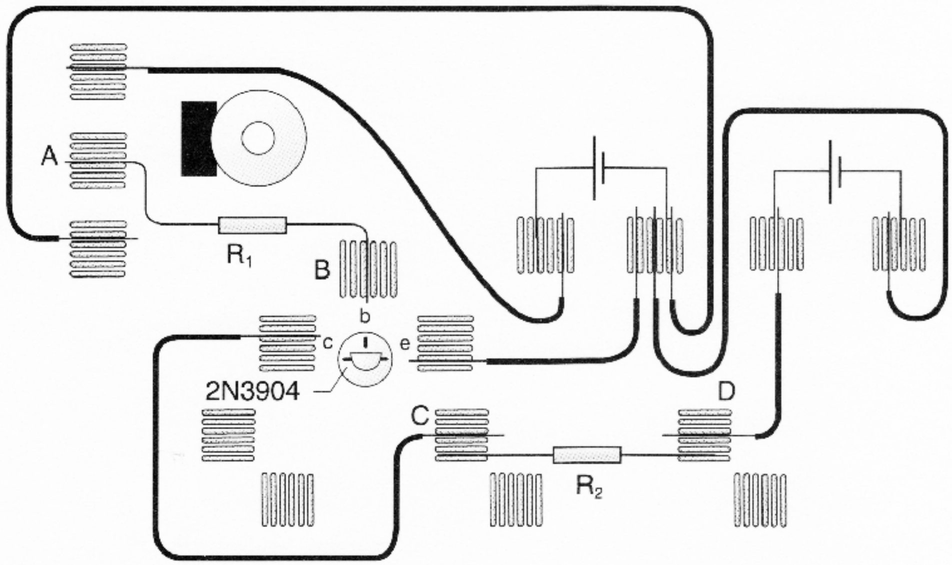
4. By adjusting the potentiometer, set $V_{\text{AB}}$ to the readings below, and record the corresponding $V_{\text{CD}}$ in the table: $V_{\text{AB}} = 0$, 0.002, 0.006, 0.010, 0.015, 0.020, 0.025, 0.030, 0.035, 0.040, 0.045, 0.050, 0.055, 0.060, 0.080, 0.100, 0.150, 0.200, 0.250 V.

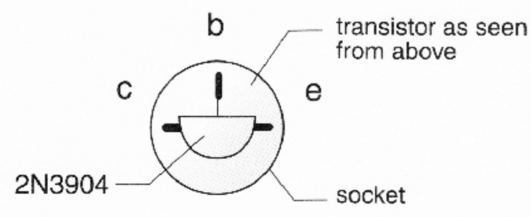
5. Calculate the corresponding currents.

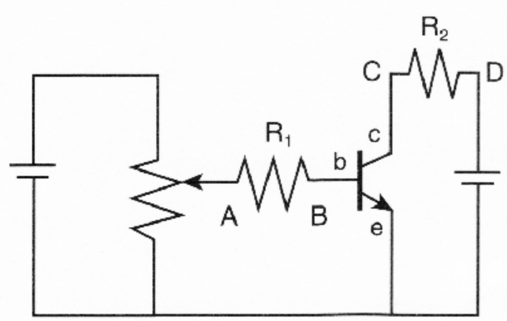
6. Plot a graph of the collector current as a function of the base current. If you find areas where more points are needed to fill out any curves or sudden changes, return to step 4 and make the appropriate measurements.

7. What is the general shape of the graph? Is there a straight-line region? Does it pass through the origin? Why or why not? Electronic engineers refer to the region of the curve where the collector current levels off as the transistor being *saturated*. At what current does this transistor saturate? What determines the saturation current?

8. The slope of the straight-line region is the current amplification of the transistor. Determine and record the current amplification.


A
R1
B
b
c
e
2N3904
C
D
R2


b
transistor as seen from above
c
e
2N3904
socket

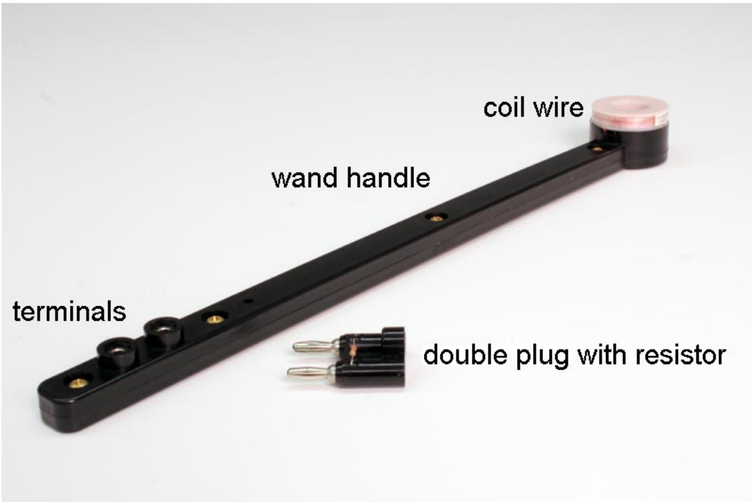

R2
C
D
R1
c
b
A
B
e

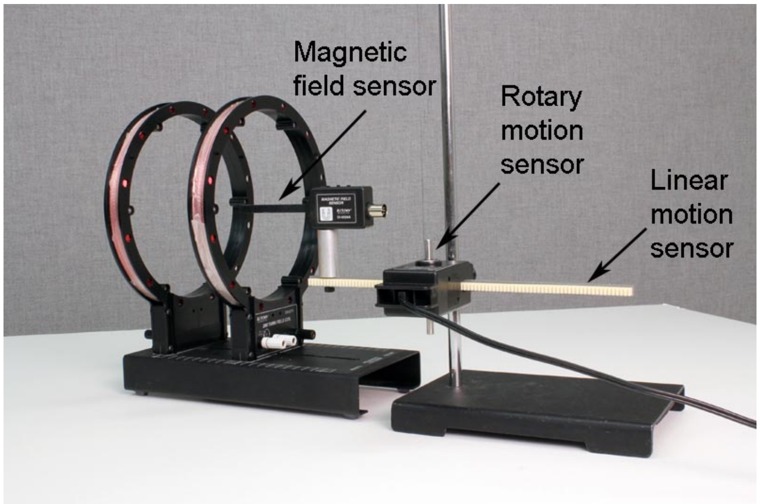
# Magnetic Fields of Coils and Faraday's Law

## APPARATUS

*Shown in the pictures below:*

- Stand with magnetic field sensor, linear motion rack, and rotary motion sensor
- Spacer to mount magnetic field sensor on linear motion accessory
- Helmholtz coils
- Two search coils with parallel 10-kΩ resistors




*Not shown in the pictures above:*

- Computer and interface
- Voltage sensor
- DC power supply to 2 A
- Fluke multimeter

- EZ angle protractor

## NOTE TO INSTRUCTORS

This experiment consists of two parts. Part 1 involves checking the magnetic field produced by a current loop, while part 2 is an investigation of Faraday's Law. Most students cannot complete these two parts in one lab session, so you should choose which part you would like them to perform. The default option (in which you do not express a preference) is part 2.

## MAGNETIC FIELDS

The most basic principle of electricity and magnetism is that charges exert forces on other charges. This picture is very simple if the charges are stationary: only the Coulomb force is present. Rather than describing the forces as action at a distance, however, we will use the field picture, whereby one charge creates a field, and other charges in the field feel forces from the field. If the charges are stationary, then only electric fields are involved; but if the charges are moving, magnetic fields also come into play. The field picture is used because the fundamental equations of electricity and magnetism — Maxwell's Equations — are much simpler when written in terms of fields than in terms of forces.

