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Acknowledgments

WELCOME TO THE PHYSICS LABORATORY

Physics is our human attempt to explain the workings of the world. The success of that attempt is evident in the technology of our society. You have already developed your own physical theories to understand the world around you. Some of these ideas are consistent with accepted theories of physics while others are not. This laboratory manual is designed, in part, to help you recognize where your ideas agree with those accepted by physics and where they do not. It is also designed to help you become a better physics problem solver.

You are presented with contemporary physical theories in lecture and in your textbook. In the laboratory you can apply the theories to real-world problems by comparing your application of those theories with reality. You will clarify your ideas by: answering questions and solving problems *before* you come to the lab room, performing experiments and having discussions with classmates *in the lab room*, and occasionally by writing lab reports *after you leave*. Each laboratory has a set of problems that ask you to make decisions about the real world. As you work through the problems in this laboratory manual, remember: **the goal is <u>not</u> to make lots of measurements**. The goal is for you to examine your ideas about the real world.

The three components of the course - lecture, discussion section, and laboratory section - serve different purposes. The laboratory is where physics ideas, often expressed in mathematics, meet the real world. Because different lab sections meet on different days of the week, you may deal with concepts in the lab before meeting them in lecture. In that case, the lab will serve as an introduction to the lecture. In other cases the lecture will be a good introduction to the lab.

The amount you learn in lab will depend on the time you spend in preparation before coming to lab.

Before coming to lab each week you must read the appropriate sections of your text, read the assigned problems to develop a fairly clear idea of what will be happening, and complete the prediction and method questions for the assigned problems.

Often, your lab group will be asked to present its predictions and data to other groups so that everyone can participate in understanding how specific measurements illustrate general concepts of physics. You should always be prepared to explain your ideas or actions to others in the class. To show your instructor that you have made the appropriate connections between your measurements and the basic physical concepts, you will be asked to write a laboratory report. Guidelines for preparing lab reports can be found in the lab manual appendices and in this introduction. An example of a good lab report is shown in Appendix E. Please do not hesitate to discuss any difficulties with your fellow students or the lab instructor.

Relax. Explore. Make mistakes. Ask lots of questions, and have fun.

WHAT TO DO TO BE SUCCESSFUL IN THIS LAB:

Safety comes first in any laboratory.
If in doubt about any procedure, or if it seems unsafe to you, STOP. Ask your lab instructor for help.

A. What to bring to each laboratory session:

1. Bring an 8" by 10" graph-ruled lab journal, to all lab sessions. Your journal is your "extended memory" and should contain everything you do in the lab and all of your thoughts as you are going along. Your lab journal is a legal document; you should **never** tear pages from it. Your lab journal **must** be bound (as *University of Minnesota 2077-S*) and must **not** allow pages to be easily removed (as spiral bound notebooks).

2. Bring a "scientific" calculator.

3. Bring this lab manual.

B. Prepare for each laboratory session:

Each laboratory consists of a series of related problems that can be solved using the same basic concepts and principles. Sometimes all lab groups will work on the same problem, other times groups will work on different problems and share results.

1. Before beginning a new lab, carefully read the Introduction, Objectives and Preparation sections. Read sections of the text specified in the *Preparation* section.

2. Each lab contains several different experimental problems. Before you come to a lab, complete the assigned *Prediction* and *Method Questions*. The Method Questions help you build a prediction for the given problem. It is usually helpful to answer the Method Questions before making the prediction. **These individual predictions will be checked (graded) by your lab instructor *immediately* at the beginning of each lab session.**
This preparation is crucial if you are going to get anything out of your laboratory work. There are at least two other reasons for preparing:

   a) There is nothing duller or more exasperating than plugging mindlessly into a procedure you do not understand.

   b) The laboratory work is a **group** activity where every individual contributes to the thinking process and activities of the group. Other members of your group will be unhappy if they must consistently carry the burden of someone who isn't doing his/her share.

C. Laboratory Reports

At the end of every lab (about once every two weeks) you will be assigned to write up one of the experimental problems. Your report must present a clear and accurate account of what you and your group members did, the results you obtained, and what the results mean. A report must

not be copied or fabricated. (That would be scientific fraud.) Copied or fabricated lab reports will be treated in the same manner as cheating on a test, and will result in **a failing grade for the course and possible expulsion from the University**. Your lab report should describe <u>your</u> predictions, <u>your</u> experiences, <u>your</u> observations, <u>your</u> measurements, and <u>your</u> conclusions. A description of the lab report format is discussed at the end of this introduction. **Each lab report is due, without fail, within two days of the end of that lab.**

D. **Attendance**

Attendance is required at all labs **without exception**. If something disastrous keeps you from your scheduled lab, contact your lab instructor **immediately**. The instructor will arrange for you to attend another lab section that same week. **There are no make-up labs in this course.**

E. **Grades**

Satisfactory completion of the lab is required as part of your course grade. *Those not completing **all** lab assignments by the end of the quarter at a 60% level or better will receive a quarter grade of F for the <u>entire course</u>.* The laboratory grade makes up <u>15% of your final course grade</u>. Once again, we emphasize that **each lab report is due, without fail, within two days of the end of that lab.**

There are two parts of your grade for each laboratory: (a) your laboratory journal, and (b) your formal problem report. Your laboratory journal will be graded by the lab instructor during the laboratory sessions. Your problem report will be graded and returned to you in your next lab session.

If you have made a good-faith attempt but your lab report is unacceptable, your instructor may allow you to rewrite parts or all of the report. A rewrite must be handed in again <u>within two days of the return of the report to you</u> by the instructor.

F. **The laboratory class forms a local scientific community. There are certain basic rules for conducting business in this laboratory.**

1.   ***In all discussions and group work, full respect for all people is required.*** All disagreements about work must stand or fall on reasoned arguments about physics principles, the data, or acceptable procedures, never on the basis of power, loudness, or intimidation.

2.   *It is OK to make a <u>reasoned</u> mistake. It is in fact, one of the most efficient ways to learn.*

This is an academic laboratory in which to learn things, to test your ideas and predictions by collecting data, and to determine which conclusions from the data are acceptable and reasonable to other people and which are not.

What do we mean by a "reasoned mistake"? We mean that after careful consideration and after a substantial amount of thinking has gone into your ideas you simply give your best prediction or explanation as you see it. Of course, there is always the possibility that your idea does not accord with the accepted ideas. Then someone says, "No, that's not the way I see it and here's why." Eventually persuasive evidence will be offered for one viewpoint or the other.

"Speaking out" your explanations, in writing or vocally, is one of the best ways to learn.

3. *It is perfectly okay to share information and ideas with colleagues. Many kinds of help are okay. Since members of this class have highly diverse backgrounds, you are encouraged to help each other and learn from each other.*

   However, it is never okay to copy the work of others.

   Helping others is encouraged because it is one of the best ways for you to learn, but copying is inappropriate and unacceptable. Write out your own calculations and answer questions in your own words. It is okay to make a reasoned mistake; it is wrong to copy.

   No credit will be given for copied work. It is also subject to University rules about plagiarism and cheating, and may result in dismissal from the course and the University. See the University course catalog for further information.

4. *Hundreds of other students use this laboratory each week. Another class probably follows directly after you are done. Respect for the environment and the equipment in the lab is an important part of making this experience a pleasant one.*

   The lab tables and floors should be clean of any paper or "garbage." Please clean up your area before you leave the lab. The equipment must be either returned to the lab instructor or left neatly at your station, depending on the circumstances.

   A note about Laboratory equipment:
   At times equipment in the lab may break or may be found to be broken. If this happens you should inform your TA and report the problem to the equipment specialist by sending an email to:

   labhelp@physics.umn.edu

   Describe the problem, including any identifying aspects of the equipment, and be sure to include your lab room number.

   If equipment appears to be broken in such a way as to cause a danger do not use the equipment and inform your TA immediately.

In summary, the key to making any community work is **RESPECT**.

Respect yourself and your ideas by behaving in a professional manner at all times.

Respect your colleagues (fellow students) and their ideas.

Respect your lab instructor and his/her effort to provide you with an environment in which you can learn.

Respect the laboratory equipment so that others coming after you in the laboratory will have an appropriate environment in which to learn.

LABORATORY I
ELECTRIC FIELDS AND FORCES

The most fundamental forces are characterized as "action-at-a-distance". This means that an object can exert a force on another object that is not in contact with it. You have already learned about the gravitational force, which is of this type. You are now learning the electric force, which is another one. Action-at-a-distance forces have two features that require some getting used to. First, it is hard to visualize objects interacting when they are not in contact. Second, if objects that interact by these action-at-a-distance forces are grouped into systems, the systems have potential energy. But where does the potential energy reside?

Inventing the concept of a field solves the conceptual difficulties of both the force and the potential energy for action-at-a-distance interactions. With a field theory, an object affects the space around it, creating a field. Another object entering this space is affected by that field and experiences a force. In this picture the two objects do not directly interact with each other: one object causes a field and the other object interacts directly with that field. The magnitude of the force on a particular object is the magnitude of the field (caused by all the other objects) at the particular object's position, multiplied by the property of that object that causes it to interact with that field. In the case of the gravitational force, that property is the mass of the object. (The magnitude of the gravitational field near the earth's surface is $g = 9.8$ m/s^2.) In the case of the electrical force, that property is the electric charge. The direction of the force on an object is determined by the direction of the field at the space the object occupies. When a system of two, or many, objects interact with each other through a field, the potential energy resides in the field.

Thinking of interactions in terms of fields is a very abstract way of thinking about the world. We accept the burden of this additional abstraction because it leads us to a deeper understanding of natural phenomena and inspires the invention of new applications. The problems in this laboratory are primarily designed to give you practice visualizing fields and using the field concept in solving problems.

In this laboratory, you will first explore electric fields by building different configurations of charged objects and mapping their electric fields. In the last two problems of, you will measure the behavior of electrons as they move through an electric field and compare this behavior to your calculations and your experience with gravitational fields.

OBJECTIVES

After successfully completing this laboratory, you should be able to:
- Qualitatively construct the electric field caused by charged objects based on the geometry of those objects.

- Determine the magnitude and direction of the force on a charged particle in an electric field.

PREPARATION

Read Tipler & Mosca: Chapter 3, sections 3-1 & 3-2; Chapter 21.

Before coming to lab you should be able to:

- Apply the concepts of force and energy to solve problems.

- Calculate the motion of a particle with a constant acceleration.

- Write down Coulomb's law and understand the meaning of all quantities involved.

PROBLEM #1: ELECTRIC FIELD VECTORS

You have been assigned to a team developing a new ink-jet printer. Your team is investigating the use of electric charge configurations to manipulate the ink particles in the printer. To begin design work, the company needs a computer program to simulate the electric field for complicated charge configurations. Your task is to evaluate such a program. To test the program, you use it to qualitatively predict the electric field from simple charge configurations and see if it corresponds to your expectations. You start with a single positive charge. You then try a single negative charge. Finally, you place one positive charge a short distance from a negative charge of equal magnitude to get a dipole configuration. You make a sketch of the electric field vectors at different points in space for each of the three cases.

EQUIPMENT

The computer program <u>EM Field</u>.

PREDICTION

Restate the problem to give a clear and complete statement of the prediction you wish to make.

WARM UP

Read: Tipler & Mosca Chapter 21 sections 21-1 – 21-5. It also might be a good idea to review Chapter 1 Section 1-6 & 1-7.

1. Draw a positively charged point object.

2. Consider a point in space some distance from that object. What is the direction of the electric field vector at this point? Remember that you can understand the electric field by considering the electric force on a positive "test charge" placed at that point. Draw the electric field vector at that point.

3. Consider another point in space at a different distance from the charged object. How should the length of the electric field vector at this point compare to the length of the vector at the previous point? Draw the electric field vector at this point. Choose various points in space and draw more electric field vectors. Continue this process until you have a satisfactory diagram of the electric field in the space surrounding the charge configuration.

4. Repeat the above steps for the other two cases. For the dipole, remember that the total electric field from multiple point charges is the vector sum of the electric fields due to each point charge. This can be understood by considering the force on a positive "test charge" and remembering that the total force is the vector sum of individual forces.

EXPLORATION

In the folder <u>PhysLab</u> on the desktop, open <u>EM Field</u> and click anywhere in the window for the instructions.