If a charge $q$ is stationary, then it creates only an electric field $\mathbf{E}$:

$$\mathbf{E} = q\mathbf{r}/4\pi\varepsilon_0 r^3. \tag{1}$$

A charge moving at velocity $v$ also creates a magnetic field $\mathbf{B}$:

$$\mathbf{B} = \mu_0 q\mathbf{v} \times \mathbf{r}/4\pi r^3. \tag{2}$$

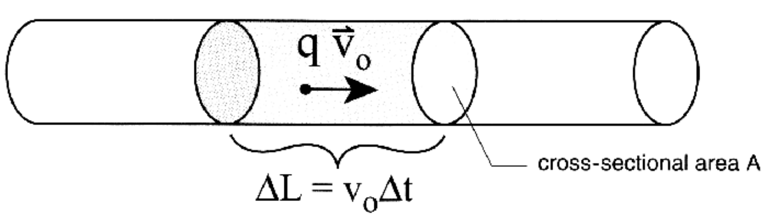
If a test charge is stationary, then it feels only an electric force $\mathbf{F}_E$:

$$\mathbf{F}_E = q\mathbf{E}. \tag{3}$$

If the test charge is moving, then it also feels a magnetic force $\mathbf{F}_B$:

$$\mathbf{F}_B = q\mathbf{v} \times \mathbf{B}. \tag{4}$$

Often for the case of magnetic fields, the moving charges are part of an electric current. Consider a current $i$ of charges $q$ moving at an average drift velocity $v_0$.




If the number of charges per unit volume in the material is $n$, then the total charge $\Delta q$ in the cylindrical volume of cross-sectional area $A$ and length $\Delta L = v_0\Delta t$ is $nqA\Delta L$, since the volume of the element is $A\Delta L$. Thus, the current $i$ which passes through one cap of the cylindrical element is

$$i = \Delta q/\Delta t = nqA\Delta L/\Delta t = nqA(v_0\Delta t)/\Delta t = nqAv_0. \tag{5}$$

To find the magnetic field produced by this element of wire, we need to sum the $qv_0$ terms in Eq. 2:

$$\mathbf{B} = \mu_0 \left(\sum q\mathbf{v}_0\right) \times \mathbf{r}/4\pi r^3. \tag{6}$$

In the cylindrical element, the total number of charges is $nA\Delta L$, so

$$\sum q\mathbf{v}_0 = (nqA\Delta L)\mathbf{v}_0 = i\Delta\mathbf{L}, \tag{7}$$

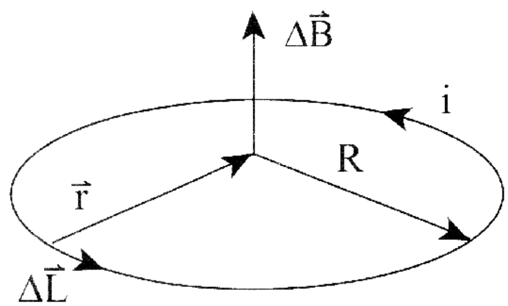
where we have used Eq. 5 in the last step, and have noted that $\Delta\mathbf{L}$ is in the same direction as $\mathbf{v}_0$. Thus, the magnetic field produced by this element of wire is

$$\Delta\mathbf{B} = \mu_0(i\Delta\mathbf{L}) \times \mathbf{r}/4\pi r^3. \tag{8}$$

Eq. 8 is the *Law of Biot and Savart.* (We call the magnetic field from this element $\Delta\mathbf{B}$ since there must be additional contributions to $\mathbf{B}$ from other parts of the wire carrying the current.)

## MAGNETIC FIELD AT THE CENTER OF A LOOP OF WIRE

Consider a circular wire loop of radius $R$ and carrying a current $i$. We are interested in the magnetic field at the center of the wire. (Of course, a real loop would need to be interrupted by a battery at some point to keep the current flowing through the resistance of the wire, unless the wire were a superconductor.)




For the current loop, the cross product $\Delta\mathbf{L} \times \mathbf{r}$ is perpendicular to the plane of the loop, so all the $\Delta\mathbf{L}$ terms contribute to the magnetic field in the same direction. Note that in this case, the magnitude of $\mathbf{r}$ (the vector from the current element to the observation point) is equal to $R$ (the radius of the loop). Therefore, to obtain the total magnetic field at the center of the loop, we need only to add all the $\Delta\mathbf{L}$ terms; no other quantities change as we move around the circle:

$$\int \mathrm{d}L = 2\pi R. \tag{9}$$

The magnitude of $\mathbf{B}$ for a loop is thus

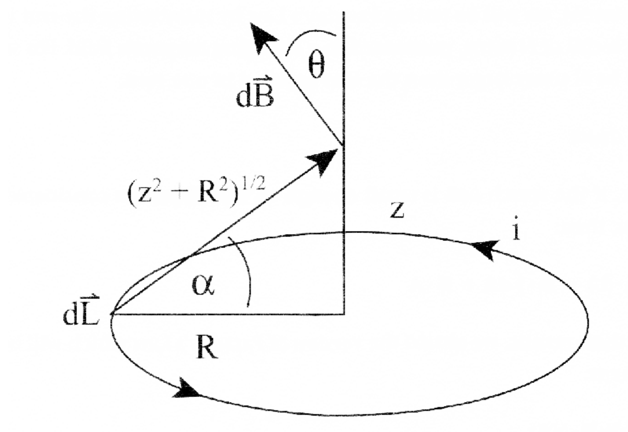
$$B = \int \mathrm{d}B = \mu_0 i \left(\int \mathrm{d}L\right) R/4\pi R^3 = \mu_0 i(2\pi R)R/4\pi R^3 = (\mu_0/4\pi)(2\pi i/R), \tag{10}$$

and the direction of $\mathbf{B}$ is perpendicular to the plane of the loop. If you curl the fingers of your right hand in the direction that the current (which, by convention, is positive) flows, then your thumb will point in the direction of $\mathbf{B}$.

For a loop of $N$ turns, the current is $N$ times the current in one turn, so the magnitude of $\mathbf{B}$ would be

$$B = (\mu_0/4\pi)(2\pi Ni/R). \tag{11}$$

Now let us find the value of $\mathbf{B}$ at a distance $z$ along the axis perpendicular to the plane of the loop.




Here the position vector $\mathbf{r}$ from the current element d$\mathbf{L}$ to the observation point a distance $z$ along the axis is the diagonal vector whose magnitude is $(z^2 + R^2)^{1/2}$. The magnetic field contribution d$\mathbf{B}$ is at an angle $\theta$ with respect to the $z$-axis. As we integrate around the circle, only the vertical $(\cos\theta)$ components add up; the horizontal $(\sin\theta)$ components are canceled by an equal contribution on the opposite side. Also note that the angle $\alpha$ is equal to $\theta$, from the geometry theorem that if two lines meet at an angle, then two other lines, each perpendicular to one of the first two lines, make the same angle. Thus, $\cos\theta = R/(z^2 + R^2)^{1/2}$, and the contribution of the magnetic field along the $z$-axis is

$$\mathrm{d}B_z = \mathrm{d}B\,\cos\theta = (\mu_0/4\pi)(Ni\mathrm{d}L/r^2)\cos\theta = (\mu_0/4\pi)[Ni\mathrm{d}L/(z^2 + R^2)][R/(z^2 + R^2)^{1/2}]. \tag{12}$$

Again, when we integrate around the loop, none of the other quantities change, so using $\int \mathrm{d}L = 2\pi R$, we obtain

$$B = (\mu_0/4\pi)[2\pi NiR^2/(z^2 + R^2)^{3/2}]. \tag{13}$$

You should be able to verify quickly that Eq. 13 reduces to Eq. 11 for $B$ at $z = 0$.

## FARADAY'S LAW

Conceptually, Faraday's Law tells us that changing magnetic fields induce electric fields. Mathematically, this law states that the emf $\mathcal{E}$ — the integral of the electric field around a closed path — is equal to the change in magnetic flux $\Phi$ through the path:

$$\mathcal{E} = \int \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\mathrm{d}\Phi/\mathrm{d}t, \tag{14}$$

where

$$\Phi = \int \mathbf{B} \cdot \mathrm{d}\mathbf{A} \tag{15}$$

The minus sign in Eq. 14 reminds us of Lenz's Law: the emf is induced in such a direction as to oppose the change in magnetic flux that produced it.

In this experiment, we will be testing Faraday's Law by monitoring the emf induced in a small search coil of $N$ turns, positioned in a changing magnetic field. For such a coil, the emf will be $N$ times larger than the emf induced in one turn:

$$\mathcal{E} = -N\,\mathrm{d}\Phi/\mathrm{d}t. \tag{16}$$

Furthermore, if the search coil is small enough so that $\mathbf{B}$ can be considered constant over the area, then

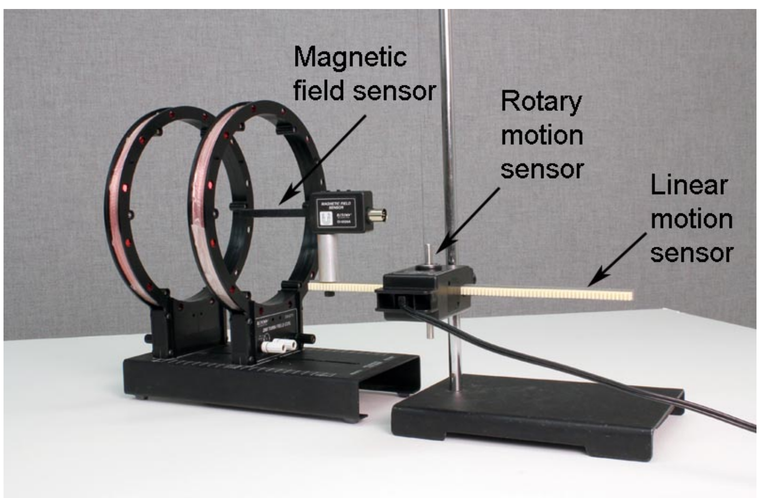
$$\Phi = \int \mathbf{B}\cdot \mathrm{d}\mathbf{A} = \mathbf{B}\cdot \int \mathrm{d}\mathbf{A} = \mathbf{B}\cdot\mathbf{A}. \tag{17}$$

Combining these results, we obtain the version of Faraday's Law which will be tested in this experiment:

$$\mathcal{E} = -(\mathrm{d}/\mathrm{d}t)(\mathbf{B}\cdot N\mathbf{A}). \tag{18}$$

The emf $\mathcal{E} = \int \mathbf{E}\cdot \mathrm{d}\mathbf{l}$ is quite similar to the potential difference $\Delta V = \int \mathbf{E}\cdot\mathrm{d}\mathbf{l}$, and can be measured with a voltmeter or the voltage sensor of Capstone.

## PROCEDURE — CHECKING THE MAGNETIC FIELD OF A CURRENT LOOP




1. We will be using the Rotary Motion Sensor with the Linear Motion Accessory to map the axial field of a current coil. Arrange your apparatus as shown in the diagram below. We are not using the second coil until step 8. It may be present, but should not be hooked to a power supply yet.

2. Open Capstone and Click "Graph & Digits". Click on "Hardware Setup" and add the Rotary Motion Sensor to the interface in Capstone. Insert its plugs into the appropriate digital channels. Also call up the Magnetic Field Sensor in the setup window, and insert the physical plug into analog channel A.

3. For magnetic field measurements, the coil draws power from the DC power supply, which is wired through the Fluke Multimeter to measure the current to the coil. Be sure to turn the coarse and fine voltage controls of the power supply to zero before switching on the power supply; otherwise, the initial current may be too large and blow the fuse in the Multimeter. To measure a current, the Multimeter must be in series with the power source. Wire one lead from the ground of the DC power supply to the "Common" plug of the Multimeter. Wire a second lead from the mA plug of the Multimeter to one of the coil plugs. The second coil plug is wired back to the other output plug of the power supply. Wire directly to the coil leads; do not use the built-in series 1.2-kΩ resistor in this part of the experiment. Set your Multimeter to read on the 2000-mA DC scale.

4. Set the voltage control of the power supply to zero, turn on the power supply, and adjust the coarse and fine voltage controls slowly until you obtain a current of 1000 mA = 1A.

5. Make a preliminary check of the magnetic field of the coil. Carefully position the end of the Magnetic Field Sensor at the center of the coil. (We are not making computer use of the rotational sensor yet.) Use the controls on the Magnetic Field Sensor (hardware) to set it to radial mode and 10× reading. Click "Select Measurement" in the digits box and choose "Magnetic Field Strength (10×)(T)". Turn "OFF" the current to the coil from the power supply, and click "Start" to see the gauss reading of the sensor. Push the "Tare" button on the sensor to zero the magnetic field reading. It is a good idea always to zero the Magnetic Field Sensor with zero current before recording measurements with the current on. Even when zeroed, the reading may jump around a bit. Now turn the power supply back on, and record the magnetic field reading and the current. (If your magnetic field measurements have negative values and you don't like this, then reverse the leads to the power supply.)

   Magnetic field (gauss) = ______________________________

   Current (mA) = ______________________________

   Compare your measured magnetic field with the calculated field from $B = (\mu_0/4\pi)(2\pi Ni/R)$ (Eq. 11). Remember that $\mu_0/4\pi = 10^{-7}$ Tm/A, and you can read off the value of $N$ (the number of turns) and $R$ (the radius of the coil). Be sure to put $R$ and $i$ in the proper SI units. This formula gives $B$ in teslas; convert to gauss using 1 tesla = $10^4$ gauss.

   Calculated magnetic field (gauss) = ______________________________

   Percentage error = ______________________________

6. Now arrange the stand with the Magnetic Field Sensor to map the magnetic field of the coil along its axis. Your arrangement should be such that as you turn the Rotary Motion Sensor, the Magnetic Field Sensor starts on one side of the coil, passes through the center of the coil, and moves beyond the other side — always staying on the axis of the coil. Click "Select Measurement on the $x$-axis of the graph and choose "Position (m)". Plot the magnetic field on the $y$-axis. Make a trial run by turning off the current, zeroing the magnetic field reading with the "Tare" button, turning on the current, clicking "Record", and moving the sensor through the field by rotating the pulley wheel on the Rotary Motion Sensor. Rotate smoothly — although the speed is not important, since we are not plotting anything as a function of time. You should see a nice graph of the magnetic field plotted against the axial distance.

7. After any readjustments, when you have a nice plot on the computer, you may print it out. DO NOT DISCARD THE DATA. Save it in a file, which you can retrieve, on the desktop. You may use it later for additional credit.

8. Now wire the second coil in parallel with the first. You want the currents in the coils to flow in the same direction, so the magnetic fields of the two coils add in the space between the coils. Again, adjust the voltage of the power supply so the current to each coil is 1 A (with a total current of 2 A). Arrange the stand with the Magnetic Field Sensor to move along the axis of both coils, particularly covering the area between them. Take three measurements of $B$ versus axial distance with the coil separations equal to $0.5R$, $1.0R$, and $1.5R$, where $R$ is the radius of the coils. (In order to make the three graphs comparable, start each measurement with the end of the Magnetic Field Sensor at the center of one coil. If the leads of the second coil prevent you from moving it to the $0.5R$ distance from the first coil, how can you manipulate the apparatus to make this measurement possible?) Arrange a graph on the computer so that all three plots appear on the same graph aligned vertically. You may print this page out for your records.

   What coil separation produces the most uniform magnetic field between the coils?

   __________________________________________

   This arrangement is called *Helmholtz coils*, and is a method of producing a relatively constant, controllable magnetic field over a considerable volume of space. Of course, we have just measured the magnetic field along the axis, but the field is fairly uniform throughout much of the volume of space between the coils. We used this property of Helmholtz coils in the previous $e/m$ experiment.

## PROCEDURE — FARADAY'S LAW

1. Disconnect and set aside the power supply, the multimeter, and the stand with the Magnetic Field Sensor. Start with a new Capstone display, being sure to save the data you might need for the additional credit.

2. Wire the signal generator output of the Science Workshop interface to one of the coils, including the 1.2-k$\Omega$ resistor in series. We will call this the "field coil". Since the resistance of the coil itself is negligible compared to the 1.2 k$\Omega$ of the resistor, the voltage of the signal generator divided by 1.2 k$\Omega$ gives the current through the field coil.

3. Wire a voltage sensor (just an analog plug with two leads) to the 2000-turn search coil, and set it up in Capstone. The search coils have 10-k$\Omega$ resistors in parallel to damp out oscillations. On the computer screen, Click on "Signal Generator" and then "SW750 Output". Set the signal generator to a 5-V triangle wave at 2000 Hz, turn it on, click "Record". Set up a scope display with two traces to measure both the voltage output of the signal generator and the output of the voltage sensor(use the "Add new $y$-axis to scope display" button). Select the signal generator voltage so the scope triggers on this signal.

4. Check the trigger setting if the wave on the scope is not stable (Use the "Activate and control scope trigger" button). Now when you bring up the search coil inside the field coil and in the same plane, and adjust the voltage sensor signal on the scope to greater sensitivity, you should see a square wave trace, possibly with some fluctuations. Notice that when you click "Stop", the last scope trace remains fixed in the scope window, facilitating some of the measurements below.