From the *Sources* pull-down menu, select *3D point charges*. Drag any positively charged point object to the center of the window of <u>EM Field.</u> Select *Field vectors* from the *Field and Potential* pull-down menu (as shown).


```
Field and Potential  Display
 * Field vectors
   Directional arrows
   Field lines
   Potential
   Potential difference
   Equipotentials
   Equipotentials with number
   Flux and Gauss's Law
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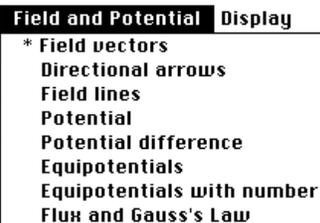
Move the cursor where you would like to place a field vector and click the mouse button. An electric field vector should appear. Repeat this procedure until you have created a reasonable map of the electric field. To clear the EM Field window, select *Clean up screen* from the *Display* pull-down menu.

You can get another visual representation of the electric field by selecting *Directional arrows* from the *Field and Potential* menu. In this representation all arrows are the same length and the magnitude of the field is given by its color. Try this out for a single positively charged point object. If you switch to *Field vectors* without clearing the screen, you can see how the representations correspond to each other. Unfortunately, the *Directional arrows* representation is not very good for printing on black and white printers.

You can get the third visual representation of the electric field by selecting *Field Lines* in the menu. What are some differences between the "field lines" and "field vectors" representations? Are they equally useful?

Repeat your favorite electric field representation for a single negatively charged point object. How does the direction and magnitude of the electric field compare to that for the positively charged point object? Try clearing the screen and selecting a larger charge. What happens to the electric field?

Clear the screen and create a dipole by dragging two equal, but oppositely charged point objects onto the window of EM Field. You can use the *Show grid* and *Constrain to grid* features in the *Display* menu to position your dipole. Using your favorite electric field representation, make a map of the electric field caused by a dipole. Map the electric field at points along all axes of symmetry of the dipole.

Try a different spacing between the two charged objects making up the dipole to see how that changes the electric field map. Try larger charges.

If you are very far away from the dipole, how does the field compare to that of a single charged point object? How does it compare if you are very close to one charged object?

ANALYSIS

After making an electric field diagram of the positively charged point object, one that is negatively charged, and the dipole, print a copy of the screen for each case (*Print Screen* from the *File* menu).

Look at the electric field diagram for your dipole. Where is the electric field the strongest? Weakest?

Consider one of the electric field vectors in one of the diagrams you have created. If a positively charged object were placed at the tail end of that vector, what would be the direction of the force on it? What if it were a negatively charged object? How would the size of the force compare to what it would be at a different point in space where the electric field vector was shorter or longer?

CONCLUSION

How does each of the computer-generated diagrams compare with your prediction? Where is the field the strongest? How is this shown in the diagram? Where is the field the weakest? How is this shown?

Suppose you placed a positively charged point object near the dipole. If the object began at rest, how would it move? Be careful not to confuse the acceleration of an object (determined by the total force on that object) with the velocity of the object. Try placing your object at several different points.

PROBLEM #2: ELECTRIC FIELD FROM A DIPOLE

You have a summer job with a solar power company. To measure the electric fields produced by solar cells the company plans to use conductive paper. They will arrange the cells on the paper and measure the field at different points on the paper. Your assignment is to test the process for measuring the fields. To find out if it works correctly, you decide to use it to determine the electric field created by a simple pattern of charged objects. You create a two-dimensional dipole field by giving two parallel metal rods opposite charges with a battery while their tips are in contact with a sheet of conducting paper. You then measure the electric field in the paper. To see if the paper can be used to correctly map an electric field you make a detailed qualitative prediction of the electric field produced by an electric dipole at different points in space.

<table><tr><td>EQUIPMENT</td></tr></table>

You will be using the conductive paper setup described in Appendix D. There is a coordinate grid printed on the conductive paper. Two brass rods (electrodes) stand upright with their tips in contact with the conductive paper and connected to opposite terminals of a battery or power supply. The electric field probe (dual tip banana jack) is connected to a digital multimeter (DMM) set to read volts.   You will also have the EM Field program. A white sheet of paper with a matching grid is useful for recording the field (do not write on the conductive paper).
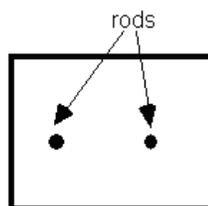
Overhead view of conductive paper
for this problem.

<table><tr><td>PREDICTION</td></tr></table>

Restate the problem. What do you wish to predict? How can you make a qualitative prediction with as much detail as possible?

<table><tr><td>WARM UP</td></tr></table>

Read: Tipler & Mosca Chapter 21 sections 21-1 – 21-5. It also might be a good idea to review Chapter 1 Section 1-6 & 1-7.

1. Draw a picture of the dipole similar to the one shown in the equipment section. Label one of the charged point objects "+" and the other "-".

2. At a point in space some distance from the charged objects, draw two vectors, one each to represent the electric field due to each charged object. Remember that you can understand the electric field by considering the electric force on a positive "test charge" placed at that point. How should the length of each vector depend on the distance to each charged object? Measure the distance from each charged object to the point where you are drawing the vectors; make sure the relative lengths of the vectors correspond correctly to those distances.

3. Draw a darker vector representing the **total** electric field at that point. Remember, if an object feels two different forces then the total force is the vector sum of the individual forces. You can add the vectors representing electric fields due to the positive and negative parts of the dipole graphically.

4. Repeat the process at different points until you have a satisfactory map of the electric field in the space surrounding the dipole. Where is the field the strongest? The weakest? What is the direction of the field on different points along the dipole's two axes of symmetry?

<div style="text-align: center">**EXPLORATION**</div>

You can compare your prediction with a field map of *2D charged rods* produced by the <u>EM Field</u> program. For instructions on how to use this program see the Exploration section of Problem 1.

Appendix D tells how to use the DMM and the conductive paper setup. Follow the instructions given there to set up the conductive paper.

Once the rods are connected to the battery, set the digital multimeter (DMM) to volts and turn it on. Place the tips of the probe on the conductive paper midway between the tips of the two rods. Based on your warm-up questions, what is the direction of the electric field at that position? Rotate the probe so that the <u>center</u> of the probe stays in the <u>same spot</u>. Record the meter readings as you rotate the probe. Do the values change (pay attention to the sign)? Is there a minimum or maximum value? Are there any symmetries in this data? If there are large fluctuations, determine how you will measure consistently. Describe how you will use the probe to determine the field **direction** at other points.

Now place the field probe near, but not touching, one of the rods and rotate the probe as you did before. Record your data. Determine the direction of the electric field. Compare the maximum DMM reading at this point to the one you found at the midway point. Compare your measurements to your prediction; does the value displayed on the DMM become larger or smaller when the electric field becomes stronger? Describe how you will use the probe to determine the electric field **strength** at other points.

Where on the conductive paper is the electric field strongest? weakest? Does this match your predictions?

Complete your measurement plan for mapping the electric field on the conductive paper. How will you record the magnitude and direction of the electric field at each point?

<div style="text-align: center">**MEASUREMENT**</div>

Select a point on the conductive paper where you wish to determine the electric field. Place the probe on the conductive paper at that point and rotate until you have found the direction of the electric field. Record the magnitude and direction of the field at that point by drawing a vector in your lab journal or on a sheet of white paper with a grid pattern similar to that on the conductive paper. At each point, take at least two measurements of magnitude and direction to gain a measure of your uncertainty.

Repeat for as many points as needed to check your prediction. When you have taken enough data, you will have a map of the electric field.

<div style="text-align: center">**CONCLUSION**</div>

How does your map compare to your prediction? How does it compare to the simulation program? Where is the field strongest? How do you show this in your map? Where is the field weakest? How do you show this in your map?

PROBLEM #3: GRAVITATIONAL FORCE ON THE ELECTRON

You work in a research laboratory that is attempting to make a better electron microscope. The project requires precise control of a beam of electrons. For your study of electron control you decide to use a Cathode Ray Tube (CRT), the same device that is the basis of most TV sets. In the CRT, electrons are emitted at one end of an evacuated glass tube and are detected by their interaction with a phosphorous screen on the other end. Every object near the Earth's surface is subject to the gravitational force. From your physics experience you also know that the acceleration of all objects in free fall is the same, independent of their mass. Your teammates worry that the gravitational force will deflect the electron from its path giving it a parabolic trajectory, and that this deflection will depend on whether the beam is vertical or horizontal. You decide to compute how far the beam deviates from a straight-line trajectory when the beam is aimed in different directions.

EQUIPMENT

You will be using the Cathode Ray Tube (CRT) described in Appendix D. The fluorescent screen has a one-half centimeter grid in front of it so you can measure the position of the beam spot.
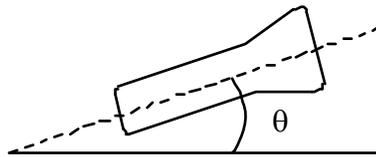
PREDICTION

Restate the problem. State clearly what you're going to study. Sketch a graph of the distance of the electron from the center of the CRT when it hits the screen (its deflection) versus the angle of incline of the CRT from the horizontal. Explain your reasoning.

WARM UP

Read: Tipler & Mosca Chapter 21 Section 21-6 and review Chapter 3 Sections 3-1 & 3-2.

1. Draw a picture of the CRT in the horizontal position. Do not include the deflection plates shown in Appendix D since they will not be used in this problem. Draw the electron's trajectory from the time it leaves the electron gun until it hits the screen. Label each important kinematics quantity in the problem. Label all forces on the electron during this time. Choose a convenient coordinate system and put it on your drawing. Does the vertical component of the electron's velocity change? Why? Does the horizontal component of its velocity change? Why?

2. Calculate the velocity of the electron just after it leaves the electron gun.

Hint: The change in the electric potential energy of an electron moving from one plate to another is the voltage difference between the two plates (V_{acc} in Appendix D) times the electron's charge. What assumptions must you make to calculate the electron's initial velocity?

3. What physics principles can you use to calculate how far the electron falls below a straight-line trajectory (its deflection from the center of the screen)? What quantities must you know to make the calculation? Make the calculation.

4. Does your solution make sense? You can check by estimating the time of flight of the electron based on its initial velocity and the distance between its starting point and the screen. In that amount of time, how far would a ball drop in free fall? If the solution does not make sense, check your work for logic or algebra mistakes.

5. Now return to step 1 and solve the problem for a CRT pointed upward, and then at an angle from the horizontal.

Hint: Keep the coordinate system you used and look for the new components of the acceleration and the velocity in that frame. What difference will this make to your solution? Does the deflection increase or decrease as the tube becomes more vertical? Is there any angle for which you predict zero deflection?

EXPLORATION

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. The **power** must be turned **off** and you must **wait** at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire**.**

Follow the directions in Appendix D for connecting the power supply to the CRT. Check to see that the connections from the power supply to the high voltage and the filament heater are correct, *before* you turn the power supply on. You should have between 250 and 500 Volts of electric potential between the cathode and anode. After a moment, you should see a spot that you can adjust with the knob labeled "Focus". If your connections are correct and the spot still does not appear, inform your lab instructor.

Do you expect the gravitational deflection to vary as a function of the angle of the CRT with the horizontal? Try different orientations in the horizontal plane to see if you can observe any difference. Does the qualitative behavior of the electron deflection agree with your prediction?

For what orientation of the CRT is it impossible for the gravitational force to deflect the electron? This is the location of the beam spot when there is no gravitational effect on the motion of the electrons.

If you observe a deflection of the electron beam, determine if this deflection is or is not caused by the gravitational force. If it is not, what does this mean and how can you minimize the effect of that force on your measurements? Is the deflection different if you move the CRT to a different position in the room?

Devise a measuring scheme to record the angle of the CRT and the position of the beam spot.

Write down your measurement plan.

MEASUREMENT

Measure the position of the beam spot at an orientation of the CRT for which you expect the gravitational deflection to be zero and the position at an angle for which the gravitational deflection should be maximum. Make measurements at several intermediate angles as well.

Note: Be sure to record your measurements with the appropriate number of significant figures (see Appendix A) and with your estimated uncertainty (see Appendix B). Otherwise, the data is nearly meaningless.

ANALYSIS

Make a graph of the position of the electron beam spot as a function of the angle that the CRT makes with the horizontal.

If you observe a deflection, how can you tell if it is caused by the gravitational force? If the deflection is not caused by gravity, what might be its cause? How will you decide?

Use your data to determine the magnitude of the deflection of the electron.

CONCLUSION

Did your data agree with your predictions? Did you observe any deflection of the electron beam? Was it in the direction you expected? What could account for any aberrant behavior? How can you arrange your CRT to minimize the aberrant behavior?

Can you measure the effect of the Earth's gravitational force on the motion of the electrons in the CRT? State your results in the most general terms supported by your data. Based on your results, do you think you need to take gravitational deflection into account when using the CRT? Why?

PROBLEM #4 DEFLECTION OF AN ELECTRON BEAM BY AN ELECTRIC FIELD

You are attempting to design an electron microscope. To precisely steer the beam of electrons you will use an electric field perpendicular to the original direction of the electrons. To test the design, you must determine how a *change in the applied electric field* affects the position of the beam spot. A colleague argues that an electron's trajectory through an electric field is analogous to a bullet's trajectory through a gravitational field. You are not convinced but are willing to test the idea. One difference that you both agree on is that the electrons in the microscope will pass through regions with an electric field and other regions with no electric field, while a bullet is always in a gravitational field. You decide to model the situation with a Cathode Ray Tube (CRT) in which electrons are emitted at one end of an evacuated glass tube and are detected by their interaction with a phosphorous screen on the other end. You will calculate the deflection of an electron that begins with an initial horizontal velocity, passes between a pair of short metal plates that produce a vertical electric field between them, and then continues through a region with no electric field until hitting the screen. Your result could depend on the strength of the electric field, the electron's initial velocity, intrinsic properties of the electron, the length of the metal plates that produce the vertical electric field, and the distance from the end of the metal plates to the screen. *NOTE: In the next lab problem you will measure the effect of changing the electron's initial speed.*

EQUIPMENT

You will use a Cathode Ray Tube (see Appendix D). Connecting the internal parallel plates to a 0-18V DC power supply (similar to the Sorensen power supply described in Appendix D) creates an applied electric field. A high voltage CENCO power supply supplies the energy used to give the electron its initial velocity. The CENCO supplies 0-5V does not provide 'clean' enough DC power.

PREDICTION

Restate the problem. What do you want to calculate? What quantity will you control? Present your results as an equation and as a graph.

WARM UP

Read: Tipler & Mosca Chapter 21 Section 21-6 and review Chapter 3 Sections 3-1 & 3-2.

1. Examine the diagram of the CRT in Appendix D. You will use only one set of the deflection plates shown. Draw a simplified diagram of an electron with an initial horizontal velocity about to enter the region between the plates. Draw the screen some distance past the end of the plates. Label the relevant distances. Assume that the electric field is vertically oriented in the region between the plates and is zero elsewhere. Indicate on your picture where an electron experiences electrical forces. Draw a coordinate axis on this picture. Sketch the electron's trajectory through the CRT, indicating where the electron should accelerate and the direction of that acceleration. Indicate on the screen of the CRT the distance by which the electron has been deflected away from its initial straight-line path. Why can you ignore the gravitational force on the electron?

2. Recall some things you already know about projectile motion. Does a force in the vertical direction affect the horizontal component of an object's velocity? In this situation, can you use the horizontal velocity component to find the time required to travel some horizontal distance?

3. Consider the motion of the electron in the region between the deflection plates. Calculate the amount of time the electron spends in this region. Calculate the vertical position and vertical velocity component of the electron when it leaves this region. Remember you are assuming that only an electric force acts on the electron and are neglecting the gravitational force.

4. Consider the motion of the electron in the region past the deflection plates. What is true about the vertical and horizontal components of its velocity in this region? Calculate where the electron hits the screen relative to where it entered this final region. Then calculate the total deflection of the electron at the screen from where it initially entered the region between the plates.

5. Using the equation you have found for the deflection of the electron beam draw a graph of the deflection vs. the electric field strength. Treat the other quantities as constant.

6. Two quantities in your expression are not directly measurable in lab. These are the electron's initial velocity and the electric field strength between the deflection plates. You will, however, know the voltage that accelerates the electrons, V_{acc}, and the voltage across the deflection plates, V_{plates}. Use conservation of energy to express the electron's initial velocity in terms of V_{acc}. Substitute this expression into your deflection equation.

Hint: The change in the electric potential energy of an electron moving from one plate to another is the voltage difference between the two plates (V_{acc} in Appendix D) times the electron's charge. What assumptions must you make to calculate the electron's initial velocity?

7. Write an equation relating V_{plates} to the electric field between the plates, and substitute it into your deflection equation. Your final deflection equation should involve only quantities that can be measured in lab or found in the textbook or in Appendix D.

Hint: the electric field between the plates equals V_{plates} divided by the distance between the plates.

EXPLORATION

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. To avoid danger, the **power** must be turned **off** and you must **wait** at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.

Follow the directions in Appendix D for connecting the power supply to the CRT. Check to see that the connections from the power supply to the high voltage and the filament heater are correct, before you turn the power supply on. You should have between 250 and 500 volts of electric potential between the cathode and anode. After a moment, you should see a spot that you can adjust with the knob labeled "Focus". If your connections are correct and the spot still does not appear, inform your lab instructor. Use the DMM to measure the actual voltage between the cathode and the anode.

Before you turn on the electric field between the deflection plates, make a note of the position of the spot on the screen. The deflections you measure will be in relation to this point. Make sure not to change the position of the CRT since external fields may affect the position of the spot.

Now apply a voltage across one set of deflection plates, noting how the electron beam moves across the screen as the voltage is increased. Determine how you will adjust the voltage level and how you will measure it. Write down the range of voltages for which you can make a good measurement. Repeat this procedure for the perpendicular set of deflection plates.

If you cannot make the electron spot sweep entirely across the screen, try changing the voltage between the anode and the cathode that you originally set somewhere between 250 and 500 volts. This voltage changes the electron's velocity entering the deflection plates. Select a voltage between the anode and cathode that gives you a useful set of measurements for your deflections.

Devise a measuring scheme to record the position of the beam spot. Be sure you have established the zero deflection point of the beam spot. Write down your measurement plan. How will you determine the strength of the electric field between the deflection plates? What quantities will you hold constant for this measurement? How many measurements do you need?

MEASUREMENT

Measure the position of the beam spot as you change the electric field applied to the deflection plates. At least two people should make a measurement at each point, so you can estimate measurement uncertainty. *Note: Be sure to record your measurements with the appropriate number of significant figures (see Appendix A) and with your estimated uncertainty (see Appendix B). Otherwise, the data is virtually meaningless.*

ANALYSIS

Draw a graph of the measured deflection of the electron beam as a function of the voltage difference across the deflector plates.

CONCLUSION

How does the graph based on your data compare to the graph based on your prediction? If they are different explain why. Is the analogy between bullets and electrons supported by your experiment?

How does the deflection of the electron beam vary with the applied electric field? State your results in the most general terms supported by your data.

PROBLEM #5: DEFLECTION OF AN ELECTRON BEAM AND VELOCITY

You are attempting to design an electron microscope. To precisely steer the beam of electrons you will use an electric field perpendicular to the original direction of the electrons. To test the design, you must determine how *a change in the initial velocity of the electrons* affects the position of the beam spot. A colleague argues that an electron's trajectory through an electric field is analogous to a bullet's trajectory through a gravitational field. You are not convinced but are willing to test the idea. One difference that you both agree on is that the electrons in the microscope will pass through regions with an electric field and other region with no electric field, while a bullet is always in a gravitational field. You decide to model the situation with a Cathode Ray Tube (CRT) in which electrons are emitted at one end of an evacuated glass tube and are detected by their interaction with a phosphorous screen on the other end. You will calculate the deflection of an electron that begins with an initial horizontal velocity, passes between a pair of short metal plates that produce a vertical electric field between them, and then continues through a region with no electric field until hitting the screen. Your result could depend on the strength of the electric field, the electron's initial velocity, intrinsic properties of the electron, the length of the metal plates that produce the vertical electric field, and the distance from the end of the metal plates to the screen.

EQUIPMENT

You will use a Cathode Ray Tube (see Appendix D).

PREDICTION

Restate the problem in terms of what you want to calculate and which parameter you will vary? Show your prediction in the form of an equation and a graph.

WARM UP

Read: Tipler & Mosca Chapter 21 Section 21-6 and review Chapter 3 Sections 3-1 & 3-2.

These questions are similar to those for Problem #4. If you have already completed Problem #4, review your answers to those warm-up questions and draw a new graph. If not, you should answer the following warm-up questions.

1. Examine the diagram of the CRT in Appendix D. You will use only one set of the deflection plates shown. Draw a simplified diagram of an electron with an initial horizontal velocity about to enter the region between the plates. Draw the screen some distance past the end of the plates. Label the relevant distances. Assume that the electric field is vertically oriented in the region between the plates and is zero elsewhere. Indicate on your picture where an electron experiences electrical forces. Draw a coordinate axis on this picture. Sketch the electron's trajectory through the CRT, indicating where the electron should accelerate and the direction of that acceleration. Indicate on the screen of the CRT the distance by which the electron has been deflected away from its initial straight-line path. Why can you ignore the gravitational force on the electron?

2. Recall some things you already know about projectile motion. Does a force in the vertical direction affect the horizontal component of an object's velocity? In this situation, can you use the horizontal velocity component to find the time required to travel some horizontal distance?

3. Consider the motion of the electron in the region between the deflection plates. Calculate the amount of time the electron spends in this region. Calculate the vertical position and vertical velocity component of the electron when it leaves this region. Remember you are assuming that only an electric force acts on the electron and are neglecting the gravitational force. (You will need

the relationship between the electric field and the electric force on a charged object, as well as the general relationship between force and acceleration.)

4. Consider the motion of the electron in the region past the deflection plates. What is true about the vertical and horizontal components of its velocity in this region? Calculate where the electron hits the screen relative to where it entered this final region. Then calculate the total deflection of the electron at the screen from where it initially entered the region between the plates.

5. Using the equation you have found for the deflection of the electron beam draw a graph of the deflection vs. the initial velocity. Treat the other quantities as constant.

6. Two quantities in your expression are not directly measurable in lab. These are the electron's initial velocity and the electric field strength between the deflection plates. You will, however, know the voltage that accelerates the electrons, V_{acc}, and the voltage across the deflection plates, V_{plates}. Use conservation of energy to express the electron's initial velocity in terms of V_{acc}. Substitute this expression into your deflection equation.

Hint: The change in the electric potential energy of an electron moving from one plate to another is the voltage difference between the two plates (V_{acc} in Appendix D) times the electron's charge. What assumptions must you make to calculate the electron's initial velocity?

7. Write an equation relating V_{plates} to the electric field between the plates, and substitute it into your deflection equation. Your final deflection equation should involve only quantities that can be measured in lab or found in the textbook or in Appendix D.

Hint: the electric field between the plates equals V_{plates} divided by the distance between the plates.

EXPLORATION

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. To avoid danger, the **power** must be turned **off** and you must **wait** at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.

Follow the directions in *Appendix D* for connecting the power supply to the CRT. Check to see that the connections from the power supply to the high voltage and the filament heater are correct, *before* you turn the power supply on. Apply between 250 and 500 Volts across the anode and cathode. After a moment, you should observe a spot on the screen that can be adjusted with the knob labeled "Focus". If your connections are correct and the spot still doesn't appear, inform your lab instructor.

TAKING EXTREME CARE!, change the voltage across the accelerating plates, and determine the range of values for which the electrons have enough energy to produce a spot on the screen. Changing this voltage changes the velocity of the electrons as they enter the deflection plates. What is the range of initial electron velocities corresponding to this range of accelerating voltages? Which of these values will give you the largest deflection when you later apply an electric field between the deflection plates?

Before you turn on the electric field between the deflection plates, make a note of the position of the spot on the screen. The deflections you measure will be in relation to this point. Make sure not to change the position of the CRT since external fields may affect the position of the spot.

Now apply a voltage across one set of deflection plates, noting how the electron beam moves across the screen as the voltage is increased. Find a voltage across the deflection plates that allows the deflection for the entire range of initial electron velocities to be measured as accurately as possible.

Devise a measuring scheme to record the position of the beam spot. Be sure you have established the zero deflection point of the beam spot.

Write down your measurement plan. How will you determine the strength of the electric field between the deflection plates? How will you determine the initial velocity of the electrons? What quantities will you hold constant for this measurement? How many measurements do you need?

MEASUREMENT

Measure the deflection of the beam spot as you change the initial velocity of the electrons in the beam, keeping the electric field between the deflection plates constant. At least two people should make a measurement at each point, so you can estimate measurement uncertainty. *Note: Be sure to record your measurements with the appropriate number of significant figures (see Appendix A) and with your estimated uncertainty (see Appendix B). Otherwise, the data is virtually meaningless.*

ANALYSIS

Draw a graph of your average measurements of the deflection of the electron beam as a function of the initial electron velocity. How do your uncertainties affect your graph?

CONCLUSION

Did your data agree with your prediction of how the electron beam deflection would depend on the initial electron velocity? If not, why? How does the deflection of the electron beam vary with initial electron velocity? State your results in the most general terms supported by your data.

☑ CHECK YOUR UNDERSTANDING

1. For each of the charge configurations below, map the electric field. Assume that each object is made of metal and that the trays are filled with water.
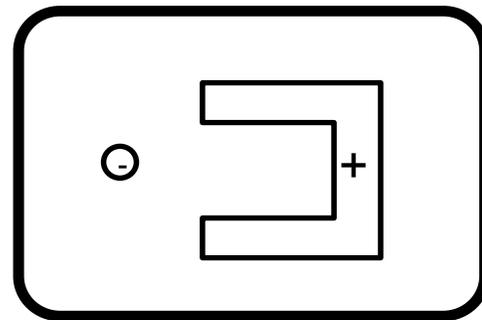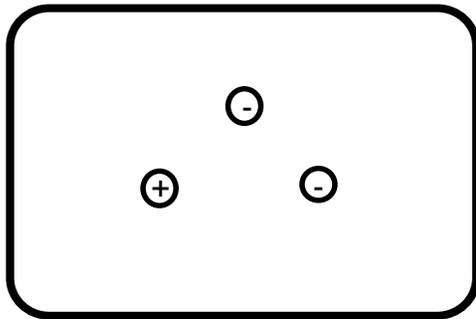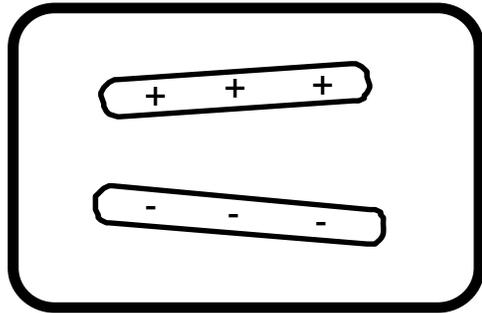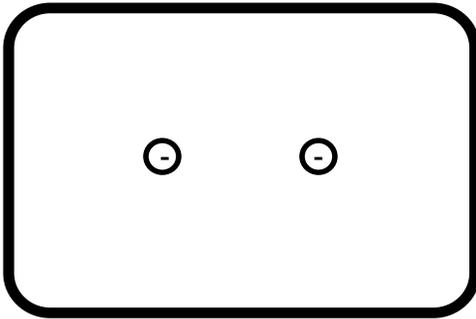
2. For a CRT with the same plates and electron gun as you used in lab, assume that the distance from the center of the Vx plate to the fluorescent screen is 10 cm and the distance from the center of the Vy plate to the screen is 8 cm. If Vacc is 300V, Vx = -8V and Vy = 3V, what is the displacement of the electron beam?

3. Assume you have two infinite parallel planes of charge separated by a distance d as shown below. Use the symbols <,>, and = to compare the force on a test charge, q, at points A, B, and C.
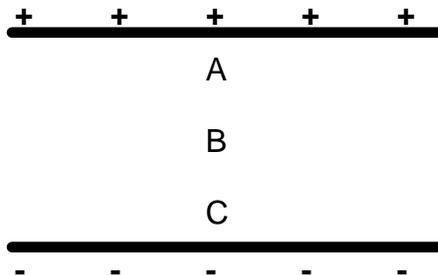
☑ **CHECK YOUR UNDERSTANDING**

TA Name:

PHYSICS 1302 LABORATORY REPORT

Laboratory I

Name and ID#:

Date performed: _____ Day/Time section meets: _____

Lab Partners' Names: _____

Problem # and Title: _____

Lab Instructor's Initials: _____

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL (incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to <u>rewrite that section only</u> and return it to your lab instructor within two days of the return of the report to you.

LABORATORY II
ELECTRIC FIELDS AND ELECTRIC POTENTIALS

In this lab you will continue to investigate the abstract concept of electric field. If you know the electric field at a point in space, you can easily determine the force exerted on a charged object placed at that point. The concept of field has the practical advantage that you can determine the forces on an object in two stages. To determine the force exerted on object A by other objects, you first determine the field, at a location to be occupied by A, *due to all objects except for object A*. You then calculate the force exerted on object A by that field. That force depends only on *the properties of object A* and *the value of the field* at object A's location. An advantage of this two-step approach is that if you make no changes but replace object A with a new object, B, it is simple to calculate the force exerted on object B. This is because replacing A with B does not change the field. *The field that exerts a force on an object depends only on the other objects.*

Keeping track of forces and accelerations is not always the simplest approach for predicting the behavior of objects. It is often more convenient to use the principle of Conservation of Energy. As mentioned in the introduction to the previous lab, the potential energy related to the position of a charged object resides in the surrounding field. As with forces on an object (A) due to a field, the change in potential energy due to the addition of an object (A) to a configuration of other objects is calculated in two stages. First you calculate the "potential," at a location to be occupied by object A, *due to all objects except for object A*. That potential depends only on the other objects and does not depend on any properties of object A. You then use the value of the potential at that location to calculate the change in potential energy when object A is placed there. That potential energy depends *only* on the properties of object A and the value of the potential at object A's location. As with forces, it would then be a simple matter to calculate the potential energy change due to replacing object A with another object B.

Because the concepts of field and potential are abstract and difficult to visualize, this laboratory uses a computer simulation based on the interaction of point charged objects (usually called point charges). With this simulation you can construct a complicated charge configuration and read out the resulting electric field and electric potential at any point in space.

OBJECTIVES

After successfully completing this laboratory, you should be able to:

- Qualitatively determine the electric field at a point in space caused by a configuration of charged objects based on the geometry of those objects.

- Calculate the electric field at a point in space caused by a configuration of charged objects based on the geometry of those objects.

- Qualitatively determine the electric potential at a point in space caused by a configuration of charged objects based on the geometry of those objects.

- Calculate the electric potential at a point in space caused by a configuration of charged objects based on the geometry of those objects.

- Relate the electric field caused by charged objects to the electric potential caused by charged objects.

PREPARATION

Read: Tipler & Mosca Chapters 21, 22 & 23.

Before coming to lab you should be able to:

- Add vectors in two dimensions.

- Calculate the electric field due to a point charge.

- Calculate the electric potential due to a point charge.

- Use the computer simulation program, EM Field.

PROBLEM #1: THE ELECTRIC FIELD
FROM MULTIPLE POINT CHARGES

You work with a biochemical engineering group investigating new insulin-fabrication techniques. Part of your task is to calculate electric fields produced by complex molecules. The team has decided to use a computer simulation to calculate the fields. Your task is to determine if the simulation agrees with the physics that you know. You decide to determine the electric field at a point from a set of charged objects that is complex enough to test the simulation but simple enough to make direct calculation possible. The first configuration you try is a square with two equal negatively charged point objects in opposite corners and a positively charged point object of 1/3 the magnitude of the negative charges in a third corner. You will calculate the electric field at the remaining corner of the square and compare your result to that of the computer simulation of the same configuration.

EQUIPMENT

The computer program <u>EM Field</u> and a ruler.

PREDICTION

Restate the problem. What do you need to calculate? How do you calculate a total electric field from a collection of point charges?

WARM UP

Read: Tipler & Mosca Chapter 21. Read carefully Sections 21.4 and 21.5 and Examples 21-7, 21-8 and 21-9.

1. Make a picture of the situation. Label the objects and their charges. At the point of interest, draw and label an electric field vector caused by each of the charged objects.

2. Determine the magnitude and direction of each of the three electric field vectors at the point of interest in terms of the charge magnitudes and the length of the square's sides. You may need geometry and trigonometry to determine distances.

3. Choose a useful coordinate system. Draw each electric field vector on your coordinate system. Write an expression for each component of each vector.

4. Find the components of the total electric field vector at the point of interest, and then use them to write an expression for both the magnitude and direction of the electric field at the point of interest. Remember what you have learned about adding vectors.

EXPLORATION

In the folder <u>PhysLab</u> on the desktop, open <u>EM Field</u> and click anywhere in the window for the instructions. From the *Sources* pull-down menu, select *3D point charges*. Drag any positive charge to the center of the window of <u>EM Field</u>. From the *Field and Potential* pull-down menu (shown to the right), select *Field vectors*.

Field and Potential **Display**
* Field vectors
  Directional arrows
  Field lines
  Potential
  Potential difference
  Equipotentials
  Equipotentials with number
  Flux and Gauss's Law
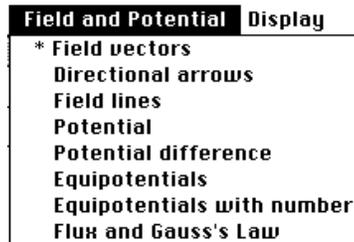
You can reveal electric field vectors using the left button on the mouse: drag the cursor to scan and release the button at the locations where you would like the electric field to remain displayed. Look at the *Display* drop-down menu and explore its options. To place objects at precise points on the

screen you can use the *show grid* and *constrain to grid* features from the *display* pull-down menu. Expand the display window to fill the entire computer screen.

Measure the length of the electric field vector at several locations, as well as the distance from the locations to the center of the charged point object. You can remove the displayed vectors using the C*lean up screen* option from the *Display* drop-down menu.

Try using different magnitudes of charge. What range of charge values allows you to accurately measure the length of the electric field vector at all points on the screen?

To check whether or not you get the correct behavior of the electric field from a point charge do the following:

1. Pick several locations at different distances *r* from the center of the single point charge. For each of the locations, measure *r* and the length of the electric field vector.

2. Draw what the Coulomb's law predicts for the field strength vs. distance (*r*) graph.

3. Plot the measured electric field vector lengths as a function of the distance to the center of the charged point object. Compare the shape of the graph to that based on the Coulombs' law.

You have to calibrate the computer simulation program to be able to translate the lengths of electric field vectors into magnitudes of the electric field represented. Using a charged point object whose electric field can be determined, you can do this in the following way.

1. Pick a distance *r*, for which you have measured the electric field vector length. Assume charges are given in Coulombs by the simulation program. Use Coulomb's law to *calculate in SI units* the magnitude of the electric field produced by the point charge at that distance.

2. Find the ratio of the calculated electric field magnitude to the vector length.

3. Repeat this for several other distances. Estimate the percentage within which you can claim that you get the same ratio for different distances. If the uncertainty is reasonably low, calculate the average value of the ratio. This number can now be used as a conversion factor to translate measured lengths of the electric field vector into electric field strengths.

Verify qualitatively that the simulation gives the correct behavior of the electric field from a pair of point charges. Try opposite charges of the same absolute value first. Where does the field go to zero? Does this behavior match what is expected? Repeat this qualitative analysis for two identical charges.

Let us explore a distribution of three charges. Drag two negative charges and one positive charge onto the screen. Look at the electric field vectors at various points around the charge distribution. Try changing the magnitudes of the charges, the signs of the charges, the distances between them, and their locations on the screen.

To reproduce the configuration under study in this problem, place two negative charges in opposite corners of a square using *constrain to grid*. (Larger charges are recommended; also, keep in mind that you will be adding a positive charge of 1/3 the magnitude.) Add the positive charge to a third corner of the square. Explore the electric field at different locations. Note the length of the electric field vector in the fourth corner of the square. What parameter can you vary to change the length of the electric field vector at that point preserving the conditions of the problem? If needed, move the charges to make the electric field vector length in the fourth corner of the square large enough for

accurate measurement. In your journal, note whether or not such manipulations change the direction of the electric field at that corner, and record the direction.

MEASUREMENT

Measure the length of the electric field vector at the point of interest.

ANALYSIS

Use the data that you have collected for the following analysis.

1. Convert the length of the electric field vector produced by the computer simulation into electric field strength.

2. Using Coulomb's law, calculate electric fields at the measurement location from each of the three charges.

3. Introduce a two-dimensional coordinate system and calculate two components for each of the three fields. When estimating components of a vector, you should always take into account its direction.

4. Add x-components (with their correct signs) of three fields to get the x-component of the electric field in the fourth corner due to all three charges. Similarly, add y-components.

5. Use the calculated components of the (total) electric field in the fourth corner to find its magnitude.

6. Compare your calculated electric field strength to that from the computer simulation. Also compare your prediction for the direction of the field to that from the computer simulation.

CONCLUSION

Did the result of your calculations using Coulomb's law match the value obtained by converting the length of the electric field vector from the computer simulation? Explain any differences.

What properties of electric field due to one or more point charges can be seen from and/or supported by the computer simulation? Use evidence from both the exploration and measurement parts of the experiment to formulate your answer.

PROBLEM #2: THE ELECTRIC FIELD FROM A LINE OF CHARGE

You are a member of a team designing an electrostatic air cleaner for the use of people suffering from allergies. The air passage through the device will contain many complicated charged electrodes. You must determine the effect of these electrodes on plant spores that cause allergic reactions. The first step is to calculate the electric field at every point in the air passage. Because the electrode configuration is complicated, your team has decided to use a computer simulation to model the resulting electric field. Your task is to determine if the simulation results agree with the physics you know for non-point-like charged objects. You decide to test the simulation for the case of a uniformly charged rod, since this situation is simple enough for you to calculate. For comparison with the simulation results, you decide to calculate the electric field at a point a short distance from the middle of the rod along a line perpendicular to it, and also at a point a short distance from the end of the rod along its axis.

The computer program <u>EM Field</u> and a ruler.

PREDICTION

Restate the problem. What do you need to calculate? How do you calculate the total electric field due to a continuous charge distribution?

WARM UP

Read: Tipler & Mosca Sections 21.4, 21.5, & 22.1 and Example 22-1.

1. Make a picture of the situation. Select one of the points of interest. Label any relevant constant quantities. Label all relevant distances and angles. Decide on an appropriate coordinate system. Draw a charge element dq somewhere along the rod.

2. At the point of interest draw a vector d**E** representing the electric field produced by the element dq. Write an expression for its magnitude. Draw and label its components. Write an expression for the magnitude of each component.

3. For any charge distribution, the total electric field is found by calculating the contribution from each charge element to the total (vector) field, and summing the contributions (as vectors). When the charge distribution is continuous, it may be mathematically divided into infinitesimal elements dq; then (for each field component) the individual contributions are added together with an integral. Write an integral for *each component of* the total field at the point of interest in terms of the charge elements dq. (Note: Always consider the symmetry of the situation. It may be that the integral for one of the components does not need to be calculated.)

4. In order to evaluate an integral, all terms in the integrand must be either constant, or be explicit functions of the integration variable. First choose an appropriate integration variable. Then rewrite all variable quantities in the integrand (including dq) in terms of the integration variable you have chosen. Determine appropriate limits for the integration variable you have chosen. Use the Pythagorean Theorem, trigonometry, and the linear charge density to write your integrand(s) in a suitable form.

5. Evaluate the integral(s) to get an expression for the total electric field's components at the point of interest. Write an expression for the total field magnitude and indicate its direction.

6. Repeat steps 1-5 for the other point of interest.

EXPLORATION

On the desktop, open the <u>EM Field</u> program. If you have done Problem #1, you are already familiar with this simulation software and it may be enough to just review the notes in your lab journal. Otherwise (or if you need to refresh or reinforce your knowledge of the <u>EM Field</u> simulation program) perform (repeat) the exploration from Problem #1. Two important goals of the Exploration part are (i) to check that the simulation software describes the electric field from a point charge correctly and (ii) to determine a conversion factor, which will be used to translate the measured lengths electric field vectors into absolute values of the vectors, i.e. into magnitudes of electric fields.

Let us now explore the configuration of charges to be studied in this experiment. From the *sources* pull-down menu select *3D Point Charges*. Drag positive charges onto the screen to create a long, uniform line of charge.

Use the mouse (click or drag) to investigate how the magnitude and direction of the electric field depends on position. Display electric field vectors by clicking at the locations of interest for this problem. To obtain electric field vectors of accurately measurable lengths at the locations of interest, you may have to adjust the number of charges and their magnitudes (use *Add more charges* from the *Sources* pull-down menu).

MEASUREMENT

Place charges on the screen to simulate the situation described in the problem. Measure the length and direction of the electric field vector, as well as any other quantities necessary for your prediction equation, at the points of interest.

ANALYSIS

Translate the length of the electric field vectors produced by the computer simulation into electric field strengths. For the situation in the problem, compare your calculated electric field strengths to those from the computer simulation. Also compare your prediction for the direction of the fields to those from the computer simulation.

CONCLUSION

Did your results match your predictions? Explain any differences. What physical principles are consistent with the computer simulation? Use evidence from the exploration and measurement to support your answer.

PROBLEM #3: ELECTRIC POTENTIAL FROM MULTIPLE POINT CHARGES

You are a member of a team building the world's highest intensity particle accelerator. In this machine, charged atomic nuclei are brought from a very slow speed to almost the speed of light by passing them through a charged electrode structure. You need to determine the effect of these electrodes on the speed of various nuclei. The first step is to calculate the electric potential that affects the nuclei. Because the charged electrode configuration is so complicated, your team has decided to use a computer simulation. Your task is to determine if the simulation results agree with the physics that you know. You decide to calculate the electric potential at a point caused by a set of charged objects that is complex enough to test the simulation but simple enough to make your calculation possible. The first configuration that you try is a square with two equal negatively charged point objects in opposite corners and a positively charged point object of 1/3 the magnitude of the negative charges in a third corner. You will calculate the electric potential at the remaining corner of the square and compare your result to that of the computer simulation of the same configuration.

EQUIPMENT

The computer program <u>EM Field</u> and a ruler.

PREDICTION

Restate the problem. What are you trying to calculate in your prediction? How do you calculate a total electric potential from a collection of point charges?

WARM UP

Read: Tipler & Mosca Sections 23.1 and 23.2 and Example 23-4.

1. Draw a schematic of the charge configuration. Label the objects and their charges. Show and label all relevant distances and angles.

2. Write down equations for the (scalar) electric potentials at the point of interest caused by each of the three charged objects using the value of each charge and the size of the square. Use geometry to determine relevant distances.

3. Get the total electric potential at the point of interest by adding the electric potentials from step 2. Remember that even though it looks like we simply add up three quantities, the charges are of different signs and so are the potentials in the sum.

EXPLORATION

Open <u>EM Field</u> and click anywhere in the window for the instructions.

From the *Sources* pull-down menu, select *3D point charges*. Drag any positive charge to the center of the window of <u>EM Field</u>. From the *Field and Potential* pull-down menu (as shown to the right), select *Potential.* Move the cursor where you would like to determine the electric potential and click the mouse button.

Field and Potential Display
Field vectors
Directional arrows
Field lines
* Potential
Potential difference
Equipotentials
Equipotentials with number
Flux and Gauss's Law
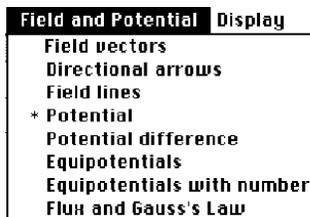
To place objects at precise points on the screen you can use the *show grid* and *constrain to grid* features of the program (from the *display* pull-down menu). It might also be helpful to expand the display

window to fill the entire computer screen. You can do this by clicking on the small box in the upper right-hand corner of the display screen.

Another useful way to view electric potential involves equipotential surfaces. Select *Equipotentials with number* from the *Field and Potential* pull-down menu. Move the cursor where you would like to determine the electric potential and click the mouse. How is this different from the *Potential* setting?

Try different magnitudes of charge. What range of charge values allows you to accurately measure the electric potential at a large number of locations on the screen?

Try using negative charges. How does this change the electric potential?

Check to see if you get the correct behavior of the electric potential from a point charge:
- Predict the shape of a graph of potential vs. distance (*r*). Graph the electric potential vs. the distance from the center of the charged point object. Is it the shape you expected?
- Predict the shape of a graph of potential vs. inverse distance (1/r). Graph the electric potential vs. (1/r). Is it the shape you expected?

You will need to translate the number the computer gives for the electric potential to appropriate units. Calibrate the computer simulation program using a charged point object whose actual electric potential can easily be determined:

- For one of the distances used to take data, calculate what the electric potential should be using Coulomb's law (assuming the value of the charge is in Coulombs).
- How does this compare to the number produced by the computer simulation program? Find the ratio between the calculated electric potential and the number produced by the simulation. How can you use this number to translate the computer simulation results into electric potentials?
- Repeat this for another distance to verify that you get the same ratio.

Qualitatively check to see if the program combines the electric potentials from two charged point objects correctly. Look at the cases of (a) equal and opposite charges and (b) two identical charges. Does the potential behave as you predict in each case? Does it go to zero where you predict it?

MEASUREMENT

Place charges on the screen to simulate the situation of interest. Measure the electric potential at the point of interest.

ANALYSIS

For the situation in the problem, compare your calculated electric potential to that from the computer simulation.

CONCLUSION

Did your results match your predictions? Explain any differences. What physical principles are consistent with the computer simulation? Use evidence from the exploration and measurement to support your answer.

PROBLEM #4: ELECTRIC POTENTIAL FROM A LINE OF CHARGE

You work with an astrophysics research group investigating the origin of high-energy particles in the galaxy. The group has just discovered a large electrically charged nebula with an irregular shape. In order to understand how this nebula affects the motion of charged particles passing nearby you must find the electric potential near the nebula. Because of its complicated shape you plan to use a computer simulation. You must determine if the simulation results match the physics you know. You decide to test the simulation for the case of a uniformly charged rod, since the situation is simple enough for direct calculation. You decide to calculate the electric potential at a point a short distance from the middle of the rod along a line perpendicular to it, and also at a point a short distance from the end of the rod along its axis. You will then compare these results with those obtained using the computer simulation, to see if the simulation can be trusted.

<div style="text-align:center">

EQUIPMENT

</div>

The computer program <u>EM Field</u> and a ruler.

<div style="text-align:center">

PREDICTION

</div>

Restate the problem. What do you need to calculate? How do you calculate the electric potential due to a continuous distribution of charge?

<div style="text-align:center">

WARM UP

</div>

Read: Tipler & Mosca Chapter 23. Pay particular attention to Sections 23.1, 23.2 & 23.4 and Examples 23-5 & 23-6.

1. Make a picture of the situation. Select one of the points of interest. Label relevant distances, angles, and constant quantities. Decide on an appropriate coordinate system. Draw a charge element dq somewhere along the rod.

2. Write an expression for the (scalar) electric potential dV at the point of interest that is caused by your small element of charge dq.

3. For any charge distribution, the total electric potential is found by calculating the contribution from each charge element to the potential, and summing the contributions. When the charge distribution is continuous, it may be mathematically divided into infinitesimal elements dq; then the individual contributions are added together with an integral. Write an integral for the total potential at the point of interest in terms of the charge elements dq.

4. In order to evaluate an integral, all terms in the integrand must be either constant, or be explicit functions of the integration variable. First choose an appropriate integration variable. Then rewrite all variable quantities in the integrand (including dq) in terms of the integration variable you have chosen. Determine appropriate limits for the integration variable you have chosen. Use the Pythagorean Theorem and the linear charge density to write your integrand in a suitable form.

5. Evaluate the integral to get an expression for the total electric potential at the point of interest. Repeat steps 1-5 for the other point of interest.

<div style="text-align:center">

EXPLORATION

</div>

In the folder <u>PhysLab</u> on the desktop open <u>EM Field</u>. If you have done Problem #3, review the notes in your journal. If you did not or your notes are incomplete, perform the exploration from Problem

#3. The exploration from Problem #3 provides a technique for translating the values for potential produced by the simulation to actual potentials expressed in appropriate units.

From the *sources* pull-down menu select *3D Point Charges*. Drag positive charges onto the screen to create a long, uniform line of charge. Use the mouse to investigate how the electric potential depends on position. What number and magnitude of charges work best to give you electric potentials that can be accurately measured at the points of interest?

MEASUREMENT

Place charges on the screen to simulate the situation described in the problem. Measure the electric potential, as well as any other quantities necessary for your prediction equation, for the object at the points of interest.

ANALYSIS

Translate the values for potential produced by the simulation into actual potentials. For the situation in the problem, compare your calculated electric potential to that from the computer simulation.

CONCLUSION

Did the computer simulation match your predictions? Explain any differences. What physical principles are consistent with the computer simulation? Use evidence from the exploration and measurement to support your answer.

Where is the electric potential defined to be zero? Is this consistent with your results? If you completed problem 2 in this laboratory, do the following. For the point along the axis of the line of charge, take the derivative (with respect to distance from the rod) of the expression for the potential. How does this compare with the magnitude of the electric field at this point that you calculated in the warm-up questions of Problem 2? How should it compare, and why?

☑ CHECK YOUR UNDERSTANDING

For each of the charge configurations below, find the electric field and the electric potential at the point marked with the "?".
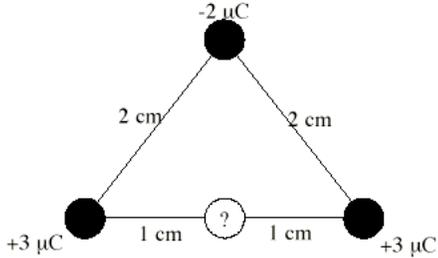
Configuration 1
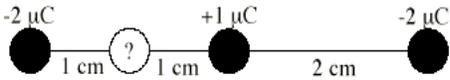
Configuration 2
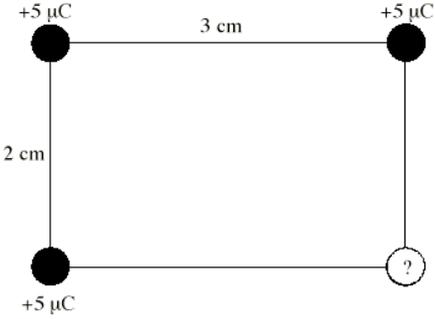
Configuration 3
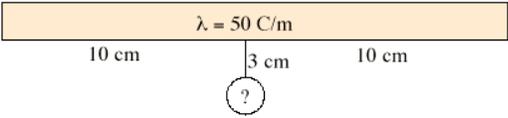
Configuration 4

PHYSICS 1302 LABORATORY REPORT

Laboratory II

Name and ID#:

Date performed: _____ Day/Time section meets:

Lab Partners' Names:

Problem # and Title:

Lab Instructor's Initials: _____

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL (incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.