5. Faraday's Law (Eq. 18) states that $\mathcal{E} = -(\mathrm{d}/\mathrm{d}t)(\mathbf{B} \cdot N\mathbf{A})$, where $\mathcal{E}$ is the emf induced in the search coil (which you are measuring with the voltage sensor). **B** is the magnetic field of the field coil, which is proportional to the current flowing through it; this current, in turn, is proportional to the triangle wave voltage from the signal generator. **A** is the area vector of the search coil, and $N$ is the number of turns of the search coil. The cosine of the dot product between **B** and **A** is 1.0 if the search coil is in the same plane as the field coil.

   Study your two scope traces, and explain clearly, briefly, and neatly the shape and the phase of the voltage sensor output using the equation above.

   ________________________________________

   ________________________________________

   ________________________________________

   ________________________________________

## PROCEDURE — DEPENDENCE OF $\mathcal{E}$ ON $\mathrm{d}i/\mathrm{d}t$

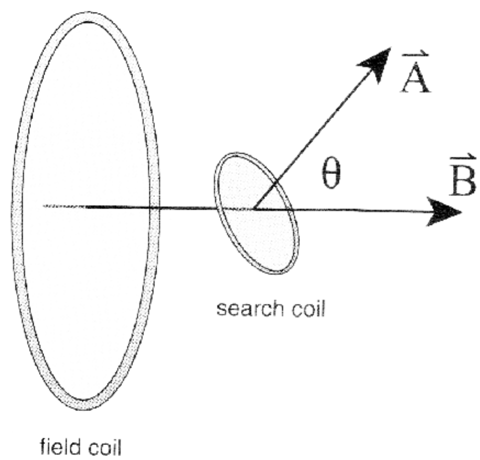
1. As you can see from Faraday's Law, $\mathcal{E}$ is proportional to $\mathrm{d}i/\mathrm{d}t$ (where $i$ is the current through the field coil), since $B$ of the field coil is proportional to $i$. In turn, $\mathrm{d}i/\mathrm{d}t$ is related to the frequency for a triangular wave. Write down the correct equation relating $\mathrm{d}i/\mathrm{d}t$ to the frequency $f$ and amplitude $i_\mathrm{m}$ for a triangular wave.

   ________________________________________

2. Check this relation. Measure $\mathcal{E}$ at 500, 1000, 1500, 2000, and 2500 Hz. Enter your data in a new Excel worksheet, chart $\mathcal{E}$ as a function of $f$ with a clear title and labels on the axes. You may print out the graph for your records. Be sure you position the search coil in the same place at the center of the field coil when making each measurement.

## DEPENDENCE OF $\mathcal{E}$ ON THE DOT PRODUCT WITH THE AREA VECTOR

1. Devise a way to use the EZ angle protractor to adjust the dot product angle in $\mathbf{B} \cdot N\mathbf{A}$ between the area vector of the search coil and the magnetic field (perpendicular to the field coil plane). The search coil should be at the center of the field coil for each measurement. It may help to have both lab partners holding parts of the equipment. Remember that when you click "Stop", the signal will remain on the scope for easy measurement.




2. Keeping the frequency and amplitude of the triangle wave constant, measure $\mathcal{E}$ for dot product angles of 0°, 30°, 45°, 60°, and 90°. Record your data in a new Excel worksheet, compute the cosines with a fill-down operation, and chart $\mathcal{E}$ as a function of the cosine of the angle. Title the chart and label the axes clearly. You may print it out for your records.

## PROCEDURE — DEPENDENCE ON $N$

1. We have been using the 2000-turn search coil up to now. Measure $\mathcal{E}$ with a triangle wave of amplitude 5 V and frequency 2000 Hz, using the 2000-turn search coil at the center of the field coil and in the same plane. Now, what should $\mathcal{E}$ be with a 400-turn search coil? Repeat the measurement with the 400-turn coil, and record your result below.

   Predicted $\mathcal{E}$ with 400 turns = ______________________________

   Measured $\mathcal{E}$ with 400 turns = ______________________________

## PROCEDURE — SINE WAVES

1. If the current to the field coil is a sine wave, what form of wave (including phase information) should the induced $\mathcal{E}$ take? Verify this with your equipment.

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## ADDITIONAL CREDIT (5 mills maximum)

Before you start the additional credit, check that you have the following graphs with good data, titles, and labeled axes:

a. Magnetic field versus axial distance for a single coil.

b. Three magnetic field measurements versus axial distance for three different coil separations plotted on the same graph.

c. An Excel chart of $\mathcal{E}$ versus $f$.

d. An Excel chart of $\mathcal{E}$ versus the cosine of the angle of the dot product.

The magnetic field on the axis at a distance $z$ from a current coil of radius $R$, $N$ turns, and current $i$ is given by Eq. 13:

$$B = (\mu_0/4\pi)\left[2\pi N i R^2/(z^2 + R^2)^{3/2}\right]. \tag{19}$$

Go back to the data that you saved earlier for the magnetic field along the axis of the coil. Set up a calculation in Capstone for the equation above, and plot it on the same graph as the magnetic field data so you can compare the theoretical magnetic field with the measured field. The reward is 5 mills if you have a neatly labeled printout, done without significant assistance from your TA. If you need assistance, you can "buy" varying amounts by giving up some of the 5 mills. Here are a couple of hints: $B$ in the equation above is in teslas, but the measured field is in gauss, so include the conversion to gauss in your calculation of the theoretical field. You will also need to change the origin of the $z$-axis in the calculation to match the position of the center of the coil for your measured field.

# Radioactivity

## APPARATUS

- Computer and interface
- Geiger-Muller detector
- Co and Sr sources
- Source and detector holder
- One in lab: neutron source with bars and silver foil

## INTRODUCTION

In this experiment, you will use weak radioactive sources with a radiation counting tube interfaced with the computer to study radioactive decay as a function of time.

## RADIATION SAFETY

California State Law requires that a permanent exposure record be filed for all persons who handle radioactive material. Therefore, everyone enrolled in the lab must be registered by the course instructor with the University Environmental Health and Safety Office. Your TA will pass out the radioactive sources for this experiment only after you print your name on the Physics Laboratory Class Roster. You are responsible for the safe return of the sources at the end of the laboratory period. Failure to comply with safety rules or failure to return the sources will result in expulsion from the course and a grade of F.

It is a University of California rule that pregnant women are not permitted to participate in the radioactivity experiment or to be in the lab room where these experiments are performed. If you think you may be pregnant, discuss it privately with your TA. He or she is authorized to excuse you completely from this experiment.

Radioactive materials are potentially dangerous to your health and should always be handled with great caution. It is a prudent practice to wash your hands thoroughly after this experiment is finished.

## THEORY

Radioactivity was discovered by Henry Becquerel in 1896. Becquerel found that compounds of uranium would expose a photographic film, even in total darkness. Marie Curie took up the research topic, coined the term radioactivity, and determined that this effect was independent of the chemical compound in which the radioactive element was found and independent of any pressures or temperatures that could be produced. In other words, radioactivity was somehow an internal property of the element itself. Marie Curie later isolated the previously unknown elements polonium and radium, and won two Nobel prizes for her work, the first of which was shared with Becquerel and her husband Pierre Curie. She and other researchers soon established that the energies per atom emitted by radioactive decay were millions of times larger than chemical energies, and that transmutation of the elements was involved.

Early researchers discovered that radiation from natural radioactive elements came in three types: (1) alpha ($\alpha$) rays, which traveled in a curved path similar to positively charged particles in a magnetic field; (2) beta ($\beta$) rays, which traveled in a curved path similar to negatively charged particles in a magnetic field; and (3) gamma ($\gamma$) rays, which traveled in a straight line in a magnetic field and were therefore neutral. Today we know that alpha "rays" are helium nuclei, beta "rays" are high-energy electrons, and gamma "rays" are high-energy photons (particles of light). Certain isotopes of radioactive elements emit positive electrons called positrons or $\beta+$ particles.