LABORATORY III
ELECTRIC ENERGY AND CAPACITORS

Our modern society functions in part because we have learned how to manipulate electrical energy. Almost all of our technology involves electrical energy in one form or another. In this laboratory you will investigate the conservation of energy as it relates to electricity.

A capacitor is the simplest device that can store electrical energy. The problems in this lab involve transforming electrical energy stored in capacitors into light, kinetic energy, and other forms of energy that may be more difficult to detect.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Apply the concept of conservation of energy to solve problems involving electrical phenomena.

- Describe the energy stored in a capacitor based on how it is connected to other capacitors and to sources of potential differences.

PREPARATION:

Read Tipler & Mosca: Chapter 6.4; Chapter 25, sections 1-3.

Before coming to lab you should be able to:

- Calculate the work done by a force exerted on a moving object.

- Calculate the relationship between power and energy.

- Write the equation for the energy stored in a single capacitor and understand the meaning of all the quantities involved.

PROBLEM #1: ELECTRICAL AND MECHANICAL ENERGY

You have a job in a University research group investigating the effect of solar flares on the Earth's magnetosphere. Your team is designing a small, cheap satellite for the investigation. As soon as the satellite achieves a stable orbit, it must extend its two solar panels. Your team must design a lightweight power source for deploying the solar panels. You have been asked to investigate the use of capacitors as a power source. You decide to calculate how the mechanical energy transferred to a device powered by a capacitor depends on the capacitance. You will test your calculation using a laboratory model in which a capacitor provides power to a motor that lifts a mass. You calculate how far the weight will move as a function of the capacitance of the capacitor. You assume that you know the initial voltage on the capacitor.

EQUIPMENT

You have a mass set, a rods and clamps for securing the motor with spool, string, several different capacitors, a battery or power supply, a meter stick, and a digital multimeter (DMM).

PREDICTION

Restate the problem. What are you trying to calculate? Express the result as both an equation and a graph.

WARM UP

Read: Tipler & Mosca Chapter 24.1 & 24.2. Also review Chapter 5.1.
1.   Draw pictures of the situation before the weight moves, while the weight is in motion, and after the weight has come to rest. Label all relevant distances, masses, forces, and potential differences. Describe the physics principles you need to solve this problem.
2.   Define the initial and final times of interest in this problem. Describe (perhaps with your diagrams) what happens to energy in the situation between those times.
3.   Are there objects in the problem whose potential or kinetic energy is relevant, and that you can calculate directly in terms of quantities measurable in the lab? If so, write down expressions for their initial and final (potential or kinetic) energies.
4.   Use the work-energy theorem to write an equation for the net work done on the weight. Use this equation and equations from previous steps to write the amount of energy transferred from the capacitor to the weight, during the entire process, as a function of the distance the weight moves.
5.   How would you define "efficiency" for this situation? Choose a system. Write an energy conservation equation for your system that relates the efficiency, the situation's initial conditions, and properties you can measure in the lab, to the distance the weight moves.
6.   Use the principal of energy conservation to write an equation for the amount of energy dissipated in this situation, in terms of measurable quantities and the efficiency. Be sure this equation is consistent with your description from step 2.
7.   Sketch a graph of the distance the weight moves as a function of the capacitor's capacitance. Assume constant efficiency, and that the capacitor is charged to the same potential difference for each trial. (You can check the "constant efficiency" assumption in the lab.)

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Take the capacitor with the smallest capacitance. Give the capacitor plates a potential difference of 6 volts by connecting the "+" terminal of the capacitor to the "+" terminal of the battery and the "-" terminal of the capacitor to the "-" terminal of the battery.

NOTE: **DO NOT reverse the polarity of the connection by connecting the battery's "+" terminal to the capacitor's "-" terminal or vice versa. Doing so would irreversibly change the capacitor's capacitance.**

Disconnect the capacitor from the battery. Explain how you can use the DMM to tell if the capacitor is fully charged or fully discharged. Explain what you mean by fully charged. Try charging for different amounts of time. Determine how long it takes the capacitor to fully charge.

Connect the weight to the motor with the string. Without touching the capacitor leads to anything else connect one lead to one terminal of the motor and the other lead to the other terminal of the motor. Which direction does the motor spin? Does the direction that the motor spins depend on how you connect the motor and the capacitor? Decide the best way to connect the motor and the capacitor.

How far is the weight pulled upward? Try the largest capacitor as well. Does the efficiency appear to be constant? If not, can you make it more constant, or will you have to average over several trials, or is the assumption of constant efficiency simply not realized by this system?

Write down your measurement plan.

MEASUREMENT

Measure the distance that each fully charged capacitor pulls the weight. Be sure to take more than one measurement for each capacitor.

ANALYSIS

Graph the distance the weight is pulled versus the voltage to which the capacitor is charged. Show the estimated measurement uncertainty on your graph.

CONCLUSION

Did your results match your predictions? Explain any differences.

How efficient is this energy transfer? Define what you mean by efficient. How good was the assumption of constant efficiency for this situation?

You have heard that energy is always conserved. Is it appropriate to say that energy was conserved in this situation? Why or why not?

PROBLEM #2: SIMPLE CIRCUITS WITH CAPACITORS

You and your friend are trying to determine if you can use a capacitor to extend the lives of batteries in circuits. You suggest that you try a simple circuit with a capacitor, originally uncharged, connected to a battery through a switch. To monitor the output energy, you put a light bulb in series with the capacitor. Your friend believes that when the switch is closed the capacitor charges up and the bulb gets brighter and brighter until the brightness levels off. The bulb then stays on until the switch is opened. Do you agree?

EQUIPMENT

You can build the circuit shown below out of wires, bulbs, capacitors and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch and a digital multimeter (DMM).

Circuit I

Legend:
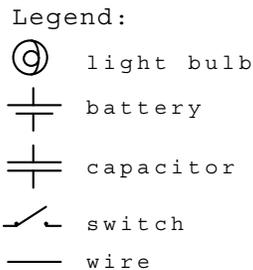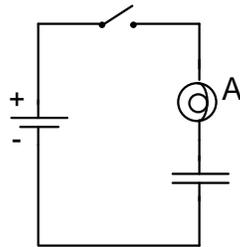
PREDICTION

Restate the problem. Do you agree with your friend? If not, describe what you think the behavior of the circuit will be. Give your reasoning. Explain what is going on in each component of the circuit.

Sketch a qualitative graph of the bulb's brightness vs. time.

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged.

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, build the circuit but do not close it yet.

NOTE*: **Be sure that the polarity of the capacitor's connection is correct -- that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "-" terminal is connected to the capacitor's "-" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.**

Now, close the circuit and observe how the brightness of the bulb changes over time.

From your observation of the bulb's brightness, how does the charge flowing through the bulb change over time? You can check this using the DMM set for current (Amps). See Appendix D for the use of the DMM. Using a mental model of the capacitor as two parallel plates separated by a short distance, how does the charge accumulated on each plate of the capacitor change as the bulb's brightness changes? Can you measure this with the DMM? Use conservation of charge to explain what you observe.

From what you know about a battery, how does the potential difference (voltage) across the battery change over time? Check this using the DMM set for potential difference (Volts). From your observations of the brightness of the bulb, how does the potential difference across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage (change of potential difference) across the capacitor over time? Can you check with a DMM? Use the concept of conservation of energy to explain what you observe.

After a few moments, open the circuit. Is the capacitor charged or uncharged? To determine if the capacitor is charged, carefully (and safely) remove the battery from the circuit and reconnect the circuit without the battery. With only the capacitor and bulb (no battery) in the circuit, does the bulb light? Use the result to answer the following questions. Was the capacitor charged before you closed the circuit? Was the capacitor still charged long after the circuit was closed? Use conservation of charge and conservation of energy to explain your results.

CONCLUSION

Was your friend correct about how the brightness of the bulb changed?

Sketch a qualitative graph of the brightness of the bulb as a function of time after you complete the circuit consisting of the *initially discharged* capacitor, battery and light bulb. How does this compare to your prediction? Sketch a qualitative graph of the charge on the capacitor as a function of time for this situation.

Sketch a qualitative graph of the brightness of the bulb as a function of time after you complete the circuit consisting of the *initially charged* capacitor, NO battery and light bulb. Sketch a qualitative graph of the charge on the capacitor as a function of time for this situation. Describe how this graph relates to the changing potential difference across the capacitor, and to the changing amounts of charge on each plate of the capacitor.

PROBLEM #3: CAPACITANCE

You have a part time job as a special effects technician at a local theater. As part of the theatrical production, the play's director wants a light bulb to dim very slowly for dramatic effect. You design a simple, inexpensive circuit to automatically accomplish this task: a battery, a switch, a light bulb, and a capacitor in series. You have been asked to demonstrate different rates of dimming for the light bulb so the director can select the one that best fits the performance. You need to determine how to adjust the amount of time it takes for the light bulb to go out by varying the capacitance. To make a proper comparison you make sure that the capacitor is initially uncharged.

You have the materials to build the circuit below with a choice of capacitors. You will also have a stopwatch and a digital multimeter (DMM). Use the accompanying legend to help you build the circuit.

Circuit I

Legend:

⊖ light bulb

╪ battery

╪ capacitor

╱ switch

— wire
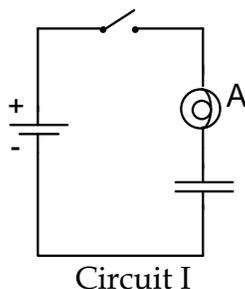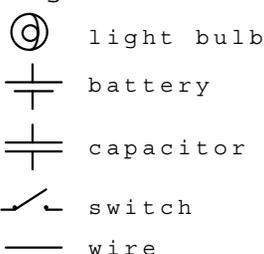
PREDICTION

Restate the problem. What is the quantity you will be measuring and what is the quantity you will be controlling? How do you think they will depend on one another? Give your reasoning. Explain what is going on in each component of the circuit.

Sketch a graph of the time it takes for the light bulb to turn completely off as a function of the capacitor's capacitance.

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Be sure the capacitors are uncharged.

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, connect the circuit but do not close it yet.

NOTE*: Be sure that the polarity of the capacitor's connection is correct -- that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "-" terminal is connected to the capacitor's "-" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.*

Now, close the circuit and observe how the brightness of the bulb changes over time. How long does it take for the bulb to turn off?

From what you know about a battery, how does the potential difference (voltage) across the battery change over time? Check this using the DMM set for potential difference (Volts). From your observations of the brightness of the bulb, how does the potential difference across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage across the capacitor over time? Can you check with a DMM? Use the concept of potential difference to explain what you observe.

Develop a measurement plan that will allow you to determine the time it takes a bulb to turn off as a function of capacitance. You will want to decide how many different capacitors you need to use, how many time measurements to take for each capacitor, what you mean by the light bulb being "off," and how to ensure that the capacitor is uncharged before you make each measurement.

MEASUREMENT

Follow your measurement plan. Be sure to record your estimated uncertainty for each measurement.

ANALYSIS

Graph the time it takes for the light bulb to turn off, as a function of capacitance, with the capacitor initially uncharged.

CONCLUSION

How did your measurement compare with your prediction? Using conservation of charge, conservation of energy, and the model of a capacitor as two plates separated by a short distance, explain how the capacitance affects the time it takes for the bulb to turn off.

PROBLEM #4: CIRCUITS WITH TWO CAPACITORS

You recently purchased a used camera with an electric flash. After taking a roll of pictures you are disappointed that the flash isn't bright enough. You look in the camera and notice that the flash works by allowing a battery to slowly charge a capacitor, and then quickly releasing the capacitor's stored electrical energy through a light bulb when a photo is taken. You think that the problem with your camera may be that not enough energy is stored in the capacitor to properly light the flash bulb. You have another capacitor with different capacitance, but aren't sure if you should connect it in series or in parallel with the original capacitor in order to store the most energy. You make an educated guess, and decide to test your prediction with circuits consisting of one or two initially uncharged capacitors, a battery, and a light bulb. You plan to measure the amount of time the bulb stays lit for one capacitor and for each of the possible arrangements of two capacitors, reasoning that if capacitors in a circuit can store more energy, they will take longer to fully charge.

EQUIPMENT

You will build the circuits shown below out of wires, *identical* bulbs, two *different* capacitors, and batteries. You will also have a stopwatch.

Circuit I   Circuit II   Circuit III

Legend:
- light bul
- battery
- capacitor
- switch
- wire
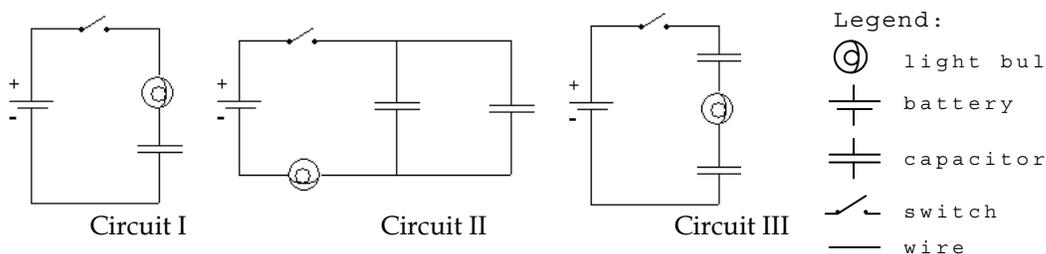
PREDICTION

Restate the problem. What quantity do you wish to compare across the three situations? Use physics to decide how they will compare. Which quantity will you be measuring directly? Describe qualitatively how it is connected to the quantity of interest.

WARM UP

Read: Tipler & Mosca Chapter 24.2 & 24.3.
1.   Draw a picture of each arrangement of the capacitors, light bulb, and battery. On each picture, label the capacitance of each capacitor. (Remember that you will have capacitors with different capacitances.)   Also, label the electric potential difference across each circuit element and the charge stored on the plates of each capacitor.
2.   Decide on the physics principles you will use. For a circuit, conservation of charge is usually useful, as is conservation of energy. What is the relationship between the total energy stored in each circuit and the energy stored on each capacitor in that circuit?
3.   For each capacitor, determine an equation that relates its stored energy, the charge collected on its plates, and its capacitance.
4.   For each capacitor, write an equation relating the charge on its plates, the potential difference across the capacitor, and its capacitance.
5.   *After the current stops flowing* through the circuit, do the two capacitors in Circuit II have the same amount of stored charge? Circuit III? At that time, what is the potential difference across the bulb in each circuit? At that time, what is the relationship between the potential difference across the battery and the potential difference across each capacitor?

6. The target quantity is the energy stored in the capacitors of each circuit. To determine which circuit stores more energy in the capacitors, you must calculate the energy stored in terms of quantities you can easily find, such as the potential difference across the battery and the capacitance of each capacitor.

7. From the previous steps, you can find the total energy stored in the capacitors in each circuit in terms of the potential difference across the battery and the capacitance of each capacitor. Now compare them to determine which is largest. *Check your equations by making the comparison when both capacitors have the same capacitance. Does the result make sense?*

8. What assumptions must you make to relate the total energy stored in the capacitors for each configuration to the time the light bulb remains lit after each circuit is closed?

<div align="center">

EXPLORATION

</div>

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Make sure all of your capacitors are uncharged before starting the exploration. Examine each element of the circuit **before** you build it. How do you know if the battery and the bulb are "good"? Connect Circuit I to use as a reference.

NOTE: **Be sure that the polarity of the capacitor's connection is correct in each circuit -- that the part of the circuit connected to the battery's "+" terminal is connected to a capacitor's "+" terminal, and the part of the circuit connected to the battery's "-" terminal is connected to a capacitor's "-" terminal. Reversing the polarity would irreversibly change each capacitor's capacitance.**

Close the circuit and observe how the brightness of the bulb changes over time. How long does it take for the bulb to turn off?

Connect Circuit II using the capacitor from Circuit I along with a capacitor with a different capacitance. *Do not close the circuit yet.* Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. *Now, close the circuit.* Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Does the order that you connect the two capacitors and the bulb in the circuit matter? Try following one capacitor with the other capacitor and then the bulb. Try switching the two capacitors.

When the brightness of the bulb no longer changes, how are the the potential differences across the circuit elements related? Check this using the DMM, set for potential difference (Volts). Use the concept of energy conservation to explain what you observe.

Connect Circuit III using the two capacitors you used in Circuit II. *Do not close the circuit yet.* Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. *Now, close the circuit.* Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Use the DMM to check the relationship between the potential differences across the elements of this circuit. Explain what you observe.

Develop a plan for measuring the time that it takes for the bulbs in Circuits I, II, and III to turn off, if they light at all.

MEASUREMENT

Use your measurement plan to record how long it takes for the light bulb to go off for each circuit. Use "0 seconds" for any bulbs that did not light. What are the uncertainties in these measurements?

ANALYSIS

Rank the actual time it took each bulb to turn off. Do all the bulbs initially light? Do all the bulbs eventually go off?

CONCLUSION

How did your initial ranking of the time it would take for the bulbs to go out compare with what actually occurred? Use conservation of charge, conservation of energy, and the concept of potential difference to explain your results.

Compare the reasoning you used in the exploration section to predict whether the bulbs would light in each circuit to the understanding you now have. If your reasoning has changed, explain why it changed.

☑ CHECK YOUR UNDERSTANDING

For each of the arrangements of identical capacitors shown below:

1) Rank them in terms of the amount of time they can light a light bulb. Assume that the leads shown have been connected to a 6 Volt battery and then removed from the battery and connected to a light bulb.

2) Calculate the potential difference between the terminals of each capacitor. Assume that the leads shown have been connected to a 6 Volt battery and that the capacitance of each capacitor is 10 μC.

3) Calculate the amount of energy stored in each capacitor and the total energy stored in each arrangement of capacitors. Assume that the leads shown have been connected to a 6 Volt battery and that the capacitance of each capacitor is 10 μC

Arrangement 1

Arrangement 2

Arrangement 3

Arrangement 4
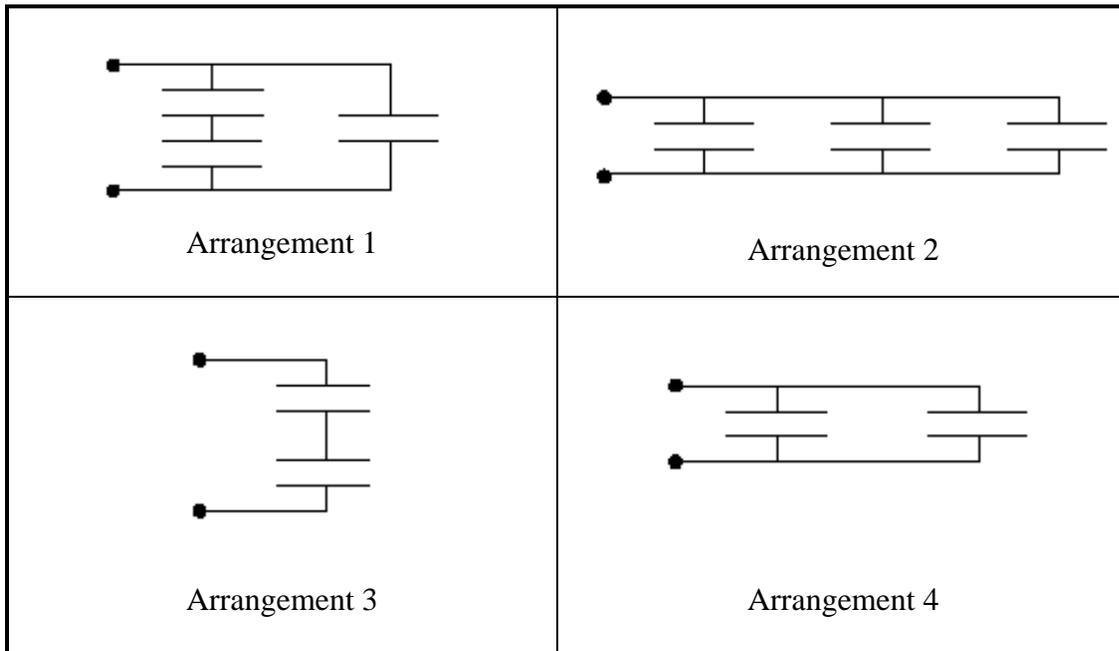
☑ **CHECK YOUR UNDERSTANDING**

TA Name:

PHYSICS 1302 LABORATORY REPORT

Laboratory III

Name and ID#:

Date performed: _____ Day/Time section meets: _____

Lab Partners' Names:

Problem # and Title:

Lab Instructor's Initials: _____

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.

LABORATORY IV
ELECTRIC CIRCUITS

In the first laboratory, you studied the behavior of electric fields and their effect on the motion of electrons using a cathode ray tube (CRT). This beam of electrons is one example of an electric current – charges in motion. The current in the CRT was simple in that the electrons moved through a vacuum. The forces on them were completely known. Their behavior could be determined by calculating the electric field and then applying kinematics.

In contrast to the CRT, common electric currents are inside materials such as wires or light bulbs. Even though the interactions of electrons inside materials are quite complicated, the basic principles of physics still apply. Conservation of energy and charge allow us to determine the overall behavior of electric currents without the need to know the details of the electrons' interactions. This approach to problem solving in the realm of electric circuits will give you more experience in applying the very useful principles of conservation.

OBJECTIVES

After successfully completing this laboratory, you should be able to:

- Apply the concepts of circuits to electrical systems.

- Apply the concept of conservation of charge to determine the behavior of the electrical current through any part of a circuit.

- Apply the concept of conservation of energy to determine the behavior of the energy output of any element in a circuit.

- Use the concept of electric potential to describe the behavior of a circuit.

- Relate the electric charge on a circuit element to the potential difference across that element and the capacitance of that element.

- Relate the electric current through a circuit element to the resistance of that element and potential difference across that element.

- Measure the current through a circuit element with a digital multimeter (DMM).

- Measure the voltage between two points in a circuit with a DMM.

- Measure the resistance of a circuit element with a DMM.

PREPARATION

Read Tipler & Mosca: Chapter 23 section 1; Chapter 24, sections 1, 2, 3; Chapter 25. It is likely that you will be doing these laboratory problems before your lecturer addresses this material. The purpose of this laboratory is to give you these experiences as an introduction to the material. So, it is very important that, when you read the text before coming to lab, you remember the objectives of the laboratory.

Before coming to lab you should be able to:

- Describe the relationship between charge and current.

- Describe the relationship between potential and potential energy.

- Describe the essential difference between an insulator and a conductor.

- Identify what is an electrical circuit and what is not.

- Apply conservation of energy and conservation of charge to current flowing around a circuit.

- Write down Ohm's law and know when to apply it.

- Describe the difference between a capacitor, a resistor, and a battery.

- Use a DMM to measure potential difference, current, and resistance.

PROBLEM #1: SIMPLE CIRCUITS

You need more light in your workroom, so you decide to add another light fixture to your track lighting. However, you are concerned that adding another light may dim the lights that are already in the track. When you proceed with the addition of another light, you notice that none of the lights are dimmer than before. You wonder what type of circuit your track lighting uses. You decide to build models of circuits with two bulbs connected across a battery, and to compare the brightness of the bulbs in these circuits to a reference circuit with a single bulb. The circuit in which each bulb is as bright as the one in your reference circuit is the same type as the circuit in your track lighting.

EQUIPMENT

You will build three simple circuits shown below out of wires, bulbs, and batteries.

Use the accompanying legend to build the circuits.

Legend:
  light bu
  battery
  wire

Circuit I   Circuit II   Circuit III
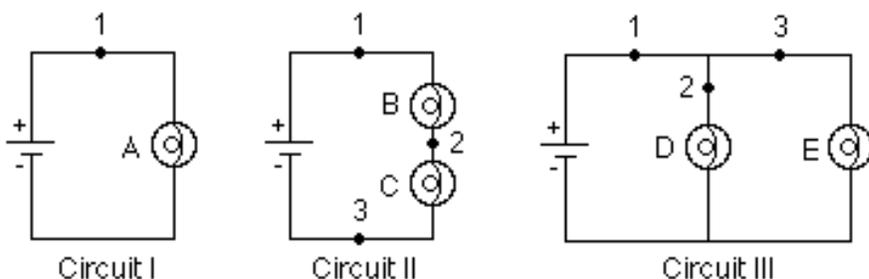
Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same. If in doubt, ask your TA.

PREDICTION

Restate the problem. Rank, in order of brightness, the bulbs A, B, C, D, and E from the brightest to the dimmest (use the symbol '=' for "same brightness as" and the symbol '>' for "brighter than"). Write down your reasoning.

EXPLORATION

Reference Circuit I
Connect Circuit I to use as a reference. Observe the brightness of bulb A. Replace the bulb with another one and again observe the brightness. Repeat until you have determined the brightness of all your bulbs when they are connected into the same type of circuit. If the bulbs are identical, they should have the same brightness.

Note: Pay attention to large differences you may observe, rather than minor differences that may occur if two "identical" bulbs are, in fact, not quite identical. How can you test whether minor differences are due to manufacturing irregularities?

Circuit II
Connect Circuit II. Compare the brightness of bulbs B and C. What can you conclude from this observation about the amount of current through each bulb?
Is current "used up" in the first bulb, or is the current the same through both bulbs? Try switching bulbs B and C. Based on your observation, what can you infer about the current at points 1, 2, and 3?

How does the brightness of bulb A (Circuit I) compare to the brightness of bulbs B and C (Circuit II)? What can you infer about the current at point 1 in each of the two circuits?

Circuit III
Connect Circuit III. Compare the brightness of bulbs D and E. What can you conclude from this observation about the amount of current through each bulb?

Describe the flow of current around the entire circuit. What do your observations suggest about the way the current through the battery divides and recombines at junctions where the circuit splits into two branches? How does the current at point 1 compare with the currents at points 2 and 3?

How does the brightness of bulb A (Circuit I) compare to the brightness of bulbs D and E (Circuit III)? What can you infer about the current at point 1 in each of the two circuits?

Comparing the three circuits, does the amount of current at point 1 appear to remain constant or to depend on the number of bulbs and how they are connected?

CONCLUSION

Rank the actual brightness of the bulbs. How did this compare to your prediction? Make sure you adequately describe what you mean in your comparisons, i.e. "the same brightness as", "brighter than", "dimmer than". What type of circuit is used in your track lighting? Circuit II is called a *series circuit* and Circuit III is called a *parallel circuit*.

Can you use conservation of energy and conservation of current to explain your results? The rate that energy is output from a bulb is equal to the potential difference (voltage) across the bulb times the current through the bulb. Does a battery supply a constant current or a constant potential difference to circuits?

To check your understanding, rank the brightness of the bulbs in the following circuits.
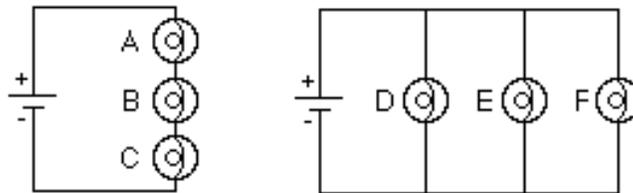
Use the lab equipment to see if your answer is correct.

PROBLEM #2: MORE COMPLEX CIRCUITS

It is the holiday season once again so you have decided to put up your decorations. You have three strings of decorative lights and only one electrical outlet between the tree and your doorway. To have enough lights to cover the tree, you will need to connect two of your light strings together end to end. The other set of lights will be enough to light up your doorway. You know that you have a few ways of connecting the lights. You want to hook up the lights so they are all as bright as possible. In order to determine which arrangement gives the most light before making your final decorating plans, you build a reference circuit and a model of the possible ways of connecting the sets of lights. In your model one light bulb represents a light string.

EQUIPMENT

You will build four simple circuits shown below out of wires, bulbs, and batteries.

Use the accompanying legend to build the circuits.

Legend:

◎ light bu

─┤├─ battery

── wire
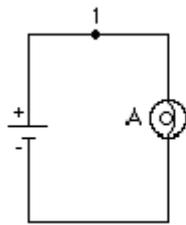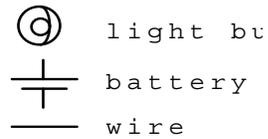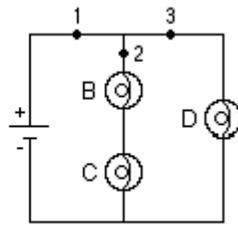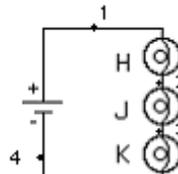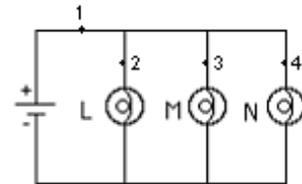
Circuit I   Circuit II   Circuit III   Circuit IV

Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same.

PREDICTION

Restate the problem. Rank the brightness of the bulbs A, B, C, D, H, J, K, L, M, and N from the brightest to the dimmest (use the symbol '=' for "same brightness as" and the symbol '>' for "brighter than"). Write down your reasoning.

EXPLORATION

It is important to measure voltages of the batteries that you will be using to verify that they are the same before experiments.

Reference Circuit I.
Connect Circuit I to use as a reference.

Note: *Pay attention to large differences you may observe, rather than minor differences that may occur if two "identical" bulbs are, in fact, not identical. How can you test whether minor differences are due to manufacturing irregularities?*

Circuit II
Connect Circuit II. Compare the brightness of bulbs B and C. Compare the brightness of bulbs B and C to bulb D. What can you conclude from this observation about the amount of current through each bulb?

How does the brightness of bulbs B and C compare to the brightness of bulb A (Circuit I)? What can you infer about the current at point 2 in Circuit II and the current at point 1 in Circuit I?

How does the brightness of bulb D compare to the brightness of bulb A (Circuit I)? What can you infer about the current at point 3 in Circuit II and the current at point 1 in Circuit I?

Describe the flow of current around the entire circuit. What do your observations suggest about the way the current through the battery divides and recombines at junctions where the circuit splits into two parallel branches? How does the current at point 1 in Circuit II compare with the current at point 1 in Circuit I? Explain any differences.

Circuit III.
Connect Circuit III. Compare the brightness of the bulbs. What can you conclude from this observation about the amount of current through each bulb?

How does the brightness of bulb H compare to the brightness of bulb A (Circuit I)? What can you infer about the current at point 1 in Circuit III and the current at point 1 in Circuit I?

Circuit IV.
Connect Circuit IV. Compare the brightness of the bulbs. What can you conclude from this observation about the amount of current through each bulb?

How does the brightness of bulb L compare to the brightness of bulb A (Circuit I)? What can you infer about the current at point 1 in Circuit IV and the current at point 1 in Circuit I?

CONCLUSION

Rank the actual brightness of the bulbs A, B, C, D, H, J, K, L, M and N. Make sure you have adequately defined your comparisons: "same brightness as", "brighter than", and "dimmer than". How did your prediction compare to your results? Can you use conservation of energy and conservation of current to explain your results?

How will you connect your three strings of lights so that they are all as bright as possible?

PROBLEM #3: SHORT CIRCUITS

A friend of yours who manages a movie theater is having a problem with the lights that surround the marquee. Some of the light bulbs don't light up. But when he takes out the bulbs and checks them individually, they all work. You tell him he must have a short circuit. You explain that you have a short circuit when a wire makes an alternate path for the current to bypass a circuit element. To demonstrate this idea, you build a few simple circuits to show the results of a short circuit.

EQUIPMENT

You will build three simple circuits shown below out of wires, bulbs, and batteries.

Use the accompanying legend to build the circuits.

Legend:

light bu

battery

wire

Circuit I   Circuit II   Circuit III

Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same.

PREDICTION
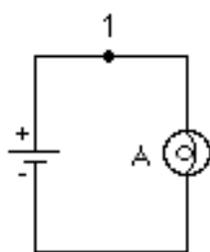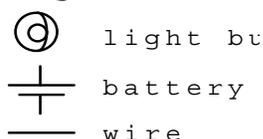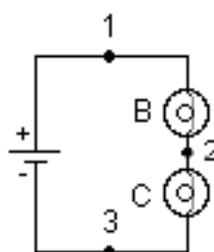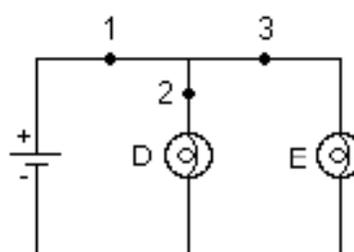
Restate the problem.
Circuit II: What happens to the brightness of bulbs B and C when a wire is attached across bulb B (from point 1 to point 2)?

Circuit III: What happens to the brightness of bulbs D and E when a wire is attached across bulb E?

Circuit I: What happens to the brightness of the bulb A when a wire is attached across the bulb?

EXPLORATION

WARNING: A short circuit is what happens any time a very low-resistance path (like a wire, or other piece of metal) is provided between points in a circuit that are at different potentials, like the terminals of a battery or power supply. **Short circuits can destroy equipment and injure people! Always avoid short circuits in other circuits!** Short circuits damage equipment by causing larger currents in a circuit than they are designed for. These currents can cause great heat and damage to nearby circuit elements or measuring devices. Any short circuits suggested in this manual have been tested, and determined not to significantly damage the equipment.

Build Circuit II. What happens to the brightness of bulbs B and C when you place a wire across bulb B? How did the current through C change? How did the current through B change? Did the current

through point 1 change? If so, in what way? Did the wire across bulb B get warmer? Explain your answers.

Build Circuit III. What happens to the brightness of bulbs D and E when you place a wire across bulb E? Did the current through D change? Did the current through E change? Did the wire across bulb E get warm? What would be the brightness of a bulb inserted in the circuit at point 1? Explain your answers.

Build Circuit I. Place a wire across the bulb. What happens to the brightness of the bulb? Hold on to the wire that is across the bulb. Is it getting warmer? How did the current through the bulb change? The current coming out of the battery? Make sure you disconnect the battery when you are done.

Placing the wire across the bulb causes a short circuit and it is called "shorting out" the bulb.

CONCLUSIONS

Did your predictions match your observed results? What have you learned from experiments, which agreed with your predictions? Draw more conclusions based on the experiments where your predictions were different from what you observed.

PROBLEM #4: CHARGING A CAPACITOR (PART A)

You have designed a circuit using a battery and a capacitor to automatically dim the lights for a theatrical production. However, the lighting consists of many different kinds of bulbs, which have been manufactured differently, and which consequently have very different resistances. You need to be able to precisely control the rate at which the lights dim, so you need to determine how this rate depends on both the capacitance of the capacitor and the resistance of the bulb. You decide to model this situation using a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series. You will try to ascertain how the current in the circuit changes with time.

EQUIPMENT

Build the circuit shown below using wires, resistors, capacitors, and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch and a digital multimeter (DMM).
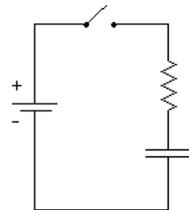
Circuit VIII

PREDICTION

When the circuit is closed, with the capacitor initially uncharged, how does the current in the circuit change with time? How long does it take for the current to fall to zero?
Sketch a graph of current against time for this circuit, assuming the capacitor is initially uncharged.

WARM UP

Read: Tipler & Mosca Section 25.6.

1. Draw a circuit diagram, similar to the one shown above. Decide on the properties of each of the elements of the circuit that are relevant to the problem, and label them on your diagram. Label the potential difference across each of the elements of the circuit. Label the current in the circuit and the charge on the capacitor.

2. Use energy conservation to write an equation relating the potential differences across all elements of the circuit. Write an equation relating the potential difference across the capacitor plates and the charge stored on its plates. What is the relationship between the current through the resistor and the voltage across it? Are these three equations always true, or only for specific times?

3. Describe qualitatively how each quantity labeled on your diagram changes with time. What is the voltage across each element of the circuit (a) at the instant the circuit is closed; (b) when the capacitor is fully charged? What is the current in the circuit at these two times? What is the charge on the capacitor plates at these two times?

4. From the equations you constructed above, determine an equation relating the voltage of the battery, the capacitance of the capacitor, the resistance of the resistor, the current through the circuit, and the charge stored on the capacitor plates.

5. Write an equation relating the rate of charge accumulation on the capacitor plates to the current through the circuit.

6. Use the equations you have written to get a single equation that relates the current and the rate of change of current to the known properties of each circuit element. To do this, you may find it helpful to differentiate one of your equations.

7. Solve the equation from step 6 by using one of the following techniques: (a) Guess the current as a function of time, which satisfies the equation, and check it by substituting your current function into your equation; (b) Get all the terms involving current on one side of the equation and time on the other side and solve. Solving the equation may require an integral.

8. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current you obtained in question 3.

<div align="center">

EXPLORATION

</div>

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.**

If you have not used the digital multimeter (DMM), read the relevant section of Appendix D, and get familiar with its different operations.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged. How can you determine the resistance of your resistor? Is there a way to confirm it?

Once you are convinced that all of the elements are working and that the capacitor is uncharged, read the note below and start building Circuit VIII. Leave the built circuit open until you begin your experiment.

NOTE: Be sure that the polarity of the capacitor's connection is correct — that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "–" terminal is connected to the capacitor's "–" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.

Close the circuit and observe how the brightness of the bulb changes with time. What can you infer about the way the current in the circuit changes with time? From what you know about a battery, how does the potential difference (voltage) across the battery change over time? Check this using the DMM set for potential difference (Volts). From your observations of the brightness of the bulb, how does the potential difference across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage across the capacitor over time? Can you check with a DMM? Use the concept of potential difference to explain what you observe.

Now, discharge the capacitor, and reconnect the DMM in such a way that it measures the current in the circuit. Close the circuit and observe how the current changes with time. Is it as you expected? How long does it take for the current to fall to zero?

Replace the light bulb with a resistor. Qualitatively, how will changing the resistance of the resistor and the capacitance of the capacitor affect the way the current in the circuit changes with time? How can you test this experimentally?

Choose a suitable capacitor and resistor combination that allows you to easily and accurately measure how the current changes with time. How many measurements will you need to make? What time interval between measurements will you choose?

Complete your measurement plan.

MEASUREMENT

Measure the current flowing through the circuit for as many times as you deem necessary. Make your measurements using a resistor, not a bulb. What are the uncertainties in each of these measurements?

ANALYSIS

Use your measured values for the resistance of the resistor, the capacitance of the capacitor, and the voltage of the battery, along with your prediction equation, to construct a graph of your predicted current against time.

Make a graph of the measured current flowing through the circuit against time.

Compare these two graphs, noting any similarities and explaining any differences.

CONCLUSION

Describe which of your predictions were confirmed by experiments and draw conclusions accordingly. To continue conclusions, explain what was incorrect in those of your predictions that your laboratory observations or measurements did not support (or what went wrong with the experiment that failed to verify your prediction). Finally, use theory and your experimental results from this problem to answer the following question: Does the current in the circuit change linearly with time?

PROBLEM #5: CIRCUITS WITH TWO CAPACITORS

You are modifying the design of a sturdy, low-cost beeper to be used as a safety device on children's bicycles. The sound-producing component of the beeper will not pass current or make noise until after the potential difference across it reaches a certain value. This component is connected in parallel to the capacitor in an RC circuit. When the threshold voltage is reached, the capacitor discharges through the sound-producing component, and then begins to charge again. The time between beeps is thus determined by the time it takes for the capacitor to charge to a certain value. You wish to shorten the amount of time between beeps and decide to modify the capacitance. You don't want to buy new capacitors because the original ones are extremely cheap and reliable. You decide to use two of the original capacitors for each beeper. There are at least two different ways to arrange the capacitors in the circuit: in series with each other, or in parallel. How would you arrange the capacitors in order to reduce the time between beeps? In order to understand the quantitative behavior of each circuit, you decide to make some measurements on the circuits with the sound emitter removed.

EQUIPMENT

You will build the circuits shown below out of wires, resistors, 2 uncharged capacitors of *equal* capacitances, and a battery. To visualize the presence of electric current in the circuits, you will replace resistors with light bulbs. (Note, however, that you cannot fairly compare capacitances in the circuits unless the bulbs are identical. Using the same bulb in all circuits is a possible way to ensure that.) You will have a stopwatch and a digital multimeter (DMM) for measurements.

Circuit IX   Circuit X   Circuit XI
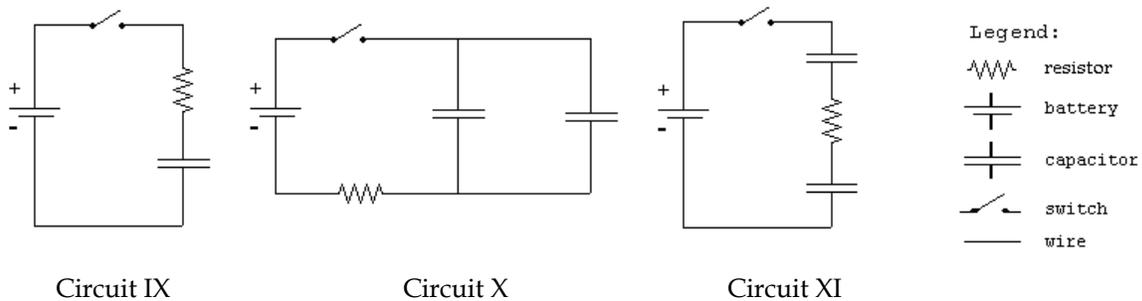
PREDICTION

For each of Circuits IX, X, and XI, draw a graph to qualitatively describe the current through the resistor (or the light bulb) as a function of time after the switch is closed, if the capacitors are initially uncharged. Compare the times it will take for light bulbs to go off in each circuit. For the comparison to be fair, do you think it is important that in each circuit
(i)   The resistances of light bulbs are the same, and
(ii)   The light bulb is connected in series with the battery?
Having made necessary assumptions for a fair comparison, rank Circuits IX, X, and XI by the time it will take for the bulbs to go off.

WARM UP

Read: Tipler & Mosca, Sections 24.3 and 25.6.

1. For each of the circuits, draw a circuit diagram, similar to those shown above. Decide on the properties of each of the elements of the circuit that are relevant to the problem, and label them on your diagram. Label the potential difference across each of the elements of the circuit. Label the current in the circuit and the charge on each capacitor. What is the relationship between the

charges on the two capacitors of Circuit X? What about the two capacitors of Circuit XI? Under what conditions will the bulb go out?

2. Write an equation relating the potential difference across each of the elements of the circuit. What is the relationship between the potential difference across the plates of each capacitor and the charge stored on its plates? What is the relationship between the current through a resistor (in the place of each bulb) and the voltage across it? Are these equations always true, or only for specific times?

3. Explain how each of the quantities labeled on your diagram changes with time. What is the voltage across each of the elements of the circuit (a) at the instant the circuit is closed, (b) when the capacitor is fully charged? What is the current through the resistor at these two times? What is the charge on each of the capacitors at these two times?

4. From the equations you constructed above, determine an equation relating the voltage of the battery, the capacitance of each of the capacitors, the resistance of the resistor, the current through the resistor, and the charge stored on each of the capacitors.

5. Write an equation relating the rate of charge accumulation on the capacitor plates to the current through the circuit.

6. Use the equations you have written to get a single equation that relates the current and the rate of change of current to the known properties of each circuit element. To do this, you may find it helpful to differentiate one of your equations.

7. Solve the equation from step 6 by using one of the following techniques: (a) Guess the current as a function of time, which satisfies the equation, and check it; (b) Get all the terms involving current on one side of the equation and time on the other side and solve. Solving the equation may require an integral.

8. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current obtained above.

Repeat the above steps for the other two circuits.

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. Do not handle the capacitors by their electrical terminals or connected wires by their metal ends. Always discharge a capacitor before you use it and when you are finished using it.

Review your exploration from Problem #4.

Before you start building a circuit, examine each element of it. How do you know if the battery is "good"? Are the capacitors charged? Carefully connect the two terminals of each capacitor to ensure it is uncharged. Make sure you that have two capacitors of the same capacitance.

NOTE: Be sure that the polarity of the capacitor's connection is correct — that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "–" terminal is connected to the capacitor's "–" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.

Check that the polarity of the capacitor's connection is correct and begin your observations by using bulbs instead of resistors.

Build Circuit IX, but do not close the switch. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference.

Build Circuit X, but do not close the switch. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Does it make a difference if you put the bulb in series with of one of the capacitors?

Build Circuit XI, but do not close the switch. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Does the order in which you connect the two capacitors and the bulb in the circuit matter? Try following one capacitor with the other capacitor and then the bulb.

Now, replace the light bulbs in your circuits with resistors. How can you determine the resistance of the resistor? Is there a way to confirm it? Connect a DMM in each of the circuits and observe how the current changes with time. For each circuit, decide how many measurements you will need to make in order to make a graph of current against time, and what time interval between measurements you will choose. Complete your measurement plan.

MEASUREMENT

Measure the current in each circuit for as many different times as you deem necessary. Make your measurements using resistors, not bulbs. What are the uncertainties in each of these measurements?

ANALYSIS

Use your measurements to plot the (measured) values of current as a function of time for circuits IX, X, and XI.

CONCLUSION

How well did your graphs drawn from your data compare to those in your predictions? Explain any differences. How did your predicted rankings of the time each bulb would remain lit compare to your measurements? Explain any differences.

PROBLEM #6: CHARGING A CAPACITOR (PART B)

You are an electrical engineer working for a company designing ultrasonic bug-repellent devices. Your group has decided that in order to find the minimum power needed for the ultrasonic emitter to be effective, you should design a circuit in which the current to the emitter falls to half its initial value, then to half of that value, then to half again, all in equal time intervals. They will then observe the insects to see at what point they are no longer repelled. You tell your colleagues that a simple circuit consisting of a capacitor and a resistor in series will have this property. They are unconvinced, so you decide to demonstrate to them that the time required for the current in the circuit to decrease to half its value is independent of the time that you begin measuring the current. You build a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series in order to demonstrate this property.

EQUIPMENT

Build the circuit shown below using wires, resistors, capacitors, and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch and a digital multimeter (DMM).
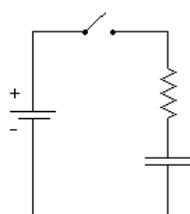
Circuit VIII

PREDICTION

In a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series, calculate the time it takes for the current to fall to half its initial value.

Sketch a graph of current against time for this circuit, assuming the capacitor is initially uncharged. Indicate on your graph the time taken for successive halving of the current in the circuit (the time at which the current is ½, ¼, ⅛ … of its initial value).

WARM UP

Read: Tipler & Mosca, Section 25-6.

1. If you have done Problem #4, you will already have the equation that describes the way in which the current in the circuit changes with time and depends upon the capacitance of the capacitor and the resistance of the resistor. If not, you should answer the warm-up questions in Problem #4.

2. Using your equation for the current, find the time taken for the current to fall to half its initial value. Now find the time taken for the current in the circuit to halve again, and so on. How does the time for the current to be cut in half depend on the amount of time after the circuit was closed?

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.**

Before you build the circuit, examine each element of it. How do you know if the battery is "good"? Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged. How can you determine the resistance of the resistor? Is there a way to confirm it?

If you have completed Problem #4, review your exploration notes from your lab journal. If not, complete the exploration from Problem #4.

Build circuit VIII. To measure the current in the circuit, connect a DMM in series.

NOTE: Be sure that the polarity of the capacitor's connection is correct — that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "−" terminal is connected to the capacitor's "−" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.

Check that the polarity of the capacitor's connection is correct and begin your experiment. Close the circuit and observe how long it takes for the current in the circuit to halve. How does changing the capacitance of the capacitor or the resistance of the resistor affect this time? Choose a combination of a resistor and a capacitor that allows you to measure this time as accurately as possible. Observe how long it takes for the current in the circuit to successively halve in value. Is this as you had predicted?

Complete your measurement plan.

MEASUREMENT

Measure the time taken for the current in the circuit to successively halve in value. Make at least two measurements for each setup for averaging.

ANALYSIS

Using the measured value of the capacitance of the capacitor, the resistance of the resistor and the voltage of the battery, calculate the times for successive halving of the current in the circuit. These times are what theory predicts for your circuit. Compare them to the measured times, at which the current decreases to ½, ¼, ⅛ … of its initial value.

CONCLUSION

How well did your prediction agree with your results? Explain any differences.

Using these times for successive halving of the current, can you determine how long it would take for the current to fall to zero? Does this agree with your experimental evidence?

PROBLEM #7: CHARGING A CAPACITOR (PART C)

You have read on the internet that you can use a large capacitor to increase the bass volume in your car stereo. However, you know from physics that a charged capacitor will only provide current for a short time before it needs to be recharged. You decide to figure out how long it will take the capacitor to recharge as a function of the total resistance of the recharging circuit. You know that one way to quantify this time is to measure how long it takes for the charging current to fall to one half of its initial value. You decide to model this situation using a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series.

<div align="center">

EQUIPMENT

</div>

Build the circuit shown below using wires, resistors, capacitors, and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch and a digital multimeter (DMM).

Circuit VIII

<div align="center">
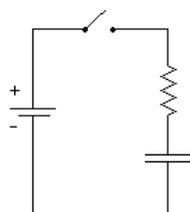
PREDICTION

</div>

For a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series, how does the time it takes for the current in the circuit to fall to half its initial value depend on the resistance of the resistor?

Use your calculation to graph the time it takes for the current to fall to half its initial value against the resistance of the resistor.

<div align="center">

WARM UP

</div>

Read: Tipler & Mosca, Section 25-6.

1. If you have done Problem #4, you will already have the equation that describes the way in which the current in the circuit changes with time and depends upon the capacitance of the capacitor and the resistance of the resistor. If not, you should answer the warm-up questions in Problem #4.

2. Using your equation for the current, find the time it takes for the current to fall to half its initial value. Sketch a graph of this time against the resistance of the resistor.

<div align="center">

EXPLORATION

</div>

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor when you are finished using it.**

Before you build the circuit, examine each element of it. How do you know if the battery is "good"? Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged. How can you determine the resistance of the resistor? Is there a way to confirm it?

If you have completed Problem #4, review your exploration notes from your lab journal. If not, complete the exploration from Problem #4.

NOTE: Be sure that the polarity of the capacitor's connection is correct — that the part of the circuit connected to the battery's "+" terminal is connected to the capacitor's "+" terminal, and the part of the circuit connected to the battery's "–" terminal is connected to the capacitor's "–" terminal. Reversing the polarity would irreversibly change the capacitor's capacitance.

Construct Circuit VIII, including a DMM in the circuit to measure the current. Check that the polarity of the capacitor's connection is correct and begin your experiment.

Close the circuit and observe how long it takes for the current in the circuit to halve. How does changing the capacitance of the capacitor or the resistance of the resistor affect this time? Choose a capacitor and a range of resistances that allow you to effectively construct a graph and test your prediction. Complete your measurement plan.

MEASUREMENT

Measure the time taken for the current in the circuit to halve in value for different resistances in the circuit. Be sure to make at least two measurements for each resistor.

ANALYSIS

Construct a graph of the measured times it takes the current to halve against resistance, using your experimental data.

CONCLUSION

Compare your prediction graph with your graph showing your data. Explain any differences.
How does the time taken for the current in the circuit to halve in value depend upon the resistance of the charging circuit? Does this time depend upon the voltage of the battery? If yes, then how?
What are possible sources of systematic uncertainty in this experiment (see Appendix B)? How do contributions to the *systematic* uncertainty from the equipment imperfections and from human error compare? Provide detailed explanations.

PROBLEM #8: RESISTORS AND LIGHT BULBS

Your research team has built a device for monitoring the ozone content in the atmosphere to determine the extent of the ozone holes over the poles. You have been assigned the job of keeping the equipment at the South Pole running during the winter months when no supplies can get in. When a piece of equipment fails, you need to replace two resistors. Unfortunately you have only one. You do have a light bulb but wonder how well a light bulb can substitute for a resistor in the circuit. You decide to make a direct comparison.

EQUIPMENT

You will have wires, a power supply, a digital multimeter (DMM), a light bulb, and a resistor.

PREDICTIONS

Restate what elements of electric circuits (and by what criteria/parameters) you are to compare in this problem. Use your experience to draw a graph of voltage versus current for (a) a standard resistor, and (b) a light bulb. Explain your reasoning, including physical assumptions you have made.

WARM UP

Read: Tipler & Mosca section 25.2.

1. What is the relationship between the current through a resistor and the potential difference (voltage) across the resistor if the resistor is made of ohmic material? Draw a graph of voltage versus current for this resistor. How is the slope of the graph related to its resistance?

2. As more current goes through a light bulb, it gets brighter. As it gets brighter, it gets hotter. Do you expect the increasing temperature to affect the resistance of the bulb? If so, how?

3. Sketch a qualitative graph of voltage across a light bulb versus current through the light bulb.

EXPLORATION

WARNING: You will be working with a power supply that can generate large electric voltages. Improper use can cause painful burns. To avoid danger, **the power** must be turned **OFF** and you must **wait at least one minute** before any wires are disconnected from or connected to the power supply. **Never grasp a wire by its metal end.**

Sketch the circuit you will build to check your prediction. Can you test both the light bulb and the resistor at the same time? Is this a good idea?

Read *Appendix D* and become familiar with the different operations of the digital multimeter (DMM).

MEASUREMENT

There are three methods for determining the electrical resistance of a resistor.

1. Use the chart provided in the laboratory (and also in Appendix D) to determine the resistance of your resistor based on its color code. What is the uncertainty in this value?

2. Use the DMM set to ohms to measure the resistance of the resistor. What is the uncertainty in this value? Why is this procedure not helpful with a light bulb?

3. Use your power supply, DMM, and resistor to determine the voltage across the resistor and measure the current through the resistor for several different voltages. What is the uncertainty in the value of the resistance obtained by this method?

ANALYSIS

Make a graph of voltage versus current for your resistor and light bulb. How do the values of the resistance compare for the different methods used?

CONCLUSION

Are the color-coded resistor and light bulb both ohmic resistors? If so, what are their resistances? Did your prediction match your results? If not, can you use the bulb over some limited range of voltages? What range? Explain your reasoning.

What are possible sources of systematic uncertainty? (See *Appendix B*) Does the equipment contribute? Do you? Be specific in explaining how and why.

PROBLEM #9: QUANTITATIVE CIRCUIT ANALYSIS (PART A)

As a member of the safety group for the space shuttle scientific program, you have been asked to evaluate a design change. In order to improve the reliability of a circuit for the next shuttle flight, a navigation electronics team has suggested adding a second battery. The proposed design is shown below. You worry about the heat generated by the circuit since it will be located next to an experiment that uses liquid oxygen. Your manager asks you to calculate the rate of thermal energy output by the proposed circuit. As a first step, you decide to calculate the current through each resistor. You consult with the team to build a prototype circuit and test your calculation.

EQUIPMENT

You will have wires, resistors, and batteries or a power supply to build a circuit shown to the right.

You will have a digital multimeter (DMM) to measure resistances, voltages, and currents.
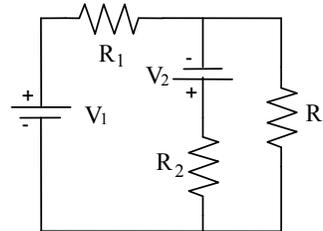
Circuit XII

PREDICTION

To predict currents through resistors in the circuit under study, you will need to use Kirchoff's laws. The goal is to derive theoretical formulas for the currents. Once you have the formulas, you can plug in the parameters of your circuit, such as voltages of the batteries and resistances of resistors, and calculate the currents. These (predicted) values will be compared with the currents measured in the experiment.

WARM UP

Read: Tipler & Mosca 25.5. Pay attention to the examples 25-10, 25-14 and 25-16.

1. Draw a circuit diagram, labeling all voltages and resistances. For this problem, the voltages and the resistances are the known quantities and the currents in the resistors are the unknowns.