As an example, $\alpha$ particles are emitted in the decay of natural uranium:

$$_{92}\mathrm{U}^{238} \;\rightarrow\; {}_{90}\mathrm{Th}^{234} + {}_{2}\mathrm{He}^{4}. \tag{1}$$

(The $_2\mathrm{He}^4$ nucleus is the $\alpha$ particle.) With the emission of $\beta$ particles, a neutron changes into a proton (or vice versa) :

$$_{6}\mathrm{C}^{14} \;\rightarrow\; {}_{7}\mathrm{N}^{14} + \mathrm{e}^{-} + \;? \tag{2}$$

(The e- is the $\beta$ particle. We will discuss the ? below.) Gamma rays are emitted when an excited state of a nucleus makes a transition to a lower level, in the same way that an atom emits a photon of ordinary light when it is deexcited. Excited states of nuclei are denoted by an asterisk ($*$):

$$_{28}\mathrm{Ni}^{*60} \;\rightarrow\; {}_{28}\mathrm{Ni}^{60} + 2\gamma. \tag{3}$$

The unique characteristics of $\alpha$, $\beta$, and $\gamma$ particles are responsible for differences in the ways that these particles lose energy when passing through matter. For example, shown below are the typical ranges of 8 million electron-volt (8 MeV) particles in aluminum:

$$\text{Range in meters: } \alpha = 0.00006\beta = 0.02\gamma = 0.2. \tag{4}$$

The description of $\beta$ decay given above is actually somewhat incomplete and must be expanded in the context of the range of $\beta$ particles in matter. While $\alpha$ and $\gamma$ particles are found to have definite energies (dependent only on the emitter), $\beta$ particles emitted by a single nuclide can have any energy between zero and some definite maximum value. Careful examination of this fact in the context of a definite decay scheme, such as Eq. 2, led scientists to conclude that $\beta$ decay violates the three basic conservation laws of energy, momentum, and angular momentum. Enrico Fermi noted in 1934 that if an additional neutral particle were emitted in $\beta$ decay, the three conservation laws would remain intact. Such neutral particles have actually been found and are called *neutrinos*. Thus, the correct description for the decay in Eq. 2 is

$$_{6}\mathrm{C}^{14} \;\rightarrow\; {}_{7}\mathrm{N}^{14} + \mathrm{e}^{-} + \nu, \tag{5}$$

where $\nu$ is the neutrino emitted in $\beta$ decay.

## HALF LIFE

Radioactive substances are unstable. They transmute from one isotope to another by the process of radioactive decay until they reach a stable isotope. The number of nuclei $\Delta n$ that decay in the subsequent time interval $\Delta t$ is proportional to the number of non-decayed nuclei $n(t)$ present and to the time interval $\Delta t$. Thus, we can write

$$\Delta n = -n(t)\,\lambda\,\Delta t. \tag{6}$$

The minus sign accounts for the fact that $n(t)$ decreases with time, and $\lambda$ is a proportionality factor called the *decay constant*. Eq. 6 leads to

$$\mathrm{d}n/\mathrm{d}t = -n(t)\,\lambda, \tag{7}$$

which can be integrated to

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where $n_0$ is the number of nuclei at $t = 0$.

We define the *half-life* $t_{1/2}$ as the time required for half of the parent nuclei to decay. Then

$$n/n_0 = 1/2 = e^{-\lambda t_{1/2}}. \tag{9}$$

Taking the natural logarithm of Eq. 9 leads to

$$\ln(1/2) = -\lambda t_{1/2}, \tag{10}$$

or

$$t_{1/2} = (\ln 2)/\lambda. \tag{11}$$

Since it is easy to obtain $\lambda$ from the slope of the exponential, Eq. 11 can be used to determine half-lives.

In this experiment, we will be measuring the half-lives of two silver isotopes. The radioactive silver is prepared in the lab by irradiating silver foil with neutrons. A strong neutron source is contained in a heavy shielded tank operated by the radiation safety officer. Inside the tank is a mixture of plutonium and beryllium. The radioactive plutonium emits $\alpha$ particles which react with beryllium according to the scheme

$${}_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 \;\rightarrow\; {}_6\mathrm{C}^{12} + \mathrm{n}. \tag{12}$$

Natural silver consists of the two isotopes ${}_{47}\mathrm{Ag}^{107}$ and ${}_{47}\mathrm{Ag}^{109}$. The neutrons react with them according to these schemes:

$$\begin{align} {}_{47}\mathrm{Ag}^{107} + \mathrm{n} \;&\rightarrow\; {}_{47}\mathrm{Ag}^{108} \tag{13}\\ {}_{47}\mathrm{Ag}^{109} + \mathrm{n} \;&\rightarrow\; {}_{47}\mathrm{Ag}^{110}. \tag{14}\end{align}$$

Some of the silver is produced in an excited state, and both isotopes decay via $\beta$ and $\gamma$ emission, but with very different half-lives. The decay schemes for the isotopes are as follows:

$$\begin{align} {}_{47}\mathrm{Ag}^{108} \;&\rightarrow\; {}_{48}\mathrm{Cd}^{108} + \mathrm{e}^- + \nu && \text{short half-life (seconds)} \tag{15}\\ {}_{47}\mathrm{Ag}^{*108} \;&\rightarrow\; {}_{48}\mathrm{Cd}^{108} + \mathrm{e}^+ + \nu && \text{greater than 5-year half-life} \tag{16}\\ {}_{47}\mathrm{Ag}^{110} \;&\rightarrow\; {}_{48}\mathrm{Cd}^{110} + \mathrm{e}^- + \nu && \text{short half-life (seconds)} \tag{17}\\ {}_{47}\mathrm{Ag}^{*110} \;&\rightarrow\; {}_{48}\mathrm{Cd}^{110} + \mathrm{e}^- + \nu && \text{253-day half-life.} \tag{18}\end{align}$$

In each case where an isotope of cadmium (Cd) is produced by $\beta$ decay, the nucleus is formed highly excited. The nuclei are stabilized by subsequent $\gamma$ emission, where the half-life is very much shorter than a microsecond. Hence, the decay rates of the radioactive silver isotopes to the stable isotopes of cadmium are completely governed by $\beta$ decay.

As you can see from the decay schemes above, there are actually two different ways each isotope of silver can undergo $\beta$ decay. One method, corresponding to the long half-life, is relatively improbable. The other method, however, occurs quite often and implies a relatively short half-life (of the order of minutes). In this part of the experiment, you will determine the short half-lives of the radioactive silver isotopes.

The proportion of two short-lived cadmium isotopes present in your specimens after irradiation depends on the probability of process 13 compared with process 14, and also on the relative concentrations of the two silver isotopes in the sample. Rather than determining the concentration of each isotope separately and studying its decay, we will utilize a simple and useful technique for half-life determinations that depends only on an accurate measurement of the variation of count rate with time.

In half-life measurements (which we will perform below), Eq. 8 gives the number of parent radioactive material left after a time t:

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where $\lambda$ is related to the half-life. A common goal is to determine the slope $\lambda$ of the exponential. Exponential relationships such as these are common in scientific work, so we would like a rapid way of obtaining the slope and checking the fit. If we plot them on ordinary graph paper, then the slope would be the curve of the exponential. A curve-fitting program could fit an exponential to the experimental curve and determine the value of the slope, but it would still be difficult to see at a glance how good the fit is.

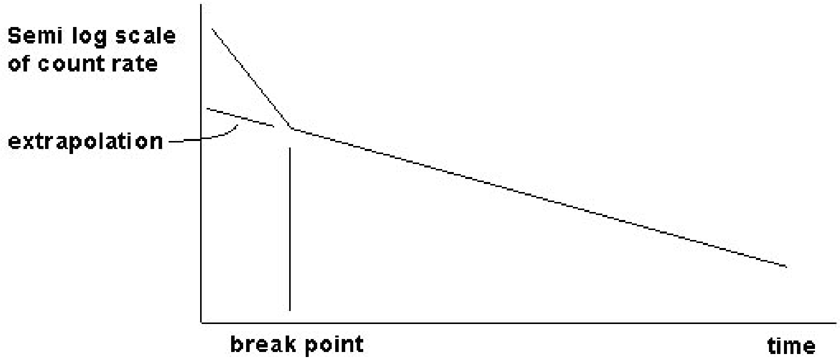
Instead, we will plot these relationships on a special kind of graph: a *semilog* graph. In a semilog graph, the exponential relationship becomes a straight line. The $y$-axis is the logarithm of the dependent variable, and the $x$-axis is the independent variable treated in the normal linear manner. Taking the natural logarithm of Eq. 8, we find

$$\ln n(t) = \ln n_0 - \lambda t. \tag{19}$$

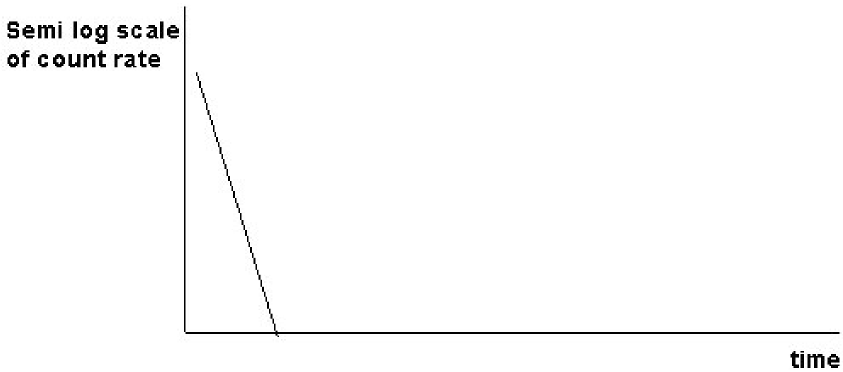
Note that the logarithm of the dependent variable ($n(t)$ in this case) now satisfies a linear relation, and can therefore be plotted as a straight line on a semilog graph. In addition, the slope of the semilog graph is equal to the coefficient $-\lambda$ of the exponential.

If the radioactive decay of only a single isotope were involved, then a semilog plot of the count data as a function of time would look as follows:

The slope of the exponential is the negative of the decay constant $\lambda$, and the half-life can be determined from Eq. 11. In our case, two isotopes are decaying at different rates, so the semilog plot looks more like Figure 2:




At long times, the slope of the graph is controlled by the longer of the two half-lives. This is sufficient to determine the long half-life, since essentially all of the short-lived isotope has decayed. By extrapolating this longer time region back to $t = 0$, one can subtract out the effect of the long-lived isotope. This corresponds to determining the contribution of the long-lived isotope to the full rate at each time and subtracting it out. From a semilog plot of the remaining data, one can determine the short half-life from the slope of its exponential:




## ANALYSIS WITH SEMILOG PLOTS

Some of the older Excel programs will perform semilog plots directly, but other recent versions do not have this feature. It is possible to do a semilog plot by hand on special semilog graph paper. However, once we have a list of the count data in an Excel column, we can simply take the logarithms of the data in the next column with the "Fill Down" operation and plot the logarithms of the counts as functions of time.

By convention, base 10 logarithms are written as just "log" (no subscript), and logarithms of base $e = 2.718\ldots$ are written as "ln". Our purpose in plotting the semilog graph of the count data is to determine the break point, as in Figure 2. Therefore, it does not matter whether we take the base 10 logarithms (log) or the base e logarithms (ln), since these quantities are related by a constant. Either the log or ln of the count data as functions of time will plot as a straight line (for a single isotope).

The basic definition of the logarithm function gives

$$x = b^{\log_b x}, \tag{20}$$

where $\log_b$ is base $b$ logarithm. Using $x = e \ln x$, we find a conversion between base 10 logarithms (log) and natural logarithms (ln) :

$$\log x = (\log e)(\ln x). \tag{21}$$

Since the different base logarithms are related by a constant ($\log e$), data that plot as a straight line in one base will also plot as a straight line in the other base.

## STATISTICS IN RADIOACTIVITY MEASUREMENTS

The process of radioactive decay is completely random. Quantum mechanics can predict the probability of a decay per second, but the time at which any particular nucleus decays cannot be predicted, even in principle. Thus, with a sample of radioactive material, the number of nuclei that will probably decay in any time period (such as the 10-second intervals we will be using in the experiments below) is determined by the half-life, but there will be random variations in the number that decay in any particular 10-second interval. The same is true of the background radiation from cosmic rays and terrestrial radioactivity: the counts detected by a Geiger counter come at random, although they have a *mean* or average rate. For example, here is a list of the counts during 10-second intervals, taken in the Knudsen nuclear lab, where the neutron source and several other sources are stored:

$$9, 18, 7, 13, 8, 11, 8, 8, 9, 12, 5, 8, 5, 13, 9, 8, 9, 12, 9, 6, 8, 5, 8, 15, 10, 5, 11, 12, 9, 8.$$

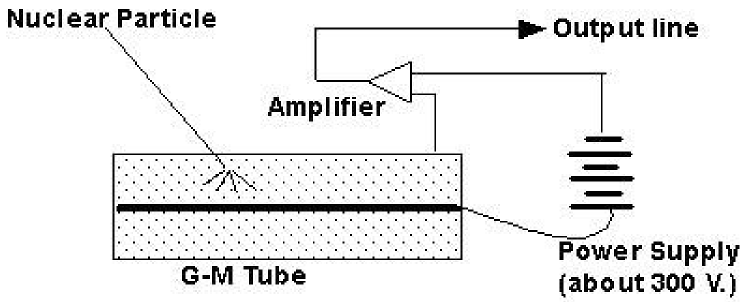
The computer calculates quickly and automatically the mean number of counts as 9.3, but also gives another number called the *standard deviation* (denoted by $\sigma$). The standard deviation is a measure of the spread in the number of counts. For the numbers above, $\sigma = 3.1$. This means that 68% of the counts in any 10-second interval fall between (9.3 − 3.1) counts and (9.3 + 3.1) counts. Please refer to the additional credit section for more discussion.

The standard deviation has an exact definition in the science of statistics. In fact, when any experimental measurement is taken, there will be a spread in the values of the measurements along a bell-shaped curve that can be described by a standard deviation. An example is if we had a large number of students measure the length of the same lab bench with a meter stick; we would find that these measurements also fit a bell-shaped curve with a mean and standard deviation.

## THE GEIGER-MULLER TUBE

The experiments below use a Labnet Geiger-Muller (GM) detector which is plugged into one of the digital channels of the Pasco signal interface. When you look into the transparent cylinder of the detector, the actual GM tube is the copper cylinder at the bottom end, which appears similar to a large bullet cartridge. The rest of the electronics inside the transparent tube consists of the power supply for the GM tube which operates at 300 − 400 V DC, and the digital interface that amplifies the GM pulses and converts them to digital pulses accepted by the signal interface box.

The GM tube is a closed cylinder containing a gas mixture which includes a halogen compound. A thin wire filament is aligned along the tube axis and maintained at a large positive voltage with respect to the outer wall. When an ionizing particle ($\alpha$, $\beta$, or $\gamma$) passes through the gas, ion-electron pairs are created. The electrons are quickly drawn to the center wire by the strong electric field, where they are collected as a “pulse” of current.




This current pulse is electronically amplified and then sent on to the signal interface. Another function of the gas is to quench the electrical breakdown quickly so that the system can count successive pulses separated in time by very small intervals. Halogens are found to be particularly effective for this purpose.

Because $\beta$ rays are easily stopped by the outer metal cylindrical shell, it is necessary to construct the GM tube with a very thin (about 1.5 mg/cm2) mica window at one end. Be careful with this end window, as it is easily damaged, rendering the tube useless and irreparable.

## PROCEDURE PART 1: THE NUCLEAR SENSOR

Pasco's generic name for the GM detector is "Nuclear Sensor". The device itself is labeled "GM - Detector". However, in the analog sensor menu of the Capstone, it is called a "Geiger Counter". These names all refer to the same instrument.

The device has a plastic cap over the detector end for protection. The actual GM tube is recessed in the plastic cylinder at the end of the detector. Remove the plastic cover for use, and replace it when you are finished. The GM tube itself has a delicate, thin mica window at its end through which radiation passes. If this window is damaged, the tube is ruined, so be careful not to poke anything into the plastic cylinder or to push the tube toward anything that pokes out.

1. Turn on the interface and the computer.

2. Call up Capstone.

3. The GM detector has a line-cord plug and a phone-cord interface to the digital plug which goes into the signal interface. When the line cord of the GM detector is plugged in, a neon bulb inside lights up, indicating that the instrument has power. The other neon bulb flashes intermittently as each count is detected. This happens whether or not you are recording or monitoring and even if there are no radioactive materials nearby, because the tube detects stray cosmic rays and terrestrial radioactivity that are always present.