2. Assign a separate current for each leg of the circuit, indicating each current on the diagram. Identify the number of circuit paths (loops) and label them on the diagram.

3. Apply conservation of current to each point in the circuit at which wires come together (a junction). Use conservation of energy to get the sum of the potential differences across all of the elements in each loop, ensuring your signs are correct. Does the potential difference increase or decrease across each circuit element, in the direction you have chosen to traverse the loop? Use Ohm's law to get the potential difference across each resistor.
Check that the number of equations you wrote above matches the number of unknowns.

4. Complete the calculations and write your solution. Simplify your equations as much as possible, but be warned that your final solutions may look quite complicated.

EXPLORATION

To get familiar with a DMM and various modes of its operation, read Appendix D.

Build Circuit XII. How can you tell if there is current flowing through the circuit? What happens to the current at each junction? What is the resistance of each resistor? What is the potential difference provided by each of the batteries? What is the potential difference across each resistor? Use the DMM to check your answers to each of these questions.

Complete your measurement plan.

MEASUREMENT

Measure the resistance of the resistors. Measure the current flowing through each resistor and the potential difference provided by each battery. So that you can check your measurements, measure the potential difference across each resistor.

ANALYSIS

Calculate the current through each resistor from your prediction equations, using your measured values of the resistance of each resistor and voltage of each battery. Compare those results to the measured values of each current.

CONCLUSION

Did your measured and predicted values of the currents through the resistors agree? If not, explain the discrepancy.

As a check for the consistency of your measurements, calculate the potential difference across each resistor using the currents that you measured. Compare these values with the potential difference across each resistor that you measured with the DMM.

PROBLEM #10: QUANTITATIVE CIRCUIT ANALYSIS (PART B)

You apply for a summer job at an electronics company. As part of the interview process, the manager gives you a circuit and asks you to calculate the current flowing through each resistor. You are then given some batteries, resistors and wires, and asked to build the circuit to check your calculation.

EQUIPMENT

You will have wires, resistors, and batteries or a power supply to build a circuit shown to the right.

You will have a digital multimeter (DMM) to measure resistances, voltages, and currents.
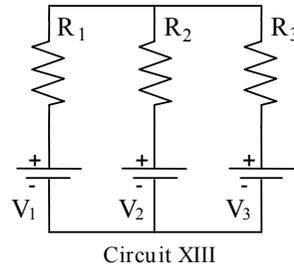
Circuit XIII

PREDICTION

Derive formulas to calculate the current through each of resistors in Circuit XIII as a function of voltages of the batteries and resistances involved in the circuit.

WARM UP

Read: Tipler & Mosca 25.5. Pay attention to the examples 25-10, 25-14 and 25-16.

1. Draw a circuit diagram labeling all voltages and resistances. For this problem, the voltages and the resistances are the known quantities and the currents in the resistors are the unknowns.

2. Assign a separate current for each leg of the circuit, indicating each current on the diagram. Identify the number of circuit paths (loops) and label them on the diagram.

3. Apply conservation of current to each point in the circuit at which wires come together (a junction). Use conservation of energy to get the sum of the potential differences across all of the elements in each loop, ensuring your signs are correct. Does the potential difference increase or decrease across each circuit element, in the direction you have chosen to traverse the loop? Use Ohm's law to get the potential difference across each resistor.

Check that the number of linear equations that you have now matches the number of unknowns.

4. Complete the calculations and write your solution. Simplify your equations as much as possible, but be warned that your final solutions may look quite complicated.

EXPLORATION

To become familiar with a DMM and various modes of its operation, read *Appendix D*.

Build Circuit XIII. How can you tell if there is current flowing through the circuit? What happens to the current at each junction? What is the resistance of each resistor? What is the potential difference provided by each of the batteries? What is the potential difference across each resistor? Use the DMM to check your answers to each of these questions.

Complete your measurement plan.

MEASUREMENT

Measure the resistance of each of the three resistors, as well as the currents flowing through each of them. Measure the potential difference provided by each battery. So that you can check your measurements, measure the potential difference across each resistor.

ANALYSIS

Calculate the current through each resistor from your prediction equations, using your measured values of the resistance of each resistor and voltage of each battery. Compare those results to the measured values of each current.

CONCLUSION

Did your measured and predicted values of the currents through the resistors agree? If not, explain the discrepancy.

As a check for the consistency of your measurements, calculate the potential difference across each resistor using the currents that you measured. Compare these values with the potential difference across each resistor that you measured with the DMM.

PROBLEM #11: QUALITATIVE CIRCUIT ANALYSIS

You have just become a manager at an engineering firm. The engineers who report to you are constantly describing complex circuits; to pinpoint possible problems with their designs, you have to quickly decide which resistors in the circuits will carry the most current. You have been using a calculator to calculate the current through each resistor, and the process is too slow.. A fellow manager suggests that a purely qualitative analysis could get you reliable results much more quickly. You decide to test the technique on the three circuits below, using identical light bulbs so that the brightnesses of the bulbs indicate which parts of the circuit carry more or less current. You will also do some practice calculations to see if you can get faster. You decide to double-check your work by actually building the circuits.

> ### EQUIPMENT

You will have batteries, wires, and five identical bulbs that you can connect to make the three circuits shown below.
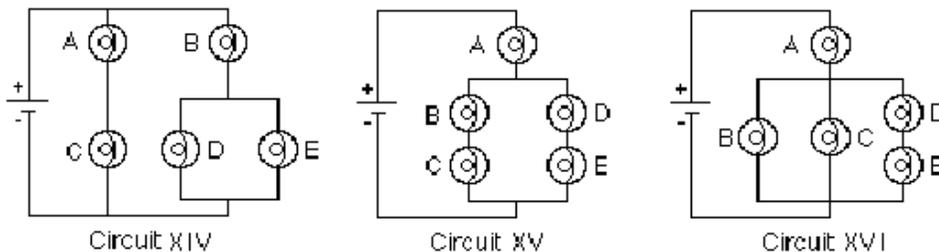
Circuit XIV   Circuit XV   Circuit XVI

Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same.

> ### PREDICTIONS

You will need to use both qualitative rules and formulas from your text book to make predictions about the brightness of the light bulbs in the circuits under study. The following rules are nothing but consequences of conservation of charge, conservation of energy, and Ohm's law in electric circuits.

1. a) Resistors in series all have the same current flowing through them.
   b) Resistances in series add.
   c) The current through a path across a fixed potential difference decreases as the total resistance of the path increases.

2. a) Current divides at a junction.
   b) The current through each path across the same potential difference depends on the resistance of the path – the larger the resistance, the smaller the current.
   c) Paths of equal resistance will have the same current.

3. a) Resistors in parallel offer less total resistance than the smallest resistance in the configuration.
   b) Parallel branches connected directly across a battery are independent – each set of parallel branches has the same potential difference as if it were the only connection to the battery.

The above rules will help you predict how the bulbs within each circuit should compare in brightness. Include in each prediction, which rule(s) you used answering the question.

Circuit XIV
How will the brightness of bulb A compare with the brightness of bulb B?
How will the brightness of bulb B compare with the brightness of bulb D?
How will the brightness of bulb C compare with the brightness of bulb D?

Circuit XV
How will the brightness of bulb A compare with the brightness of bulb B?
How will the brightness of bulb B compare with the brightness of bulb C?
How will the brightness of bulb B compare with the brightness of bulb D?

Circuit XVI
How will the brightness of bulb A compare with the brightness of bulb B?
How will the brightness of bulb B compare with the brightness of bulb C?
How will the brightness of bulb B compare with the brightness of bulb D?
Now, try to rank the circuits by the brightness of bulb A. First decide which quantity the brightness of a bulb depends on. Then construct an equation for this quantity in terms of two variables – the resistance of each bulb, say R, (remember that all the bulbs are identical) and the voltage of each battery, say V (same in each of the three circuits). Begin by finding equivalent resistances of certain parts of the circuits. In your textbook (Tipler & Mosca Section 25.4) or lecture notes, look up equations for equivalent resistances of two resistors connected in parallel and in series. Gradually simplify each circuit applying appropriate equations to pairs of bulbs in series or in parallel up to the point when you can use qualitative considerations to rank the circuits by the current through bulb A or by the potential difference across this bulb.

EXPLORATION

Set up each circuit and observe the brightness of the bulbs. How can you test whether minor differences you observe are due to manufacturing irregularities in "identical" bulbs?

MEASUREMENT

Coordinate with other groups to compare the brightness of bulb A in each of the three circuits. If necessary, use a DMM (see *Appendix D*) to measure the current through bulb A in each of the three circuits.


CONCLUSION

Qualitative circuit analysis is very useful for quickly checking the results of the algebra that come from quantitative circuit analysis. It is a great way to catch mistakes before you fry expensive circuits.

Explain any differences between your predictions and your observations.

Each qualitative rule is the result of applying conservation of energy (Kirchhoff's loop rule), conservation of charge (Kirchhoff's junction rule), and Ohm's law to different circuit configurations. . To summarize the material learned, for each qualitative rule, write the corresponding equation(s).

☑ CHECK YOUR UNDERSTANDING

1a. What would happen to the brightness of bulb A in the circuit below if more bulbs were added parallel to bulbs B and C?
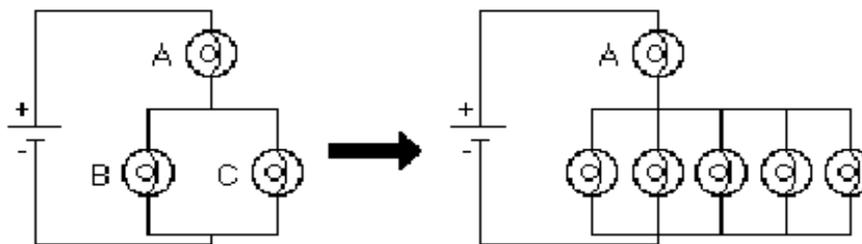

1b. In household circuits, a fuse or circuit breaker is in the position occupied by bulb A, why?

2. In circuits I through IV below, the four batteries supply the same voltage and all bulbs are identical. Rank the circuits from the largest current at point 1 to the smallest current at point 1. Explain your reasoning.
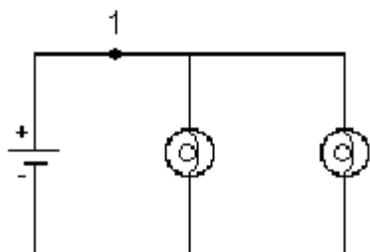

Circuit I
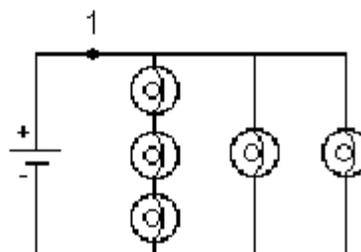
Circuit II
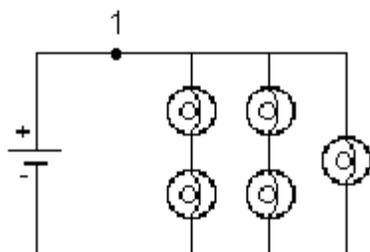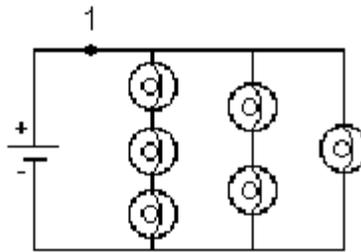
Circuit III

Circuit IV

3. Predict what will happen to the brightness of bulbs A, B, C and D if bulb E were removed from its socket. Explain your reasoning.
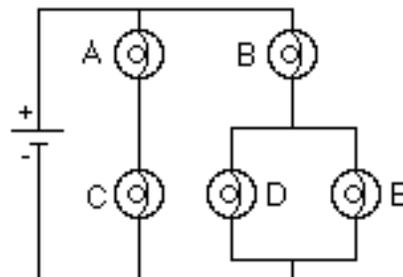
☑ CHECK YOUR UNDERSTANDING

4. For the circuit below, determine the current in each resistor.
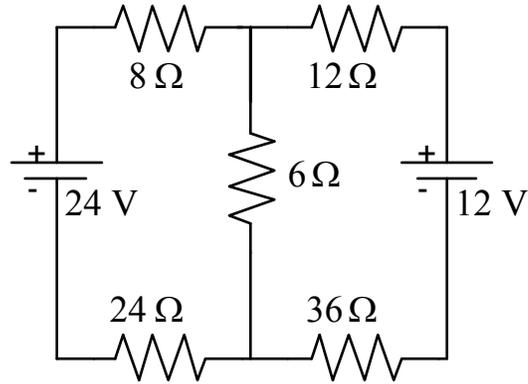
5. For the circuit below, determine the value for R such that the current I3 is 0.1A with the indicated direction.
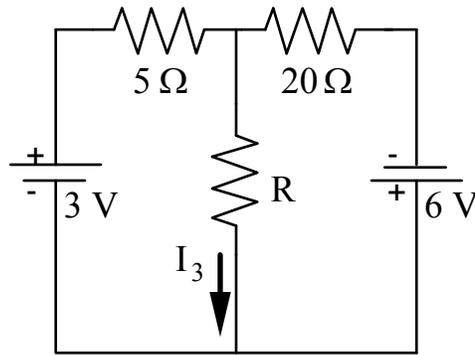
What is the value for R that will give a current I_3 = 0.1 A, but in the opposite direction to what is shown?

TA Name:

PHYSICS 1302 LABORATORY REPORT

Laboratory IV

Name and ID#:

Date performed: _____ Day/Time section meets: _____

Lab Partners' Names:

Problem # and Title:

Lab Instructor's Initials: _____

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.

LABORATORY V
MAGNETIC FIELDS AND FORCES

Magnetism plays a large part in our modern world's technology. Magnets are used today to image parts of the body, to explore the mysteries of the human brain, and to store analog and digital data. Magnetism also allows us to explore the structure of the Universe, the atomic structure of materials, and the quark structure of elementary particles.

In this set of laboratory problems, you will map magnetic fields from different sources and use the magnetic force to deflect electrons. The magnetic interaction can best be described using the concept of a field. For this reason, your experiences exploring the electric field concept in the first lab are also applicable in this lab. There are similar activities in both labs so you can experience the universality of the field concept. Although they are related, the magnetic force is not the same as the electric force. You should watch for the differences as you go through the problems in this lab.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Explain the differences and similarities between magnetic fields and electric fields.

- Describe magnetic fields near sources, such as permanent "bar" magnets, straight current-carrying wires, and coils of wire.

- Calculate the magnetic force on a charged particle moving in a uniform magnetic field and describe its motion.

PREPARATION:

Read Tipler & Mosca: Chapter 26, sections 1-4 and Chapter 27.1. Review your notes from the first lab (Electric Fields and Forces).

Before coming to lab you should be able to:

- Add fields using vector properties.

- Use the vector cross product.

- Calculate the motion of a particle with a constant acceleration.

- Calculate the motion of a particle with an acceleration of constant magnitude perpendicular to its velocity.

- Write down the magnetic force on an object in terms of its charge, velocity, and the magnetic field through which it is passing.

PROBLEM #1: PERMANENT MAGENTS

You have a job working at a company that designs magnetic resonance imaging (MRI) machines. The ability to get a clear image of the inside of the body depends on knowing precisely the correct magnetic field at that position. In a new model of the machine, the magnetic fields are produced by configurations of permanent magnets. You need to know the map of the magnetic field from each magnet and how to combine magnets to change the magnetic field at any point. You decide to determine the form of the magnetic field for various combinations of bar magnets, and to draw vector diagrams (field maps) for each combination.

EQUIPMENT

You will have two permanent magnets and a clear plate filled with a viscous liquid along with small pieces of Taconite, an iron-rich ore. When a magnet is placed on top of one of these plates, the Taconite pieces at each point align themselves with the magnetic field. You will also have a compass. Some possible magnet configurations are as follows:

Figure I
Figure II
Figure III
Figure IV
Figure V
Figure VI
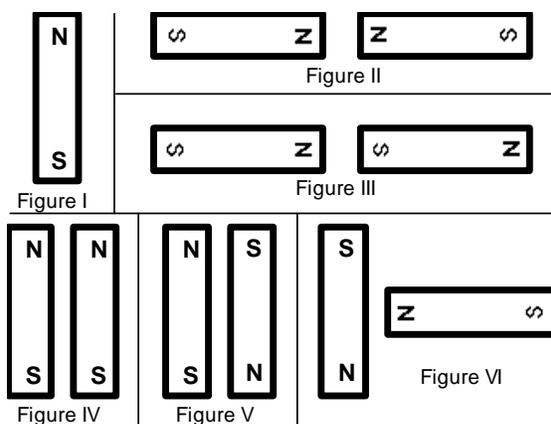
PREDICTION

Draw vector diagrams to describe the field for each configuration above.

WARM UP

Read: Tipler & Mosca Chapter 26 Section 1.

1. Make a sketch of all the magnets in each figure. Be sure to label the poles of the magnets.

2. Choose a point near the pole of a magnet. At that point draw a vector representing the magnetic field at that point. The length of the vector should give an indication of the strength of the field. Keep in mind that:

   The field can have only one value and direction at any point.

   The direction of the magnetic field points away from a North pole, and toward a South pole.

   The field at a point is the vector sum of the fields from all sources.

3. Move a short distance away in the direction of the vector and choose another point. At that point draw another magnetic field vector. Continue this process until you reach another magnetic pole. Choose another point near a pole and start the process again. Continue until you can see the pattern of the magnetic field vectors for all parts of the configuration.

EXPLORATION

WARNING: The viscous liquid (glycerin) in the Taconite plate may cause skin irritation. **If a plate is leaking, please notify your lab instructor immediately.**

Check to make sure your Taconite plate is not leaking. Gently shake the plate until the Taconite is distributed uniformly.

Properties of magnets can change with handling. Check the poles of the magnet with your compass. Inform your lab instructor if the magnet does not seem to be behaving as you would expect.

Place a permanent magnet on the Taconite plate. How long do you need to wait to see effect of the magnetic field? Is it what you expected? Try some small vibrations of the Taconite plate. How does the pattern in the Taconite relate to the direction that a compass needle points when it is directly on top of the Taconite sheet?

Try different configurations of magnets and determine how to get the clearest pattern in the Taconite. What can you do to show that the poles of a magnet are not electric charges? Try it.

MEASUREMENT AND ANALYSIS

Lay one bar magnet on the Taconite plate. In your journal, draw the pattern of the magnetic field produced.

Repeat for each figure in the predictions.

CONCLUSION

How did your predictions of the shape of the magnetic field for each configuration of magnets compare with your results? What influence does the field have on the Taconite filings? Does the field cause a net force? Does the field cause a net torque? If so, in what direction?

PROBLEM #2: CURRENT CARRYING WIRE

Your friend's parents, who live on a dairy farm, have high-voltage power lines across their property. They are concerned about the effect the magnetic field from the power lines might have on the health of their dairy cows grazing nearby. They bought a device to measure the magnetic field. The instructions for the device state that it must be oriented perpendicular to the magnetic field. To measure the magnetic field correctly, they need to know its direction at points near a current carrying wire. They know you have taken physics, so they ask you for help. First, you decide to check a simulation of the magnetic field of a current carrying wire. Next, to confirm your prediction and simulation, you decide to use a compass along with a current carrying wire. You decide to investigate both a straight wire and a loop of wire.

EQUIPMENT

You will have a magnetic compass, lengths of banana wire, a meter stick, a power supply, and the EMField application. You will also have a Hall probe and the accompanying software. Use the 0-18V 5A power supplies, the CENCO power supplies should not be used for this problem.

PREDICTIONS

Sketch your best guess of the situations described in the problem.

EXPLORATION

To open the EMField application, just open the folder PhysLab on your desktop and click on the EMField icon. Click anywhere for instructions.

To study magnetic fields of current carrying wires, you will want to choose the *2D Line Currents* option in the *Sources* menu. At the bottom of the window, there will be a list of various line currents of different magnitudes. Choose one by clicking and dragging it into the screen. Under the *Field and Potential* menu, you should choose the *Field Vector* option. This option for magnetic fields behaves exactly like that for electric fields. Hence, it is useful to review the EMField instructions from labs 1 and 2. Once you have a clear picture of what the direction of the field is, print it out using the *Print* command under *File*. You might also find it useful to try different sizes of current to note any changes.

Once you are finished with EMField, it is time to move to the physical apparatus. Keep in mind that a compass needle, because it is a small magnet, aligns itself parallel to the local magnet field.

Attach enough wires together to give a total length of at least half a meter. Is there any evidence of a magnetic field from a non current-carrying wire? To check this, stretch the wire vertically and move your compass around the center of the wire. Does the compass always point in the same direction?

WARNING: You will be working with a power supply that can generate large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. NEVER GRASP A WIRE BY ITS METAL ENDS!**

Connect the wire to the power supply and turn the power supply on (*do not use the PASCO power source*). The circuit breaker built into the power supply minimizes the hazard of this short circuit.

Stretch the wire vertically and move your compass around the wire. Start where you expect the magnetic field to be largest. Is there any evidence of a magnetic field from a current carrying wire? Watch the compass as you turn the current on and off. Does the compass always point in the same direction? How far from the wire can the compass be and still show a deflection? Develop a measurement plan.

Now make a single loop in the wire through which you can easily move the compass. Move the compass around the loop. In which direction is the compass pointing? How far away from the loop can you see a deflection? Is this distance larger along the axis of the loop or somewhere else?

Set up your Hall probe and MagnetLab sofware as explained in Appendices D and E. Before you push any buttons on the computer, locate the magnetic field strength window. You will notice that even when the probe is held away from obvious sources of magnetic fields, such as your bar magnets, you see a non-zero reading. From its behavior determine if this is caused by a real magnetic field or is an electronics artifact or both.

Go through the MagnetLab calibration procedure outlined in Appendix E. Be sure the switch on your amplification box agrees with the value on the computer. Does the Hall probe ever read a zero field?

Hold the Hall probe next to the wire; how can you use the information from your compass to decide how to orient the probe? Read the value displayed by the MagnetLab program. What will happen when you move the probe further from the wire? Will you have to change the orientation of the probe? How will you measure the distance of the probe from the wire?

MEASUREMENT

Use your measurement plan to create a map of the magnetic field around the stretched wire and the looped wire. Include the magnitude and direction of the magnetic field for each distance.

ANALYSIS

The direction of the magnetic field at a point near a current-carrying wire can be found by using the "right-hand rule" that is described in your text. How does the "right-hand rule" compare to your measurements?

CONCLUSION

How did your predictions of the map of the magnetic field near current-carrying wires compare with both physical and simulated results? How do they compare with the "right-hand rule"?

PROBLEM #3: MEASURING THE MAGNETIC FIELD OF PERMANENT MAGENTS

Your team is designing a probe to investigate space near Jupiter. One device uses strong permanent magnets to track the motion of charged particles through Jupiter's magnetic field. You worry that their magnetic fields could damage computers on the probe. To estimate how close a magnet can be to a computer without causing damage, you have been asked to determine the magnitude of the field near the magnet.

No isolated magnetic monopoles have ever been discovered (a difference between magnetism and electricity) but you wonder how accurately one could *mathematically model* the field of a bar magnet as the vector sum of fields produced by monopoles located near each end of the magnet. With this model, you calculate how the magnetic field would vary with distance along each symmetry axis of a bar magnet. You assume that a magnetic monopole would produce a magnetic field similar to the electric field produced by a point charge. To test your model, you decide to measure the magnetic field near a bar magnet with a Hall probe.

EQUIPMENT

You will have a bar magnet, a meter stick, a Hall probe (see Appendix D), and a computer data acquisition system (see Appendix E). You will also have a Taconite plate and a compass.

PREDICTION

Restate the problem. What are you trying to calculate? What assumptions are you making?

WARM UP

Review your notes from Lab I problem 2, "Electric Field from a Dipole"

1. Draw a bar magnet as a magnetic dipole consisting of two magnetic monopoles of equal strength but opposite sign, separated by some distance. Label each monopole with its strength and sign, using the symbol "g" to represent the strength of the monopole. Label the distance. Choose a convenient coordinate system.

2. Select a point along one of the coordinate axes, outside the magnet, at which you will calculate the magnetic field. Determine the position of that point with respect to your coordinate system. Determine the distance of your point to each pole of the magnet, in terms of the position of your point with respect to your coordinate system.

3. Assume that the magnetic field from a magnetic monopole is analogous to the electric field from a point charge, i.e. the magnetic field is proportional to g/r^2 where g is a measure of the strength of the monopole. (What are the dimensions of this "g"?) Determine the direction of the magnetic field from each pole at the point of interest.

4. Calculate the magnitude of each component of the magnetic field from each pole at the point of interest. Add the magnetic field (remember it is a vector) from each pole at that point to get the magnetic field at that point.

5. Graph your resulting equation for magnetic field strength along that axis as a function of position along the axis.

6. Repeat the above steps for the other axis.

EXPLORATION

Using either a Taconite plate or a compass check that the magnetic field of the bar magnet appears to be a dipole.

Start the MagnetLab program and go through the Hall probe calibration procedure outlined in *Appendix E*. Be sure the switch on your amplification box agrees with the value on the computer.

Take one of the bar magnets and use the probe to check out the variation of the magnetic field. Based on your previous determination of the magnetic field map, be sure to orient the Hall probe correctly. Where is the field the strongest? The weakest? How far away from the bar magnet can you still measure the field with the probe?

Write down a measurement plan.

MEASUREMENT

Based on your exploration, choose a scale for your graph of magnetic field strength against position that will include all of the points you will measure.

Choose an axis of the bar magnet and take measurements of the magnetic field strength in a straight line along the axis of the magnet. Be sure that the field is always perpendicular to the probe. Make sure a point appears on the graph of magnetic field strength versus position every time you enter a data point. Use this graph to determine where you should take your next data point to map out the function in the most efficient manner.

Repeat for each axis of the magnet.

ANALYSIS

Compare the graph of your calculated magnetic field to that which you measured for each axis of symmetry of your bar magnet. Can you fit your prediction equation to your measurements by adjusting the constants?

CONCLUSION

Along which axis of the bar magnet does the magnetic field fall off faster? Did your measured graph agree with your predicted graph? If not, why? State your results in the most general terms supported by your analysis.

How does the shape of the graph of magnetic field strength versus distance compare to the shape of the graph of electric field strength versus distance, for an electric dipole along each axis? Is it reasonable to assume that the functional form of the magnetic field of a monopole is the same as that of an electric charge? Explain your reasoning.

PROBLEM #4: THE MAGNETIC FIELD OF ONE COIL

You are working with a group researching new techniques to miniaturize the read-write head (the device in hard drives that reads and writes data to the disk). You suggest that a permanent magnet in the head could be replaced with a loop of wire to control the strength of the magnetic field. You read in your physics text that a coil of wire carrying a current gives the same magnetic field as a bar magnet: a magnetic dipole field. Your partners doubt that this is the case, so you decide to check it using a large coil of wire and a Hall probe, as well as a simulation. You decide to measure the strength of the magnetic field as a function of position along the central axis of the coil and compare it to the measurements you have for a bar magnet. As a qualitative check you also use the Hall probe to make a map of the magnetic field everywhere near the current carrying coil, and compare that to what the simulation predicts.

EQUIPMENT

You will have a 200 turn field coil, a power supply, a compass, a meter stick, a digital multimeter (DMM), a Hall probe, and a computer data acquisition system. You will also have the <u>EMField</u> application.
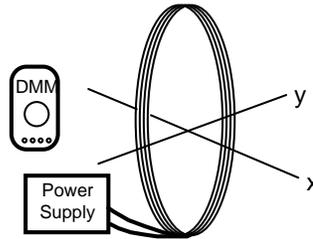
PREDICTION

Sketch the magnetic field around a current-carrying coil of wire and compare to the magnetic field around a bar magnet.

WARM UP

If you have done Problem #3, you already have the equation that describes the magnetic field strength of a magnetic dipole along an axis of symmetry. If not, answer the method questions in Problem #3.

Draw the coil and label the current through it.

Using the right hand rule, determine the direction of the magnetic field along the central axis of the coil. Using this information, which symmetry axis of a magnetic dipole corresponds to this central axis?

EXPLORATION

First, see what the simulation gives you. If you do not remember how to use EMField, review labs 1, 2, and the second problem of this lab.

Once you are in the *2D Line Currents* mode, you will need to figure out how to model a coil. You should think of the fact that a coil and its field are symmetric about the coil's central axis and the simulation plots fields in a plane perpendicular to the current flow. Once you have your model of a simple coil input into the program, use the *Field Vectors* option in the *Field and Potential* menu to study the field. You should pick points both inside and outside the coil for a complete map of the magnetic field. Once you have done this, print it out, using *Print* under *File*. **Note that you will use this for qualitative comparisons only!**

Now you should start working with the physical apparatus.

WARNING: You will be working with a power supply that can generate large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. NEVER GRASP A WIRE BY ITS METAL ENDS!**

Connect the large coil to the power supply using the adjustable voltage. Using your compass, make a qualitative map of the magnetic field produced. To get the most obvious effect on the compass, should the central axis of the coil be oriented N-S or E-W?

Using your compass an indicator, adjust the current up and down to determine the sensitivity of the magnetic field to the current. For a reasonable current in the coil, use the compass to determine how far a measurable magnetic field along the axis of the coil extends. Also check out the magnetic field outside the coil. Is it large or small? Compared to what?

Try reversing the current through the coil. What happens to the magnetic field at each point? Connect the Hall probe according to the directions in Appendices D and E. Explore the strength of the magnetic field in the plane of the coil. Is the field stronger inside or outside the coil? Where is the field the strongest inside the coil? Decide whether you should set the amplifier to high or low sensitivity.

How far from the center of the coil along the axis can you measure the field? Is it the same on both sides of the coil? How can you tell by your magnetic field reading if you are on the axis? How far from the axis can you move the Hall probe without introducing additional uncertainty to your measurement? Write down a measurement plan.

MEASUREMENT

Based on your exploration, choose a scale for your graph of magnetic field strength as a function of position that will include all of the points that you will measure.

Use the MagnetLab software to measure the magnitude and direction of the magnetic field as a function of position along the axis of the coil. Measure the field on both sides of the coil. Be sure your Hall Probe is calibrated and has the correct orientation to accurately measure the magnetic field.

Use the Hall probe to complete the field map for the coil.

Use the DMM to measure the current in the coil. Try measuring the field along the axis at several different currents.

Don't forget to measure the diameter of the coil and record the number of turns. What considerations need to be made when measuring the diameter?

ANALYSIS

Graph the magnetic field of the coil along its axis as a function of position and compare to the magnetic field of the bar magnet along the comparable axis. The graphical comparison is easier if you normalize the function describing the bar magnet's magnetic field to that of the coil. You can do this by dividing the largest magnetic field strength of the coil by the largest magnetic field strength of the bar magnet. Use the resulting number to multiply the function representing the bar magnet's

magnetic field strength. You may also need to use the same process on the x-values. You can then put both functions on the same graph.

CONCLUSION

Is the graph of magnetic field strength as a function of position along the central axis similar to that for a bar magnet? Does the magnetic field map for a current-carrying coil have the same pattern as for a bar magnet? Do you believe that this coil gives a magnetic dipole field? Is this true everywhere? Why or why not?

How does the magnetic field strength of a current-carrying coil depend on the current? What measurements justify your statement?

PROBLEM #5: DETERMINING THE MAGNETIC FIELD OF A COIL

You have a job in a microelectronics laboratory and need to shape a silicon wafer with a precision of a few microns. Your team decides to investigate using an ion beam to do this accurate cutting. You know that an ion is just an atom with some of its electrons stripped off, so you could direct it with a magnetic field. One of the members of your group suggests that a coil of wire can be used to produce a variable magnetic field. You have been assigned to calculate the magnetic field along the axis of the coil as a function of its current, number of turns, radius, and the distance along the axis from the center of the coil. To make sure you are correct, you decide to compare your calculation to measurements.

EQUIPMENT

If you have done Problem #4, you can use those measurements for this Problem. If not, you will use the following equipment.

You will have a 200 turn field coil of wire, a power supply, a digital Multimeter (DMM), a compass, a meter stick, a Hall probe, and a computer data acquisition system.
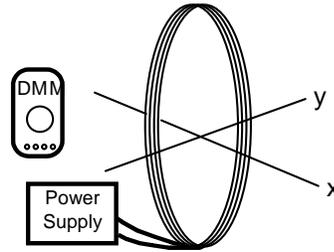
PREDICTION

Restate the problem. What are you trying to calculate? Express the result in the form of an equation and a graph with respect to distance along the axis.

WARM UP

Read: Tipler & Mosca Chapter 27 Section 2 and Example 27-2.

1. Make a sketch of a coil of radius R. Define a coordinate axis, label the relevant quantities, and indicate the direction of the current through the coil.

   Select a point along the axis at which you will calculate the magnetic field.

2. Select a small element of current along the coil, which will cause a small fraction of this magnetic field. Label the length of that current element. Draw a position vector from that current element to the selected point along the axis of the coil.

   Use the Biot-Savart law to draw a vector representing the direction of the small part of the magnetic field from your current element at the position of interest. Determine the components of this vector along the axes of your coordinate system. Are there any symmetries that allow you to neglect one or more components of the magnetic field at the point of interest?

3. Use the Biot-Savart law to calculate the small part of the desired component of the magnetic field, at the selected point, from the small element of current. Now add up (using an integral) all of the small fractions of that component of the magnetic field from all of the small elements of current around the coil.

   Determine the magnitude of the magnetic field at that point along the axis for one loop of wire, writing your answer as a function of the distance along the axis of the coil. What will be the effect of N identical loops on the magnitude of the magnetic field?

4. Graph the magnitude of magnetic field strength as a function of the position along the central axis of the coil of wire.

EXPLORATION

If you have the data from Problem #4 you do not need to make any additional measurements. Go directly to the analysis section. If you have not done Problem #4, continue with the exploration.

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. NEVER GRASP A WIRE BY ITS METAL ENDS!**

Connect a large coil to the power supply using the adjustable voltage. Using your compass, make a qualitative map of the magnetic field produced. To get the most obvious effect on the compass, should the central axis of the coil be oriented N-S or E-W? Decide whether you should set the amplifier to high or low sensitivity.

Using your compass as an indicator, adjust the current up and down to determine the sensitivity of the magnetic field to the current. For a reasonable current in the coil, use the compass to determine how far a measurable magnetic field along the axis of the coil extends. Also check out the magnetic field outside the coil. Is it large or small? Compared to what?

Try reversing the current through the coil. What happens to the magnetic field at each point?

Connect the Hall probe according to the directions in Appendices D and E. Explore the strength of the magnetic field in the plane of the coil. Is the field stronger inside or outside the coil? Where is the field the strongest inside the coil?

How far from the center of the coil along the axis can you measure the field? Is it the same on both sides of the coil?

How can you tell by your magnetic field reading if you are on the axis? How far from the axis can you move the Hall probe without introducing additional uncertainty to your measurement? Write down a measurement plan.

MEASUREMENT

Based on your exploration, choose a scale for your graph of magnetic field strength against position that will include all of the points you will measure.

Use the MagnetLab applicaton to measure the magnitude and direction of the magnetic field as a function of position along the axis of the coil. Measure the field on both sides of the coil. Be sure your Hall probe is calibrated and has the correct orientation to accurately measure the magnetic field. Make sure you take at least two measurements for averaging.

Use the Hall probe to complete the field map for the coil.

Use the DMM to measure the current in the coil. Try measuring the field along the axis at several different currents.

Don't forget to measure the diameter of the coil and record the number of turns. What considerations need to be made when measuring the diameter?

ANALYSIS

Graph the measured magnetic field of the coil along its axis as a function of position and compare with your prediction.

CONCLUSION

Does the graph of magnetic field strength as a function of distance agree with your prediction? Is this true everywhere? Why or why not?

PROBLEM #6: MEASURING THE MAGNETIC FIELD OF TWO PARALLEL COILS

You have a part time job working in a laboratory developing large liquid crystal displays that could be used for very thin TV screens and computer monitors. The alignment of the liquid crystals is very sensitive to magnetic fields. It is important that the material sample be in a fairly uniform magnetic field for some crystal alignment tests. The laboratory has two nearly identical large coils of wire mounted so that the distance between them equals their radii. You have been asked to determine the magnetic field between them to see if it is suitable for the test. You decide to make a graph of the field strength along the axis of the coils.

<table>
<tr><td>EQUIPMENT</td></tr>
</table>

Connect two coils to a power supply in series. Each coil has 200 turns. The coils should be separated by a distance equal to the radius.
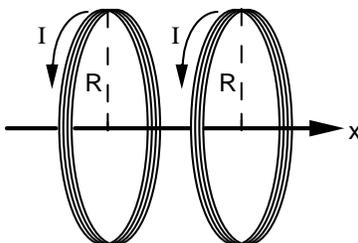
You will have a digital Multimeter (DMM), a compass, a meter stick, and a Hall probe.

<table>
<tr><td>PREDICTION</td></tr>
</table>

Restate the problem. Express the results in the form of an equation and a graph.

<table>
<tr><td>WARM UP</td></tr>
</table>

Read: Tipler & Mosca Chapter 27 Section 2 and Example 27-2.

1. Draw a picture of the situation showing the direction of the current through each coil of wire. Establish a single convenient coordinate system for both coils.

   Label all of the relevant quantities.

2. Select a point along the axis of the two coils at which you will determine an equation for the magnetic field. In the previous problem, you calculated the magnetic field of one coil as a function of the position along its axis. To solve this problem, add the magnetic field from each coil at the selected point along the axis. Remember to pay attention to the geometry of your drawing. The origin of your coordinate system for this problem cannot be at the center of both coils at once. Also remember that the magnetic field is a vector.

3. Use your equation to graph the magnetic field strength as a function of position from the common origin along the central axis of the coils. Describe the qualitative behavior of the magnetic field between the two coils. What about the region outside the coils?

<table>
<tr><td>EXPLORATION</td></tr>
</table>

WARNING: You will be working with a power supply that can generate large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. NEVER GRASP A WIRE BY ITS METAL ENDS!**

Connect the large coils to the power supply with *the current flowing in opposite directions in the two coils*, using the adjustable voltage. With the compass, explore the magnetic field produced. Be sure to look both between the coils and outside the coils.

Now connect the large coils to the power supply *with the current flowing in the same direction in each coil*, using the adjustable voltage. With the compass, explore the magnetic field produced. Be sure to look both between the coils and outside the coils.

Based on your observations, should the currents be in the same direction or in opposite directions to give the most uniform magnetic field between the coils?

Connect the Hall probe according to the directions in Appendices D and E. For the current configuration that gives the most uniform magnetic field between the coils, explore the strength of the magnetic field along the axis between the coils. Follow the axis through the coils. Is the field stronger between or outside the coils? Where is the field strongest between the coils? The weakest?

See how the field varies when you are between the two coils but move off the axis. How far from the axis of the coils can you measure the field? Is it the same on both sides of the coils? Decide whether to set the amplifier to high or low sensitivity.

When using the MagnetLab program, consider where the zero position should be to simplify comparison with your prediction. Write down a measurement plan.

MEASUREMENT

Based on your exploration, choose a scale for your graph of magnetic field strength against position that will include all of the points you will measure.

With the Hall probe, measure the magnitude of the magnetic field along the axis of the coils. Measure the field on both sides of the coils. What are the units of your measured magnetic fields? Do they match those in your prediction equations?

Use the DMM to measure the current in the two coils. As a check, repeat these measurements with the other current configuration.

ANALYSIS

Graph the measured magnetic field of the coil along its axis as a function of position and compare to your prediction.

CONCLUSION

For two large, parallel coils, how does the magnetic field on the axis vary with distance along the axis? Did your measurements agree with your predictions? If not, explain. Describe the limitations on the accuracy of your measurements and analysis.

Does this two-coil configuration meet the requirement of giving a fairly uniform field? Over how large a region is the field constant to within 20%? This very useful configuration of two coils (distance between coils equals radius) is called a Helmholtz coil.

# PROBLEM #7: MAGNETS AND MOVING CHARGE

You are leading a technical team at a company that is redesigning the cathode ray tubes (CRT's) used for computer monitors. To introduce this project to a group of stockholders, you need to demonstrate how an electron beam can be moved across a screen by a magnetic field. You decide to use an ordinary bar magnet held outside of the CRT to deflect the electrons. Before you do the demonstration, you need to know the *qualitative* effect of bringing a bar magnet up to a CRT. In the laboratory you qualitatively determine how the direction and size of the electron deflection is related to the magnetic field direction, the magnetic field strength, and the velocity of the electron. You also determine how the deflection is affected by how close the magnet is held to the CRT.

EQUIPMENT

For this problem you will need a cathode ray tube (CRT) and accessories, a bar magnet, a meter stick, and a compass. Review the information from Laboratory I and *Appendix D* regarding the design of the CRT and the proper way to use it.

PREDICTION

Restate the problem. What are you trying to predict? Make sure to describe the qualitative effects of *each variable* mentioned in the problem. Use a diagram like the one below to help make your prediction.
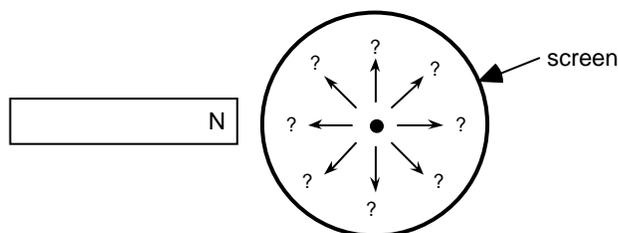
EXPLORATION

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. Never grasp a wire by its metal ends.**

Connect the CRT according to the directions in *Appendix D* and your lab journal from Lab I. Select the accelerating voltage that gave the largest deflection for the smallest electric field based on your explorations from Lab I. Record the location of the undeflected beam spot.

Determine which pole on your bar magnet is the north magnetic pole. Make a qualitative field map of your magnet to make sure it is a simple dipole. If it is not, ask your instructor to replace it. Describe the magnetic field at the end of the magnet.

Place the magnet near the side of the CRT. Did the deflection match your prediction? Why or why not? Repeat this procedure for the south pole. Should there be any difference? In which direction did the beam spot deflect?

Put the bar magnet perpendicular to the screen of the CRT. Do you see a deflection? Try this with both poles of the magnet. Record your results. Were they what you had expected? Can you orient the bar magnet so that it attracts

or repels the electron beam?

Place the north pole of your magnet a fixed distance away from the side of the CRT near the screen. Record the deflection. Increase the speed of the electrons by increasing the accelerating voltage as much as possible. Calculate the increase in speed. How does the deflection change? Try this with both poles of the magnet. Record your results. Were your results what you had anticipated?

Place the north pole of your magnet a fixed distance away from the side of the CRT near the screen. Record the deflection. Increase the magnetic field by adding more magnets. How does the deflection change? Try this with both poles of the magnet. Record your results. Were your results what you had anticipated?

What effect does the Earth's magnetic field have on the electron beam of a CRT? What is the direction of the Earth's magnetic field in your laboratory room? Arrange the CRT to see the maximum effect. Arrange it to observe the minimum effect. By measuring the electron deflection, what would you say is the relative strength of the magnet and the Earth's magnetic field in the lab? Remember to take account of the distance that the electron travels through each magnetic field. What is the effect of the Earth's magnetic field on the CRT beam relative to the Earth's gravitational field? How did this affect your results from Lab 1, Problem #5?

Devise your own exploration of the effect of a magnetic field on electrons using the CRT and the bar magnets. What variables can you control with the magnets and the CRT? Record your questions that will guide your exploration and check it with your lab instructor for safety before starting.

ANALYSIS

Draw a picture relating the three vectors representing the velocity of the electron, the magnetic field, and the force on the electron that is consistent with your results.

CONCLUSION

Did the electron beam deflection, in the presence of a magnetic field, agree with your prediction? Why or why not? What was the most interesting thing you learned from this exploration?

PROBLEM #8: MAGNETIC FORCE ON A MOVING CHARGE

You are working with a team to design a better electron microscope. To precisely control the beam of electrons, your research team decides to try a magnetic field. For your study of electron control you decide to use a Cathode Ray Tube (CRT) with a magnetic field perpendicular to its axis. From your work with Helmholtz coils in Problem #5, you know that the magnetic field between these parallel coils is fairly uniform, so you decide to use them for your test. Before you can evaluate the sensitivity of the electron microscope design, you need to determine how the magnitude of a constant magnetic field affects the position of the beam spot.

EQUIPMENT

You will be using the cathode ray tube (CRT) described in Appendix D. The magnetic field will be provided by connecting the Helmholtz coils to the power supply and placing the CRT between the coils. You will also have a digital multimeter (DMM), a compass, a meter stick, and a Hall probe connected to a computer data acquisition system.

PREDICTION

Restate the problem. What are you trying to calculate? What quantity(s) can you control in the lab? What quantities will be fixed for you? Express results in the form of an equation and a graph.

WARM UP

Read: Tipler & Mosca Chapter 26.2 Chapter 27 Section 1.

1. Draw a picture of the CRT in the Helmholtz coils. Since you will not be using electric fields, do not include the deflection plates in your sketch. Be sure you have all the other components in your sketch. Draw a coordinate axis on this sketch and show the magnetic field direction and the region occupied by the magnetic field. Draw the electron trajectory through all regions of the CRT together with its velocity and acceleration. Draw the electron trajectory if there were no magnetic field. The difference between where these two trajectories hit the CRT screen is the deflection.

2. What path does an electron follow while traveling through a constant magnetic field? The magnetic force is always perpendicular to the electron's velocity. Are there any forces other than the magnetic force that need to be considered?

3. Determine the velocity of the electrons as they leave the electron gun in the CRT. (See your notes from Lab 1, Problems #4 and #5 or the Method Questions from those problems.)

4. Determine the position, direction, and velocity of an electron *entering* the region of constant magnetic field. Determine the position, direction, and velocity of an electron as it *leaves* the region of constant magnetic field. What type of curve is the electron's trajectory in that region?

5. Determine the path of the electron as it travels after it leaves the magnetic field region until it strikes the screen. Use geometry to determine how far from the center the electron strikes the screen.

<div style="text-align:center">

EXPLORATION

</div>

Review your notes from your exploration in Problem #7.

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

Check to see that the connections from the power supply to the high voltage accelerating plates and the filament heater of the CRT are correct, then turn the power supply on. You should have between 250 and 500 volts between the cathode and anode. After a moment, you should see a spot that you can adjust with the knob labeled "Focus". If your connections are correct and the spot still does not appear, inform your lab instructor.

Devise a measuring scheme to record the position of the beam spot. Record your zero deflection position and do not move the CRT once you have started taking measurements.

Review the magnetic field map from the Helmholtz Coils. How will you orient the CRT with respect to the coils? Would the deflection be the same if the magnetic field were reversed? Try it. How will you determine the length of the CRT within the magnetic field? Is the field uniform throughout the flight of the electrons? Write down a measurement plan.

<div style="text-align:center">

MEASUREMENT

</div>

Measure the position of the beam spot as you change the magnetic field. Make at least two measurements for averaging. Measure the magnetic field between the Helmholtz coils, using the Hall probe.

<div style="text-align:center">

ANALYSIS

</div>

Graph your measurements of the deflection of the electron beam for the different values of the magnetic field at a fixed electron speed and compare to your prediction.

Repeat for deflection as a function of electron speed for a fixed magnetic field.

<div style="text-align:center">

CONCLUSION

</div>

How does the deflection of the electron beam depend on the magnetic field? Did your data agree with your prediction? If not, why? What are the limitations on the accuracy of your measurements and analysis?

How does the deflection of the electron beam depend on the electron speed? Did your data agree with your prediction? If not, why? What are the limitations on the accuracy of your measurements and analysis?

Is controlling the deflection of an electron beam easier with a magnetic field or an electric field? Write down what you mean by easier.

☑ CHECK YOUR UNDERSTANDING

1. For each of the configurations of magnets below, sketch the magnetic field map. Assume that the figures do not interact with each other.

Figure I
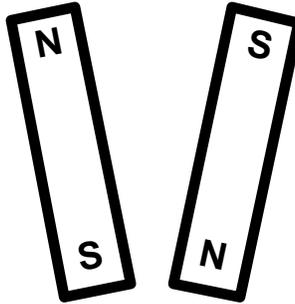
Figure III

Figure II

2. You and your friends are watching an old Godzilla movie. In one scene, a scientist broke a magnet in half because he needed a monopole for his experiment. You cringe and start laughing, but your friends don't understand what you found so funny. Explain the joke.

3. For a cathode ray tube (CRT) with the same electron gun as you used in lab, assume that the distance from the center of the V_X plate to the fluorescent screen is 10 cm, V_{acc} is 500V and $V_X = 6V$. The CRT is then placed between the large parallel coils (also used in this lab) which have a current of 1 ampere flowing through them. Assume that the CRT is oriented in the large parallel coils such that the electric field between the V_X plates and the magnetic field are <u>in the same direction</u>. What is the displacement of the electron beam on the screen? This is a difficult problem!!

TA Name:

PHYSICS 1302 LABORATORY REPORT

Laboratory V

Name and ID#:

Date performed: _____ Day/Time section meets: _____

Lab Partners' Names: _____

Problem # and Title: _____

Lab Instructor's Initials: _____

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.

LABORATORY VI
ELECTRICITY FROM MAGNETISM

In the previous problems you explored the magnetic field and its effect on moving charges. You also saw how electric currents could create magnetic fields. This lab will carry that investigation one step further, determining how changing magnetic fields can give rise to electric currents. This is the effect that allows the generation of electricity, which powers the world.

The problems in this laboratory will explore different aspects of changing the magnetic flux through a coil of wire to produce an electric current. You will investigate the current produced in a coil of wire by moving the coil, moving the magnet causing the magnetic field, changing the area of the coil perpendicular to the magnetic field, and changing the magnetic field.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Explain what conditions are necessary for a magnetic field to produce an electric current.

- Determine the direction of a current induced by a magnetic field.

- Use the concept of magnetic flux to determine the electric effects of a changing magnetic field.

- Use Faraday's law to determine the magnitude of a potential difference across a wire produced by a change of magnetic flux.

PREPARATION:

Read Tipler & Mosca: Chapter 28, sections 1,2 & 4.

Before coming to lab you should be able to:

- Use a DMM to measure current, potential difference, and resistance.

- Sketch the magnetic fields from permanent magnets and current carrying coils of wire.

- Use vector addition to combine magnetic fields from several sources.

- Use the right-hand rule to determine the direction of the magnetic fields from circuit loops and wires.

- Use a Hall probe to determine the strength of a magnetic field.

- Use the definition of magnetic flux.

PROBLEM #1: MAGNETIC INDUCTION

One of the great technical problems in modern society is how to generate enough electricity for our growing demand. You work with a team investigating efficiency improvements for electric generators. Before becoming involved with a lot of math and computer simulations, you decide to get a feel for the problem by seeing how many different ways you can generate a potential difference with just a bar magnet and a coil of wire, and how you can influence the size of that potential difference.

You will have a small coil of wire encased in plastic and a bar magnet. The coil has the number of turns marked on its side. You will use the SensorDAQ™ interface (see *Appendix D*) to convert the potential difference into a digital signal suitable for your computer data acquisition program, VoltagetimeLab software (see *Appendix E*), which records time varying potential differences.
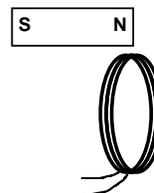
PREDICTION

Restate the problem. How many different ways can you use the magnetic field of the bar magnet to induce a potential difference across the ends of a coil of wire? Draw a diagram of each procedure that, you predict, will induce a potential difference across the ends of the coil. What do you think will influence the size of the potential difference? Explain how you arrived at your predictions.

EXPLORATION

If necessary, disconnect the magnetic field probe from the SensorDAQ™ interface. Plug the voltage Probe into the SensorDAQ™ interface (*Appendix D*). Attach the clips to the two ends of the coil and start the VoltagetimeLab program (*Appendix E*).

Use the magnet and the coil to make sure that the apparatus is working properly and that you are getting appropriate potential difference graphs on the screen.

From your predictions, how many different motions did members of your group think of to induce a potential difference across the ends of the coil? List them in your journal. Test each method and record the results. Did any method not produce a potential difference? For each method, what factors affect the magnitude and sign of the induced potential difference? *Make sure everyone gets a chance to manipulate the magnet and coil and control the computer.*

Can you discover any methods you didn't think of earlier? What is the largest potential difference you can generate?

CONCLUSION

How do your results compare with your predictions? Explain any differences, using pictures or qualitative graphs where they are helpful. State clearly the physics involved .

List the important characteristics for inducing a potential difference in the coil of wire. Explain how they are related to the magnitude and sign of the induced potential difference. How do you get the largest potential difference?

PROBLEM #2: MAGNETIC FLUX

You are working on a project to build a more efficient generator. A web search reveals that most existing generators use mechanical means such as steam, water, or airflow to rotate coils of wire in a constant magnetic field. To design the generator, you need to calculate how the potential difference generated depends on the orientation of the coil with respect to the magnetic field. A colleague suggests you use the concept of magnetic flux, which involves both the magnetic field strength and the orientations of the coil and magnetic field. You decide that you need to calculate the magnetic flux through the coil as a function of the angle between the coil and the magnetic field. To help you qualitatively check your calculation, you use a computer simulation program. You then quantitatively test your calculation by modeling the situation in the laboratory.

You will use the computer <u>Flux</u> <u>Simulation</u> (see *Appendix E*).

Picture of <u>Flux Simulation</u> Screen to right.
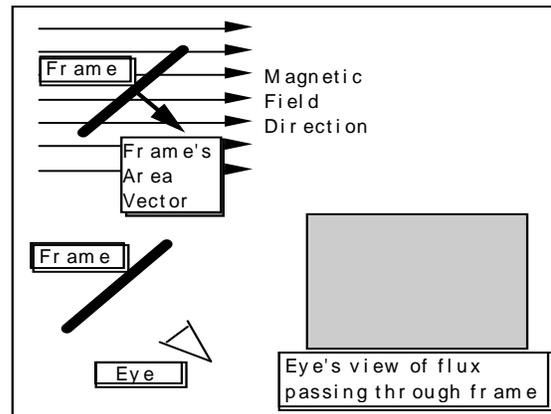
To make the measurement, a magnetic field sensor (Hall probe) is placed midway between two Helmholtz coils as shown to the right. The sensor can be rotated about a vertical axis and the angle of rotation measured. The sensor measures the amount of magnetic field perpendicular to the area of the Hall effect chip (white dot).

The magnetic field application written in LabVIEW™ will be used to analyze the measurements obtained with the magnetic field sensor (MagnetLab).
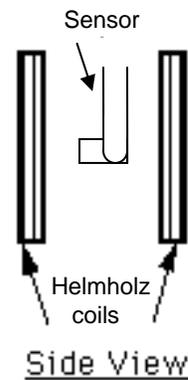

WARNING: You will be working with equipment that generates large electric currents. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply.**

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PREDICTION

Calculate the magnetic flux through an area (the frame of the simulation or the Hall effect transducer chip for the measurement) as a function of the angle that the area makes with the direction of the magnetic field. Use this expression to graph the magnetic flux versus angle.

In the simulation program, under what conditions will the "eye" "see" the most intense blue color? The most intense red color? Will there ever be no color, or white? As the Frame is slowly rotated, will the transitions in intensity be sudden, or gradual? Is the change in intensity linear or something else?

WARM UP

Read: Tipler & Mosca Chapter 28.1.
1. Draw the coil of wire at an angle to a magnetic field.
2. Draw and label a vector that you can use to keep track of the direction of the coil. The most convenient vector is one perpendicular to the plane of the coil, the area vector. Label the angle between the area vector and the magnetic field.
3. The magnetic flux for a constant magnetic field is the component of the magnetic field perpendicular to the plane of the coil times the area of the coil. Write an equation for the magnetic flux through the coil as a function of the strength of the magnetic field and the angle between the area vector and the magnetic field direction. For what angle is this expression a maximum? Minimum? Zero?

EXPLORATION

Open the Flux Simulation movie. Use the control bar with slider, which advances through the movie, to control the rotation of the frame. Try it.