4. Choose the "Table & Graph" option in Capstone. Under "Hardware Setup", click on Channel 1 of the interface and select "Geiger Counter". At the bottom of the screen, change the sample time to 10 seconds. This will give you one measurement every 10 seconds of recording time. Click on the $y$-axis of the graph and select "Geiger Counts (counts/sample)". Click on "Select Measurement" in your table and choose "Geiger Counts (counts/sample)". If your watch has a continuously illuminated night dial, it may contain a small amount of radioactive material. Check the watch with the detector if you wish, and take it off and move it some distance away

if you find that it is radioactive.

5. Move all radioactive materials at least one meter from the detector and take a background count by clicking "Record" and counting for 100 – 120 seconds. Then click "Stop". Your table should now have approximately 10 entries for the count every 10 seconds.

6. When you click the $\sum$ symbol on the table, the computer will calculate the mean count and standard deviation below (along with the minimum and maximum count). Record the mean background count and its standard deviation. Your count will be higher than "normal" if your lab station is close to the neutron source used in the half-life measurement below.

   Background count (mean) = ______________________________

   Standard deviation = ______________________________

PROCEDURE PART 2: HALF-LIFE MEASUREMENTS

(The instructions for Excel are abbreviated, as it is assumed that you are familiar with the operations.)

1. Check that you are counting for 10-second intervals. Prepare your computer to start taking count data on the next mouse click by setting the mouse arrow on the "Record" button.

2. When you are ready, the radiation safety officer will hand you a rod with the activated silver foil on the end. As quickly as possible, but still being careful, place the rod in the holder with the silver close to the GM counter, and click to start recording. Stop after approximately 10 minutes.

3. Copy the silver count data from your table into a column of a new Excel worksheet.

4. Subtract out the background count in the next column of the worksheet.

5. Use the "Fill Series" operation to fill the next column of the worksheet with the time of the center of the 10-second intervals (i.e., 5, 15, 25, etc.), up to 10 minutes.

6. Use the "Fill Down" operation to take the logs or lns of the count data (it doesn't matter which) in the next column.

7. Chart the logs of the data as functions of time. (Select and chart the last two columns.) This semilog chart should look something like Figure 2: a straight line of steeper slope breaking to a line of shallower slope, corresponding to the two half-lives involved. The data at large times is likely to look ragged due to fluctuations in the statistics. We now wish to extract the two half-lives.

8. Locate the break point in time where the slope changes at about 150 seconds.

   Break point = ______________________________

9. Back in Excel, select and chart only count data after the break point. (Chart the actual data, not their logs.) Select the data points on the chart, and use the trendline operation to fit an exponential curve. Check the box for "Equation on Chart" to obtain the slope of the

exponential. From this slope, extract the longer half-life using Eq. 11, and record this half-life below.

Longer half-life = ______________________________

10. To obtain the shorter half-life, start a new column in Excel, and subtract from the background-corrected data, the data for the longer half-life using the equation that you obtained in step 10. (Your entry before "Fill Down" will look something like "= C4 - 609*exp(-0.0035*B4)".)

11. Chart the resulting data, and extract the shorter half-life as before with the trendline operation.

    Shorter half-life = ______________________________

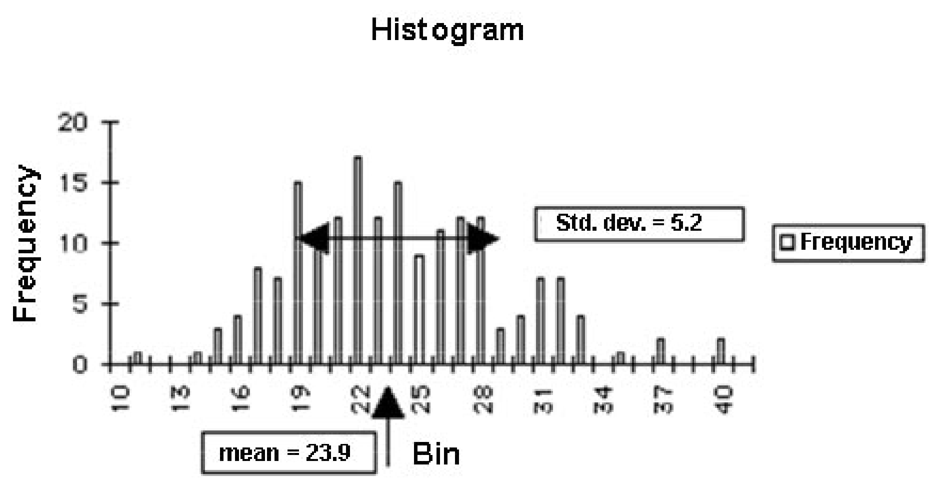
12. Rearrange your Excel tables and charts neatly on one or two sheets.

## ADDITIONAL CREDIT: HISTOGRAM OF NUCLEAR STATISTICS (up to 3 mills)

Prepare an annotated histogram of radiation counting data in Capstone (2 mills) or Excel (3 mills). The additional credit is for figuring out how to do this without the help of your TA.

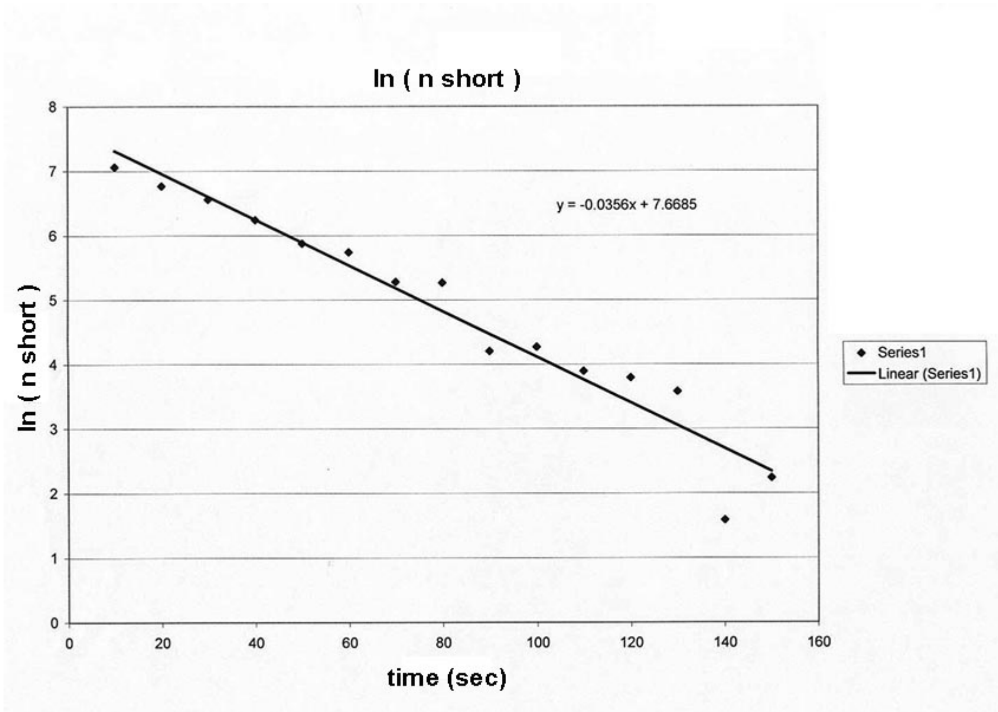
Obtain a sample of radioactive material in plachet form from the radiation officer, and place it near the GM counter front. Arrange the GM tube, plachet, and shielding pieces so that you are obtaining a fair number of counts in the 10-second intervals (say, 50 – 100). Count for 10 minutes or so.

Calculate the mean count and standard deviation. Use the "Help" sections of the programs if needed. For Excel, pull the "Tools" menu down to "Data Analysis", and choose "Histogram". Follow the instructions, using the "Help" function as necessary. Below is a sample histogram.

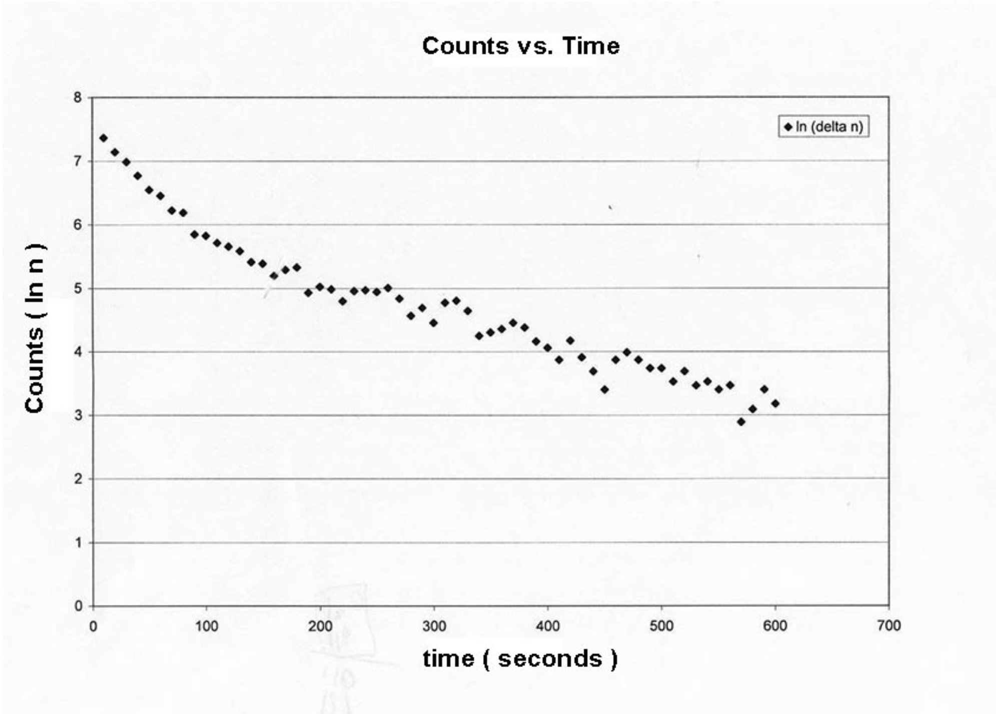



Annotate your graph with the mean and standard deviation. For Excel, you need to use the "Draw" and "Text Box" functions to put in the mean and standard deviation in some nice way, perhaps even better than shown above. (Note that this histogram, which is based on 30 minutes of counting, will probably be "smoother" than one based on 10 minutes of counting.)

**RETURN YOUR RADIOACTIVE PLACHET TO THE RADIATION OFFICER.**



| Time ( s ) | counts (delta n total) | counts - bg (n = n total - n bg) | ln (n) | n long | n short | ln (n short) |
|---|---|---|---|---|---|---|
| 10 | 1588 | 1582 | 7.366445 | 414.304 | 1167.696 | 7.062788 |
| 20 | 1271 | 1265 | 7.142827 | 394.4924 | 870.5076 | 6.769076 |
| 30 | 1088 | 1082 | 6.986566 | 375.6283 | 706.3717 | 6.560142 |
| 40 | 878 | 872 | 6.770789 | 357.6661 | 514.3339 | 6.242873 |
| 50 | 703 | 697 | 6.546785 | 340.563 | 356.437 | 5.876158 |
| 60 | 642 | 636 | 6.455199 | 324.2776 | 311.7224 | 5.742113 |
| 70 | 511 | 505 | 6.224558 | 308.771 | 196.229 | 5.279282 |
| 80 | 494 | 488 | 6.190315 | 294.0059 | 193.9941 | 5.267827 |
| 90 | 353 | 347 | 5.849325 | 279.9469 | 67.05308 | 4.205485 |
| 100 | 344 | 338 | 5.823046 | 266.5602 | 71.43983 | 4.268856 |
| 110 | 309 | 303 | 5.713733 | 253.8136 | 49.18644 | 3.895618 |
| 120 | 292 | 286 | 5.655992 | 241.6765 | 44.32351 | 3.791515 |
| 130 | 272 | 266 | 5.583496 | 230.1198 | 35.88021 | 3.580186 |
| 140 | 230 | 224 | 5.411646 | 219.1157 | 4.884278 | 1.586022 |
| 150 | 224 | 218 | 5.384495 | 208.6379 | 9.362145 | 2.236674 |
| 160 | 186 | 180 | 5.192957 | 198.661 | -18.66103 | |
| 170 | 204 | 198 | 5.288267 | 189.1613 | 8.838717 | |
| 180 | 212 | 206 | 5.327876 | 180.1158 | 25.8842 | |
| 190 | 144 | 138 | 4.927254 | 171.5029 | -33.50287 | |
| 200 | 158 | 152 | 5.023881 | 163.3018 | -11.3018 | |
| 210 | 152 | 146 | 4.983607 | 155.4929 | -9.492889 | |
| 220 | 127 | 121 | 4.795791 | 148.0574 | -27.05739 | |
| 230 | 148 | 142 | 4.955827 | 140.9775 | 1.022543 | |
| 240 | 150 | 144 | 4.969813 | 134.2361 | 9.763925 | |
| 250 | 146 | 140 | 4.941642 | 127.8171 | 12.18294 | |
| 260 | 155 | 149 | 5.003946 | 121.705 | 27.29501 | |
| 270 | 132 | 126 | 4.836282 | 115.8852 | 10.11481 | |
| 280 | 102 | 96 | 4.564348 | 110.3437 | -14.3437 | |
| 290 | 115 | 109 | 4.691348 | 105.0672 | 3.932815 | |
| 300 | 92 | 86 | 4.454347 | 100.043 | -14.04299 | |
| 310 | 124 | 118 | 4.770685 | 95.25905 | 22.74095 | |
| 320 | 128 | 122 | 4.804021 | 90.70387 | 31.29613 | |
| 330 | 110 | 104 | 4.644391 | 86.36651 | 17.63349 | |
| 340 | 76 | 70 | 4.248495 | 82.23656 | -12.23656 | |
| 350 | 80 | 74 | 4.304065 | 78.3041 | -4.304103 | |
| 360 | 84 | 78 | 4.356709 | 74.55969 | 3.440311 | |
| 370 | 92 | 86 | 4.454347 | 70.99433 | 15.00567 | |
| 380 | 86 | 80 | 4.382027 | 67.59946 | 12.40054 | |
| 390 | 70 | 64 | 4.158883 | 64.36693 | -0.366931 | |
| 400 | 64 | 58 | 4.060443 | 61.28898 | -3.288977 | |
| 410 | 54 | 48 | 3.871201 | 58.35821 | -10.35821 | |
| 420 | 71 | 65 | 4.174387 | 55.56758 | 9.432417 | |
| 430 | 56 | 50 | 3.912023 | 52.9104 | -2.910404 | |
| 440 | 46 | 40 | 3.688879 | 50.38029 | -10.38029 | |
| 450 | 36 | 30 | 3.401197 | 47.97116 | -17.97116 | |
| 460 | 54 | 48 | 3.871201 | 45.67723 | 2.322767 | |
| 470 | 60 | 54 | 3.988984 | 43.493 | 10.507 | |
| 480 | 54 | 48 | 3.871201 | 41.41321 | 6.586786 | |
| 490 | 48 | 42 | 3.73767 | 39.43288 | 2.567119 | |
| 500 | 48 | 42 | 3.73767 | 37.54724 | 4.452755 | |
| 510 | 40 | 34 | 3.526361 | 35.75178 | -1.751778 | |
| 520 | 46 | 40 | 3.688879 | 34.04217 | 5.957832 | |
| 530 | 38 | 32 | 3.465736 | 32.41431 | -0.41431 | |
| 540 | 40 | 34 | 3.526361 | 30.86429 | 3.135705 | |
| 550 | 36 | 30 | 3.401197 | 29.3884 | 0.611601 | |
| 560 | 38 | 32 | 3.465736 | 27.98308 | 4.016921 | |
| 570 | 24 | 18 | 2.890372 | 26.64496 | -8.64496 | |
| 580 | 28 | 22 | 3.091042 | 25.37083 | -3.370828 | |
| 590 | 36 | 30 | 3.401197 | 24.15762 | 5.842377 | |
| 600 | 30 | 24 | 3.178054 | 23.00243 | 0.997567 | |



Counts vs. Time
Counts ( ln n )
time ( seconds )
ln (delta n)
0
1
2
3
4
5
6
7
8
0
100
200
300
400
500
600
700