```
          15
┌──┬──┬────────────────────────────────────────────────────┐
│  │  │                   Angle (degrees)                   │
└──┴──┴────────────────────────────────────────────────────┘
```

   Slider

As you rotate the frame, observe both the angle that the frame's area vector makes with the magnetic field and the color seen by the eye. Is the change in color gradual with a slow change in the angle? Is the relationship between color change and angle change linear (i.e. does the same amount of angle change always seem to cause the same amount of color change?) Does the eye in the simulation "see" what you expected it to? Why or why not?

Now examine the apparatus with which you will make your measurement. Remember to calibrate the Hall probe before you turn on the coils. You will want as large a magnetic field as you can produce safely with the equipment available.

Check to see if the magnetic field varies in time. Move the sensor slightly without changing its orientation to see if the magnetic field changes with position in the region of the sensor. If it does, this will add to the uncertainty of your measurement.

Slowly rotate the Hall Probe sensor through a complete circle noting the size of the readings. What is the best way to read the angle? When you return to the same angle, do you get the same reading? For what orientation(s) is the magnetic flux largest? Smallest? Is that as you expected?

Make sure you understand the correspondence between the simulation program, the measurement apparatus, and the objects in the problem statement.

MEASUREMENT

Use the Hall probe to measure, for a particular angle, the magnitude of the magnetic field between the Helmholtz coils. Rotate the probe through 360 degrees, making measurements at appropriate angle intervals. Record uncertainties with the data.

ANALYSIS

Describe the color and intensity change seen by the eye as the frame rotates. What does this represent?

After the Hall probe measurement, choose an equation, based on your prediction, that best represents your data points and adjust the coefficients to get the best correspondence with the data.

CONCLUSION

How is the magnetic flux through the coil dependent on the angle it makes with the magnetic field? Is the flux ever zero? When is the flux a maximum? How did the results compare to your prediction?

PROBLEM #3: THE SIGN OF
THE INDUCED POTENTIAL DIFFERENCE

For the next polar expedition, your engineering firm has developed an electric generator that can operate in extreme conditions. The expedition team is convinced that they need to understand generators, "just in case one breaks." You find yourself trying to describe to the leader how the sign of the induced potential difference across the ends of a coil of wire depends on the physical arrangement and relative motions of the materials. You decide to do a quick demonstration with the simplest situation possible; you first push the north pole of a bar magnet through the coil, and then you repeat with the south pole of the magnet. What happens? What else could you do with the same equipment?

EQUIPMENT

You will have a small coil of wire and a bar magnet. You will also have a computer data acquisition system with an application written in LabVIEW™ to display potential difference as a function of time (see Appendix E).
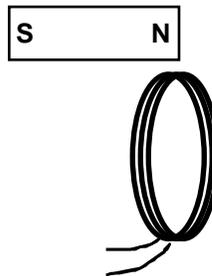
PREDICTION

Restate the problem. How do you determine the sign of the induced potential difference across the ends of a coil of wire?

WARM UP

Read: Tipler & Mosca Chapter 28.2.
1. Draw a picture of each situation. Draw and label the velocity vector of the magnet relative to the coil. Also draw the direction of the magnetic field vectors in the coil. Where is the magnetic field of the magnetic strongest?
2. Use Lenz's Law to relate the changing flux through the coil to the sign of the potential difference induced across the ends of the coil. How does the potential difference induced across the ends of the coil relate to the current induced in the coil?

EXPLORATION

If necessary, disconnect the magnetic field probe from the SensorDAQ™ interface. Plug the voltage probe into the SensorDAQ™ interface. Attach the clips to the two ends of the coil and start the VoltagetimeLab program.

Use the magnet and the coil to make sure that the apparatus is working properly and that you are getting appropriate graphs of potential difference as a function of time on the screen.

Push one end of the magnet into the coil and note the sign of the induced potential difference. Is the sign of the induced potential difference the same if you hold the magnet steady and instead move the coil? How does changing the velocity of the moving magnet (or the moving coil) change the magnitude and sign of the induced potential difference?

How does the sign of the induced potential difference change when you (i) push the magnet into the coil; (ii) leave it in the coil without moving, and iii) pull it out of the coil?

What happens if you move the magnet next to the coil? Try it.

<div style="border:1px solid #000; text-align:center;">

MEASUREMENT

</div>

Determine the sign of induced potential difference across the ends of the coil when you push the north pole of the magnet through the coil and when you push the south pole of the magnet through the coil.

Repeat the measurements, but this time keep the magnet still and move the coil.

<div style="border:1px solid #000; text-align:center;">

CONCLUSION

</div>

Did your results agree with your predictions? Explain any differences.

PROBLEM #4: THE MAGNITUDE OF THE INDUCED POTENTIAL DIFFERENCE

You're part of a team designing a bicycle speedometer. It is a circuit with a small pick-up coil on the bicycle's front fork, near the wheel's axle. When riding the bike, a tiny magnet attached to one of the spokes passes by the coil and induces a potential difference in the coil. That potential difference is read by a detector, which sends the information to the speedometer. You wonder how fast the bike must move to produce a detectable signal. You decide to model the situation by calculating how the induced potential difference across the ends of a coil of wire depends on the velocity with which a magnet is thrust through it. To check your calculation, you set up a laboratory model in which you can systematically vary the speed of the magnet by mounting it on a cart and rolling the cart down a ramp from different positions on the ramp. At the end of the ramp, the cart passes through the center of a coil of wire.

EQUIPMENT
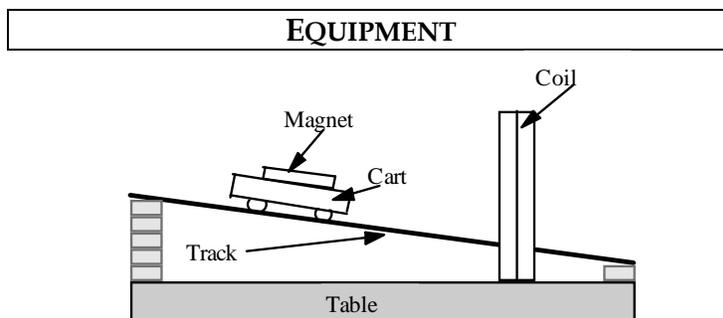
You will have a 200 turn field coil, magnets, a meter stick, a PASCO cart, and an aluminum track. The track can be raised at an incline using wooden blocks. You will also have a computer data acquisition system with a differential voltage probe and an application written in LabVIEW™ to display potential difference as a function of time (see *Appendix E*).

PREDICTION

Restate the problem. Which parameters will be fixed for you, which ones can you control in the lab, and how do they all relate to the quantities of interest?

WARM UP

Read: Tipler & Mosca Chapter 28.2.
1. Draw a picture of the situation. Label important distances and kinematics quantities. Decide on an appropriate coordinate system and add it to your picture.
2. Use Faraday's Law to relate change of magnetic flux to the magnitude of the induced potential difference in the coil.
3. Draw a magnetic field map of a bar magnet. Draw the coil of wire on the magnetic field map. As the bar magnet passes through the coil, when is the flux change the strongest? What is the relationship between the velocity of the bar magnet and the change of the magnetic flux through the coil? This tells you, qualitatively how the flux changes with time.
4. Look at the time rate of change of the magnetic flux. How is it related to the velocity of the cart? It is important to note whether or not the quantities of interest vary with time or with the cross-sectional area of the coil.
5. What physics principles can you use to determine the velocity of the magnet as it passes through the coil to the starting position of the cart?
6. Write an equation giving the induced potential difference across the ends of the coil of wire as a function of the velocity of the magnet through the coil.
7. Write an expression for the velocity of the cart through the coil as a function of its starting distance from the coil. Substitute that into the equation for the induced emf.

EXPLORATION

Before you begin exploring, consider what the signal displayed by the VoltagetimeLab program will look like. Will you be able to tell by the signal when the cart has not passed through the ring, and when it has? Will the peaks be sharp or rounded? Will there be many peaks or only one? How will the signal look different from background noise? Draw on your experiences from problems 1 and 3 in this lab.

If necessary, disconnect the magnetic field probe from the SensorDAQ™ interface. Plug the voltage probe into the SensorDAQ™ interface. Attach the clips to the two ends of the coil and start the VoltagetimeLab program.

Push the magnet through the coil to make sure that the apparatus is working properly and that you are getting appropriate potential difference graphs on the screen. How does the graph compare to your expectations?

Can you see your entire signal on the screen? What triggers the signal to display? Is pushing the cart through the coil once different from passing it through many times?

How often does the VoltagetimeLab program update the screen? How much data does it display?

Set up the track at an incline so that a rolling cart will go through the center of the coil. Try different angles to get the most reproducible situation in which you can change the velocity of the cart over the widest range without damaging the equipment. Be sure to have someone catch the cart when it reaches the end of the incline.

Securely attach a magnet to the cart and let it roll down the track while observing the potential difference displayed by the computer. Check that the release position does affect the potential difference graph on the computer. Try different time scales over which the computer makes the measurement. Are the differences large enough to measure reliably?

Letting the cart roll through the coil from up the slope is one option for completing this lab. Are there any other ways to release the cart and still keep track of energy?

Does the orientation of the magnet matter? Try it.

Does the display of the potential difference as a function of time on the computer look as you expected? Be sure you can qualitatively explain the behavior you see. You might want to move the magnet by hand to check your understanding.

Try adding another magnet to the cart to increase the magnitude of the induced potential difference. Does it matter how the second magnet is oriented?

Try adding another magnet to spread apart the time between the peaks of the potential difference displayed by the computer.

Write down a measurement plan for testing your prediction.

MEASUREMENT

Follow your measurement plan to find the dependence of the maximum potential difference across the ends of the coil of wire on the velocity of the magnet through the coil.

ANALYSIS

From your data construct a graph of maximum induced potential difference in the coil as a function of the distance from the coil at which the cart is released.

Add the graph of your prediction to the same plot and compare. You may need to normalize the graphs.

CONCLUSION

Did your results agree with your predictions? Explain any differences.

From the computer screen, make a sketch of the shape of the induced potential difference across the ends of the coil as a function of time for one pass of the magnet. Label each feature of the graph and indicate where the magnet is in the coil at that time and why the graph looks like it does at that time.

PROBLEM #5: THE GENERATOR

To begin investigating how to improve the efficiency of electric generators, your supervisor assigns you the task of building a working model of a generator from which it is easy to take measurements. Your model consists of Helmholtz coils to generate a well-defined magnetic field and a small coil of wire, mounted in between the Helmholtz coils, to generate the current. The small coil is mounted to a motor so that it spins at a uniform speed. Before presenting the model to your supervisor you calculate the potential difference induced in a coil of wire spinning in a uniform magnetic field as a function of its angular speed. You then take some measurements to make sure that the results correspond to your understanding of the situation.

EQUIPMENT

A small coil is mounted between Helmholtz coils in a Lucite box, as shown to the right. The Helmholtz coils are connected to a power supply. The small coil is labeled with the # of turns of wire, and can be rotated by a motor. A second power supply is required to power the motor.
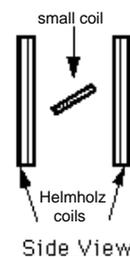
You will have a Hall probe, a DMM, and a meter stick. You will also have a computer data acquisition system with an application written in LabVIEW™ to display potential difference as a function of time (see *Appendix E* - Measuring Time-Varying Voltage).

PREDICTION

Restate clearly the problem, and formulate a prediction.

WARM UP

Read: Tipler & Mosca Chapter 28.4.

1. Draw a picture of the equipment labeling the direction of the magnetic field and the orientation of the small coil. Choose a coordinate system on the small coil.
2. Use Faraday's Law to relate the changing magnetic flux through the coil to the potential difference across the ends of the coil of wire. The changing magnetic flux is caused by the angular speed of the coil.
3. Draw a diagram showing only the small coil, a vector giving the direction of the magnetic field, and the area vector for the coil.
4. Write an equation for the magnetic flux through the small coil when it is stationary and at some angle to the magnetic field.
   As the small coil is rotated, how does the angle its area vector makes with the magnetic field vary with time? That variation is related to its angular speed.
5. Write an expression for the change in magnetic flux through the small coil as it turns.

EXPLORATION

WARNING: You will be working with equipment that generates large electric currents. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply.**

You will want the largest magnetic field you can produce safely with the equipment. Develop a plan for measuring the magnetic field using the Hall probe and Magentlab application. Where will you

want to measure the magnetic field? Over what region do you need the magnetic field to be reasonably constant? Check to see if it is.

Disconnect the Hall probe from the interface and plug the voltage probe into the interface, attaching the clips to the ends of the small coil. The ends of the small coil are wired to the terminals on opposite ends of the axle about which the coil spins. Use the VoltageTime application to get an on-screen display of the small coil's potential difference versus time.

With the Helmholtz coils generating a magnetic field, align the small coil such that its area vector is parallel to that magnetic field. What does the display of potential difference versus time read? Is this what you expected? Repeat by rotating the small coil so the area vector is perpendicular to the field.

Now power the motor using a DC supply and note the appearance of the potential difference versus time display. Determine how you will measure the rotational period of and the potential difference across the small coil. How can you determine the angular speed of the coil from its rotational period?

Try changing the motor's speed by increasing the voltage applied to it. How does changing the speed affect the display?

Determine the range of potential differences and rotational periods that you will use for your measurements so that you can set the scale for your graph of maximum potential difference as a function of rotational period.

MEASUREMENT

Note that the area of the small coil enclosed by the inner loops of wire is smaller than that enclosed by the outer loops of wire. Decide how to determine the effective area for the coil.

Measure the strength of the magnetic field produced by the Helmholtz coils in the region of interest.

Measure the maximum potential difference induced in the small coil and the rotational period of the small coil (see *Appendix E*).

Do several trials, rotating the coil at a different constant speed for each.

ANALYSIS

Determine the equation that best represents your collected data. What physical quantities do the constants in your equation represent? What do the variables in your equation represent?

CONCLUSION

What is the potential difference induced in a coil spinning in a uniform magnetic field? Did your measured potential difference agree with the predicted potential difference? Did the period of the signal agree with your predictions? If not, why not? What are the limitations on the accuracy of your measurements and analysis?

How does the amount of potential difference produced by the generator depend on the angular speed at which the generator rotates?

PROBLEM #6: TIME-VARYING MAGNETIC FIELDS

You have been hired by a research team that is developing a method to electronically detect cancer in the lining of a patient's intestine. The patient swallows a small probe that gathers data as it works its way through the intestine. You plan to power the probe with a small pick-up coil of wire inside the probe, and an externally-generated time-varying magnetic field. Your boss is concerned that it won't work reliably because you can't control the angle dependence between the coil and the magnetic field. You have been asked to investigate the seriousness of this problem. You decide to calculate how the induced potential difference across the ends of a coil of wire depends on the angle between the time-varying magnetic field and the coil. From the expression, you make a graph of the maximum potential difference as a function of the angle.

<div align="center">

EQUIPMENT

</div>

A small "pick-up coil" is mounted between Helmholtz coils in a Lucite box, as shown to the right. The small coil is labeled with the # of turns of wire.

A function generator outputs an electrical current, which changes with time as a sine function. When the Helmholtz coils are connected to a function generator, an alternating current goes through the coils. *Use frequencies less than 100 Hz*.
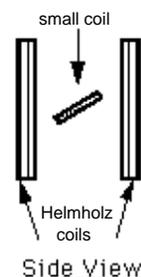
You will have a DMM, compass, meter stick, and a protractor. You will also have a computer system to display potential difference as a function of time (*Appendix E* - Measuring Time-Varying Voltage).

<div align="center">

PREDICTION

</div>

Restate the problem. What do you need to calculate?

<div align="center">

WARM UP

</div>

Read: Tipler & Mosca Chapter 28.2 and Example 28.2
  1. Draw a picture of the equipment, labeling the direction of the magnetic field and the orientation of the small coil. Choose a coordinate system on the small coil.
  2. Use Faraday's Law to relate the changing magnetic flux (by the Helmholtz coils) through the induction coil to the potential difference across the ends of the coil of wire.
  3. Draw a diagram showing only the small coil, a vector giving the direction of the magnetic field, and the area vector for the coil. Write an equation relating the magnetic flux through the small coil, when it is stationary and at some angle to the magnetic field, to the strength of the magnetic field.
  4. Write an equation for the magnetic field produced by the current in the Helmholtz coils, assuming the current through the Helmholtz coils varies with time as a sine function.
  5. Write an expression for the change in magnetic flux through the small coil.
  6. Combine the expressions you have written to write an expression for the time-varying potential difference across the ends of the small coil at some angle to the magnetic field. Use that result to write an expression for the maximum potential difference across the ends of the coil at any particular angle and graph the maximum potential difference vs. the angle.

<div align="center">

EXPLORATION

</div>

Use the function generator to drive a low frequency AC current through the large parallel coils:
  •   Set the function generator to create a sinusoidal voltage.
  •   Set the frequency of the function generator to less than 100 Hertz.

- Use the output labeled LOΩ on the function generator to drive the current through the coils.
- Set the amplitude of the function generator near its maximum.
- Connect the Helmholtz coils in series so that they carry the same current. Check to see which way the current is going in each coil. Does it matter?

If you placed a compass in the magnetic field near the pick-up coil, what would you expect to see? Try it. Slowly increase the frequency of the current in the Helmholtz coils. What happens to the compass needle? Is this consistent with what you expected?

Use the Hall probe to measure the magnetic field near the pick-up coil. What do you observe? Reduce the frequency setting on the function generator if necessary to more clearly see the behavior of the magnetic field. Position the Hall probe to measure the maximum magnetic field and note the range of values you find.

Orient the pick-up coil so that the largest magnetic flux passes through it. Attach the DMM to the pick-up coil set to read AC voltage. Increase the frequency on the function generator to about 60 *Hertz.* Slowly change the orientation of the pick-up coil to see how the AC voltage varies.

Attach the voltage probe to the pick-up coil to read the potential difference across it. Use the VoltagetimeLab application to view the potential difference as a function of time. Choose a frequency and amplitude setting on the function generator to produce a clean plot.

Select a range of angles to use in your measurement and note the range of potential difference amplitudes you expect for the signal generator frequency and amplitude you have chosen to use.

MEASUREMENT

For a fixed function generator output, measure how the amplitude of the potential difference across the pick-up coil varies as a function of its angle with the magnetic field. Take data sufficient to convince others of your findings.

ANALYSIS

Using your measurements, graph the potential difference across the pick up coil as a function of time, for a fixed function generator output. What is the period of the potential difference? The frequency? How does this behavior change as the angle between the pick up coil and the magnetic field changes?

How does the time structure of the induced potential compare to the output of the function generator?

Graph the maximum potential difference across the pick up coil as a function of the angle the coil's area vector makes with the magnetic field.

CONCLUSION

Does the time variation of the potential difference across the pick up coil agree with your prediction? If not, why?

☑ CHECK YOUR UNDERSTANDING

1. A long solenoid, with the axis perpendicular to the plane of the paper, carries a current that continually increases with time. A loop of wire with two light bulbs is connected around the solenoid. What is the direction of the induced current in the wire loop? Compare the brightness of light bulbs 1 and 2.

Magnetic field increasing into plane of paper

A

2

1

Light bulb

B

Wire loop
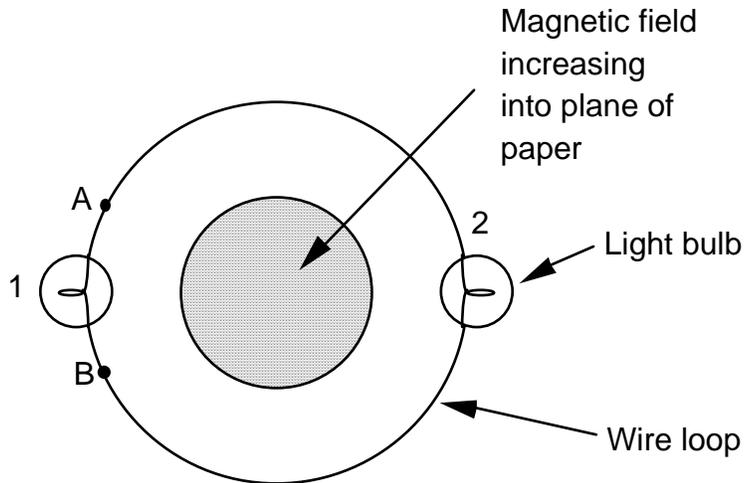
If a wire was connected from point A to point B, compare the brightness of bulbs 1 and 2.

2. A coil with 50 turns, a diameter of 8 cm, and a resistance of 9 Ω is placed perpendicular to a uniform magnetic field of 2.0 T. The magnetic field suddenly reverses direction. What is the total charge that passes through the coil?

☑ CHECK YOUR UNDERSTANDING

TA Name:

PHYSICS 1302 LABORATORY REPORT Laboratory VI

Name and ID#:

Date performed: Day/Time section meets:

Lab Partners' Names:

Problem # and Title:

Lab Instructor's Initials:

Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

 * An "R" in the points column means to <u>rewrite that section only</u> and return it to your lab instructor within two days of the return of the report to you.

Appendix A: Significant Figures

Calculators make it possible to get an answer with a huge number of figures. Unfortunately, many of them are meaningless. For instance, if you needed to split $1.00 among three people, you could never give them each exactly $0.333333 ⋯   The same is true for measurements. If you use a meter stick with millimeter markings to measure the length of a key, as in figure A-1, you could not measure more precisely than a quarter or half or a third of a mm. Reporting a number like 5.37142712 cm would not only be meaningless, it would be misleading.

Figure A-1
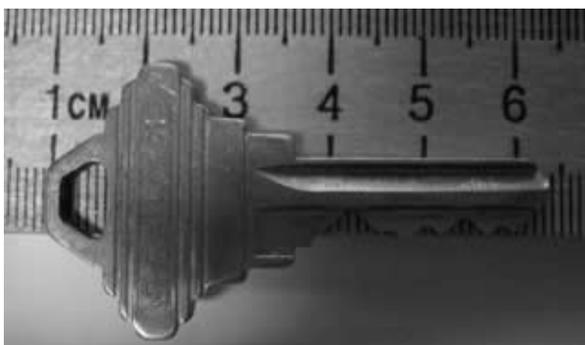
In your measurement, you can precisely determine the distance down to the nearest millimeter and then improve your precision by estimating the next figure. It is always assumed that the last figure in the number recorded is uncertain. So, you would report the length of the key as 5.37 cm. Since you estimated the 7, it is the uncertain figure.   If you don't like estimating, you might be tempted to just give the number that you know best, namely 5.3 cm, but it is clear that 5.37 cm is a better report of the measurement.   An estimate is always necessary to report the most precise measurement.   When you quote a measurement, the reader will always assume that the last figure is an estimate. Quantifying that estimate is known as **estimating**

uncertainties. Appendix B will illustrate how you might use those estimates to determine the uncertainties in your measurements.

What are significant figures?

The number of significant figures tells the reader the precision of a measurement. Table A-1 gives some examples.

Table A-1

Length (centimeters)	Number of Significant Figures
12.74	4
11.5	3
1.50	3
1.5	2
12.25345	7
0.8	1
0.05	1

One of the things that this table illustrates is that not all zeros are significant. For example, the zero in 0.8 is not significant, while the zero in 1.50 is significant. Only the zeros that appear after the first non-zero digit are significant.

A good rule is to always express your values in scientific notation. If you say that your friend lives 143 m from you, you are saying that you are sure of that distance to within a few meters (3 significant figures). What if you really only know the distance to a few tens of meters (2 significant figures)? Then you need to express the distance in scientific notation 1.4×10^2 m.

Is it always better to have more figures?

Consider the measurement of the length of the key shown in Figure A-1. If we have a scale

with ten etchings to every millimeter, we could use a microscope to measure the spacing to the nearest tenth of a millimeter and guess at the one hundredth millimeter. Our measurement could be 5.814 cm with the uncertainty in the last figure, four significant figures instead of three. This is because our improved scale allowed our estimate to be more precise. This added precision is shown by more significant figures. The more significant figures a number has, the more precise it is.

How do I use significant figures in calculations?
When using significant figures in calculations, you need to keep track of how the uncertainty propagates. There are mathematical procedures for doing this estimate in the most precise manner. This type of estimate depends on knowing the statistical distribution of your measurements. With a lot less effort, you can do a cruder estimate of the uncertainties in a calculated result. This crude method gives an overestimate of the uncertainty but it is a good place to start. For this course this simplified uncertainty estimate (described in Appendix B and below) will be good enough.

Addition and subtraction
When adding or subtracting numbers, the number of decimal places must be taken into account.

*The result should be given to as many decimal places as the term in the sum that is given to the **smallest** number of decimal places.*

Examples:

Addition	Subtraction
6.24**2**	5.87**5**
+4.2**3**	-3.3**4**
+0.01**3**	2.5**35**
10.4**85**	

10.4**9**	2.5**4**

The uncertain figures in each number are shown in **bold-faced** type.

Multiplication and division

When multiplying or dividing numbers, the number of significant figures must be taken into account.
*The result should be given to as many significant figures as the term in the product that is given to the **smallest** number of significant figures.*

The basis behind this rule is that the least accurately known term in the product will dominate the accuracy of the answer.

As shown in the examples, this does not always work, though it is the quickest and best rule to use. When in doubt, you can keep track of the significant figures in the calculation as is done in the examples.

Examples:

Multiplication

15.8**4**	17.2**7**
x 2.**5**	x **4.0**
7920	69.**080**
316**8**	
3**9.600**	

4**0**	69

Division

11**7**	2**5**
23)269**1**	75)1875
23	1**50**
3**9**	37**5**
23	**375**
16**1**	
16**1**	

1.**2** x 10^2	2.**5** x 10^1

PRACTICE EXERCISES

1.   Determine the number of significant figures of the quantities in the following table:

Length (centimeters)	Number of Significant Figures
17.87	
0.4730	
17.9	
0.473	
18	
0.47	
1.34×10^2	
2.567×10^5	
2.0×10^{10}	
1.001	
1.000	
1	
1000	
1001	

2.   Add: 121.3 to 6.7×10^2:

[Answer: $121.3 + 6.7 \times 10^2 = 7.9 \times 10^2$]

3.   Multiply: 34.2 and 1.5×10^4

[Answer: $34.2 \times 1.5 \times 10^4 = 5.1 \times 10^5$]

Appendix B: Accuracy, Precision and Uncertainty

How tall are you? How old are you? When you answered these everyday questions, you probably did it in round numbers such as "five foot, six inches" or "nineteen years, three months." But how true are these answers? Are you exactly 5' 6" tall? Probably not. You estimated your height at 5' 6" and just reported two significant figures. Typically, you round your height to the nearest inch, so that your actual height falls somewhere between 5' 5½" and 5' 6½" tall, or 5' 6" ± ½". This ± ½" is the **uncertainty,** and it informs the reader of the precision of the **value** 5' 6".

What is uncertainty?

Whenever you measure something, there is always some uncertainty. There are two categories of uncertainty: **systematic** and **random**.

(1)   **Systematic uncertainties** are those that consistently cause the value to be too large or too small. Systematic uncertainties include such things as reaction time, inaccurate meter sticks, optical parallax and miscalibrated balances. In principle, systematic uncertainties can be eliminated if you know they exist.

(2)   **Random uncertainties** are variations in the measurements that occur without a predictable pattern. If you make precise measurements, these uncertainties arise from the estimated part of the measurement. Random uncertainty can be reduced, but never eliminated. We need a technique to report the contribution of this uncertainty to the measured value.

How do I determine the uncertainty?

This Appendix will discuss two basic techniques for determining the uncertainty: **estimating the uncertainty** and measuring the **average deviation.** Which one you choose will depend on your need for precision. If you need a precise determination of some value, the best technique is to measure that value several times and use the average deviation as the uncertainty. Examples of finding the average deviation are given below.

How do I estimate uncertainties?

If time or experimental constraints make repeated measurements impossible, then you will need to estimate the uncertainty. When you estimate uncertainties you are trying to account for anything that might cause the measured value to be different if you were to take the measurement again. For example, suppose you were trying to measure the length of a key, as in Figure B-1.

Figure B-1
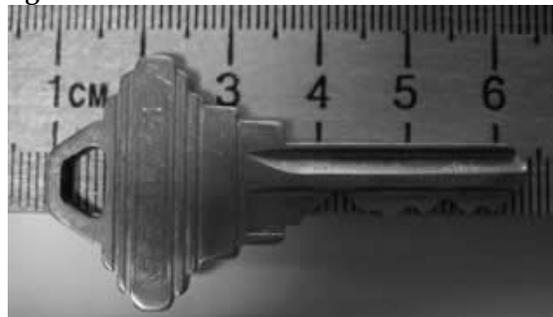
If the true value were not as important as the magnitude of the value, you could say that the key's length was 5cm, give or take 1cm. This is a crude estimate, but it may be acceptable. A better estimate of the key's length, as you saw in Appendix A, would be 5.37cm. This tells us that the worst our measurement could be off is a fraction of a mm. To be more precise, we can estimate it to be about a third of a mm, so we can say that the length of the key is 5.37 ± 0.03 cm.

Another time you may need to estimate uncertainty is when you analyze video data. Figures B-2 and B-3 show a ball rolling off the

edge of a table. These are two consecutive frames, separated in time by 1/30 of a second.

Figure B-2
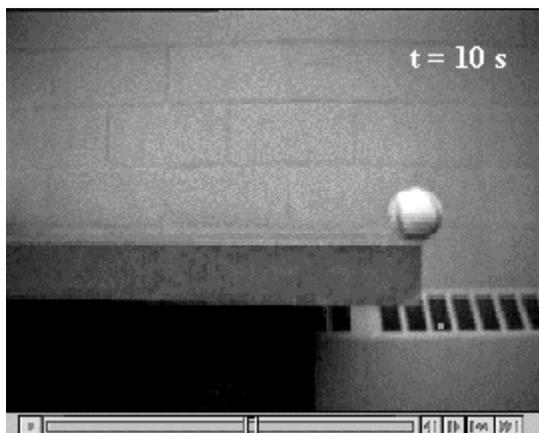
Figure B-3
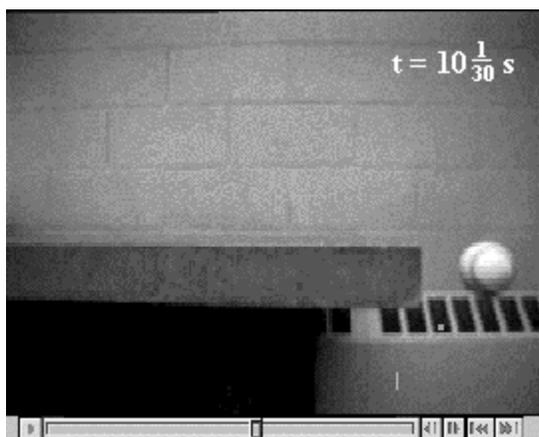
The exact moment the ball left the table lies somewhere between these frames. We can estimate that this moment occurs midway between them ($t = 10\frac{1}{60}s$). Since it must occur at some point between them, the worst our estimate could be off by is $\frac{1}{60}s$. We can therefore say the time the ball leaves the table is $t = 10\frac{1}{60} \pm \frac{1}{60}s$.

How do I find the average deviation?

If estimating the uncertainty is not good enough for your situation, you can experimentally determine the un-certainty by making several measure-ments and calculating the average deviation of those measurements. To find the average deviation: (1) Find the average of all your measurements; (2) Find the absolute value of the difference of each measurement from the average (its deviation); (3) Find the average of all the deviations by adding them up and dividing by the number of measurements. Of course you need to take enough measure-ments to get a distribution for which the average has some meaning.

In example 1, a class of six students was asked to find the mass of the same penny using the same balance. In example 2, another class measured a different penny using six different balances. Their results are listed below:

Class 1: Penny A massed by six different students on the same balance.

Mass (grams)
3.110
3.125
3.120
3.126
3.122
3.120
3.121 average.
The deviations are: 0.011g, 0.004g, 0.001g, 0.005g, 0.001g, 0.001g
Sum of deviations: 0.023g
Average deviation: (0.023g)/6 = 0.004g
Mass of penny A: 3.121 ± 0.004g

Class 2: Penny B massed by six different students on six different balances

Mass (grams)
3.140
3.133
3.144
3.118
3.126
3.125
3.131 average
The deviations are: 0.009g, 0.002g, 0.013g, 0.013g, 0.005g, 0.006g
Sum of deviations: 0.048g
Average deviation: (0.048g)/6= 0.008g
Mass of penny B: 3.131 ± 0.008g

However you choose to determine the uncertainty, you should always state your method clearly in your report. For the

remainder of this appendix, we will use the results of these two examples.

How do I know if two values are the same?

If we compare only the average masses of the two pennies we see that they are different. But now include the uncertainty in the masses. For penny A, the most likely mass is somewhere between 3.117g and 3.125g. For penny B, the most likely mass is somewhere between 3.123g and 3.139g. If you compare the ranges of the masses for the two pennies, as shown in Figure B-4, they just overlap. Given the uncertainty in the masses, we are able to conclude that the masses of the two pennies could be the same. If the range of the masses did not overlap, then we ought to conclude that the masses are probably different.

Figure B-4
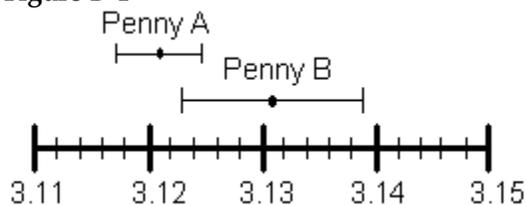
Mass of pennies (in grams) with uncertainties

Which result is more precise?

Suppose you use a meter stick to measure the length of a table and the width of a hair, each with an uncertainty of 1 mm. Clearly you know more about the length of the table than the width of the hair. Your measurement of the table is very precise but your measurement of the width of the hair is rather crude. To express this sense of precision, you need to calculate the percentage uncertainty. To do this, divide the uncertainty in the measurement by the value of the measurement itself, and then multiply by 100%. For example, we can calculate the precision in the measurements made by class 1 and class 2 as follows:

Precision of Class 1's value:
(0.004 g ÷ 3.121 g) x 100% = 0.1 %
Precision of Class 2's value:

(0.008 g ÷ 3.131 g) x 100% = 0.3 %

Class 1's results are more precise. This should not be surprising since class 2 introduced more uncertainty in their results by using six different balances instead of only one.

Which result is more accurate?

Accuracy is a measure of how your measured value compares with the real value. Imagine that class 2 made the measurement again using only one balance. Unfortunately, they chose a balance that was poorly calibrated. They analyzed their results and found the mass of penny B to be 3.556 ± 0.004 g. This number is more precise than their previous result since the uncertainty is smaller, but the new measured value of mass is very different from their previous value. We might conclude that this new value for the mass of penny B is different, since the range of the new value does not overlap the range of the previous value. However, that conclusion would be **wrong** since our uncertainty has not taken into account the inaccuracy of the balance. To determine the accuracy of the measurement, we should check by measuring something that is known. This procedure is called calibration, and it is absolutely necessary for making accurate measurements.

Be cautious! It is possible to make measurements that are extremely precise and, at the same time, grossly inaccurate.

How can I do calculations with values that have uncertainty?

When you do calculations with values that have uncertainties, you will need to estimate (by calculation) the uncertainty in the result. There are mathematical techniques for doing this, which depend on the statistical properties of your measurements. A very simple way to estimate uncertainties is to find the *largest possible uncertainty* the calculation could yield. **This will always overestimate the uncertainty of your calculation**, but an overestimate is better than no estimate. The method for performing arithmetic operations on quantities

with uncertainties is illustrated in the following   examples:

Addition:	Multiplication:
(3.131 ± 0.008 g) + (3.121 ± 0.004 g) = ?	(3.131 ± 0.013 g) x (6.1 ± 0.2 cm) = ?

First, find the sum of the values:
    3.131 g + 3.121 g = 6.252 g
	First, find the product of the values:
	    3.131 g x 6.1 cm = 19.1 g-cm

Next, find the largest possible value:
    3.139 g + 3.125 g = 6.264 g
	Next, find the largest possible value:
	    3.144 g x 6.3 cm = 19.8 g-cm

The uncertainty is the difference between the two:
    6.264 g – 6.252 g = 0.012 g
	The uncertainty is the difference between the two:
	    19.8 g-cm - 19.1 g-cm = 0.7 g-cm

Answer: 6.252 ± 0.012 g.	**Answer: 19.1 ± 0.7g-cm.**
Note: This <u>uncertainty</u> can be found by simply adding the <u>individual</u> <u>uncertainties</u>: *0.004 g + 0.008 g = 0.012 g*	*Note: The <u>percentage</u> <u>uncertainty</u> in the answer is the sum of the <u>individual</u> <u>percentage</u> <u>uncertainties</u>:* $\dfrac{0.013}{3.131} \times 100\% + \dfrac{0.2}{6.1} \times 100\% = \dfrac{0.7}{19.1} \times 100\%$
Subtraction:	Division:
(3.131 ± 0.008 g) – (3.121 ± 0.004 g) = ?	(3.131 ± 0.008 g) ÷ (3.121 ± 0.004 g) = ?

First, find the difference of the values:
    3.131 g - 3.121 g = 0.010 g
	First, divide the values:
	    3.131 g ÷ 3.121 g = 1.0032

Next, find the largest possible difference:
    3.139 g – 3.117 g = 0.022 g
	Next, find the largest possible value:
	    3.139 g ÷ 3.117 g = 1.0071

The uncertainty is the difference between the two:
    0.022 g – 0.010 g = 0.012 g
	The uncertainty is the difference between the two:
	    1.0071 - 1.0032 = 0.0039

Answer: 0.010±0.012 g.	**Answer: 1.003 ± 0.004**
Note: This <u>uncertainty</u> can be found by simply adding the <u>individual</u> <u>uncertainties</u>: *0.004 g + 0.008 g = 0.012 g* *Notice also, that zero is included in this range, so it is possible that there is no difference in the masses of the pennies, as we saw before.*	*Note: The <u>percentage</u> <u>uncertainty</u> in the answer is the sum of the <u>individual</u> <u>percentage</u> <u>uncertainties</u>:* $\dfrac{0.008}{3.131} \times 100\% + \dfrac{0.004}{3.121} \times 100\% = \dfrac{0.0039}{1.0032} \times 100\%$ *Notice also, the largest possible value for the numerator and the smallest possible value for the denominator gives the largest result.*

The same ideas can be carried out with more complicated calculations. Remember this will always give you an overestimate of your uncertainty. There are other calculation techniques, which give better estimates for uncertainties. If you wish to use them, please discuss it with your instructor to see if they are appropriate.

These techniques help you estimate the random uncertainty that always occurs in measurements. They will not help account for mistakes or poor measurement procedures. There is no substitute for taking data with the utmost of care. A little forethought about the possible sources of uncertainty can go a long way in ensuring precise and accurate data.

PRACTICE EXERCISES:

B-1. Consider the following results for different experiments. Determine if they agree with the accepted result listed to the right. Also calculate the precision for each result.

a) $g = 10.4 \pm 1.1$ m/s^2 $g = 9.8$ m/s^2

b) $T = 1.5 \pm 0.1$ sec $T = 1.1$ sec

c) $k = 1368 \pm 45$ N/m $k = 1300 \pm 50$ N/m

Answers: a) Yes, 11%; b) No, 7%; c) Yes, 3.3%

B-2. The area of a rectangular metal plate was found by measuring its length and its width. The length was found to be 5.37 ± 0.05 cm. The width was found to be 3.42 ± 0.02 cm. What is the area and the average deviation?

Answer: 18.4 ± 0.3 cm^2

B-3. Each member of your lab group weighs the cart and two mass sets twice. The following table shows this data. Calculate the total mass of the cart with each set of masses and for the two sets of masses combined.

Cart (grams)	Mass set 1 (grams)	Mass set 2 (grams)
201.3	98.7	95.6
201.5	98.8	95.3
202.3	96.9	96.4
202.1	97.1	96.2
199.8	98.4	95.8
200.0	98.6	95.6

Answers:

Cart and set 1:	299.3±1.6 g.
Cart and set 2:	297.0±1.2 g.
Cart and both sets:	395.1±1.9 g.

Appendix C: A Review of Graphs

Graphs are visual tools used to represent relationships (or the lack thereof) among numerical quantities in mathematics. In particular, we are interested in the graphs of functions. Before we go into functions, let us consider the more primitive idea of relations.

Relations and Functions

A relation is any mapping from one set of quantities to another. For example, the following is a relation:

$$a \rightarrow \alpha$$
$$b \rightarrow \beta$$
$$c \rightarrow \beta$$
$$c \rightarrow \gamma$$

In this relation, the set of Roman letters $\{a, b, c\}$ is the domain – the thing from which the relation maps; the set of Greek letters $\{\alpha, \beta, \gamma\}$ is the range – the thing to which the relation maps.

Functions are special kinds of relations. All functions are relations, but not vice-versa. A function can map each element of the domain to only one element of the range: in the above relation, c maps to both β and γ; this is not allowed. A function can, however, map two different elements of the domain to the same element of the range: in the above relation, both b and c map to β; this is allowed.

We represent a function f of a variable t with the notation $f(t)$; this means "the value of f evaluated at t." Strictly speaking, f is a function and $f(t)$ is a number.

What is a graph?

In this course, we will be dealing almost exclusively with graphs of functions and relations. When we graph a quantity A with respect to a quantity B, we mean to put B on the horizontal axis of a two-dimensional region and A on the vertical axis and then to draw a set of points or curve showing the relationship between them. We do not mean to graph any other quantity from which A or B can be determined. For example, a plot of acceleration versus time has acceleration itself, $a(t)$, on the vertical axis, not the corresponding velocity $v(t)$; the time t, of course, goes on the horizontal axis. See Figure 1.

Canonically, we call the vertical axis the "y-" axis; the horizontal axis, the "x-" axis. Please note that there is nothing special about these variables. They are not fixed, and they have no special meaning.

(a)   (b)
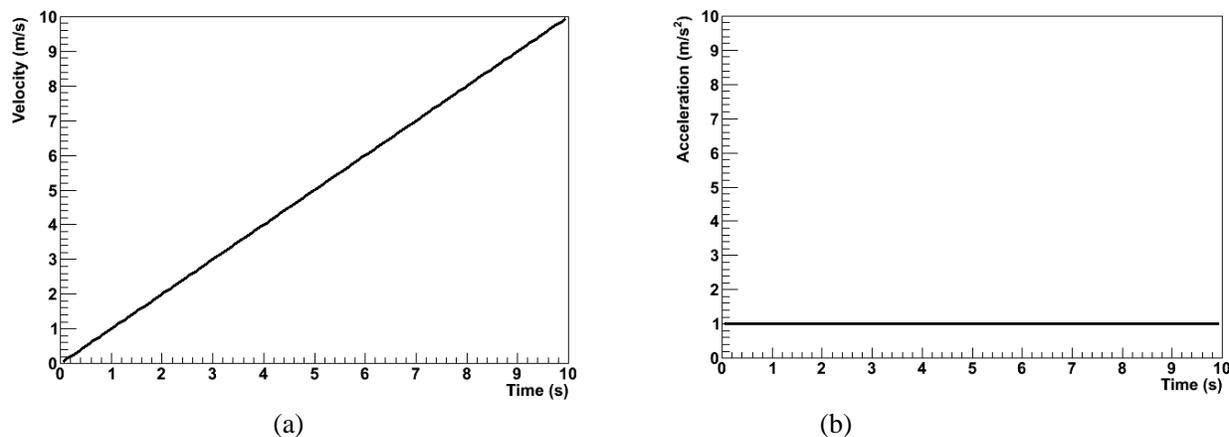
Figure 1: Graphs of acceleration a and velocity v for an object in 1-dimensional motion with constant acceleration.

If we are graphing, say, a velocity function $v(t)$ with respect to time t, then we do not bother trying to identify

$v(t)$ with y or t with x; in that case, we just forget about y and x. This can be particularly important when representing position with the variable x, as we often do in physics. In that case, graphing $x(t)$ with respect to t would give us an x on both the vertical and horizontal axes, which would be extremely confusing. We can even imagine a scenario wherein we should graph a function x of a variable y such that y would be on the horizontal axis and $x(y)$ would be on the vertical axis. In particular, in MotionLab, the variable z, not x, is always used for the horizontal axis; this represents time. Both x and y are plotted on vertical axes as functions of the time z.

Graphs of Functions

On a graph, the idea that a function maps one element of the domain to only one element of the range means that any possible vertical line can cross the function not more than once. This is because the horizontal axis is canonically used to represent the independent variable, or domain, while the vertical axis is canonically used to represent the dependent variable, or range; if the vertical line crossed the function twice or more, that would represent mapping one element of the domain to more than one element of the range.

We will almost always be graphing functions in this class; fits to data, for example, will always be functions. Relations which are not functions will be relevant only as data itself. For example, if we measured the acceleration due to gravity of two balls with the same mass, and if we did not measure exactly the same acceleration for the two, then a graph of acceleration versus ball mass would be a graph of a relation, not of a function.

| (a) | (b) |
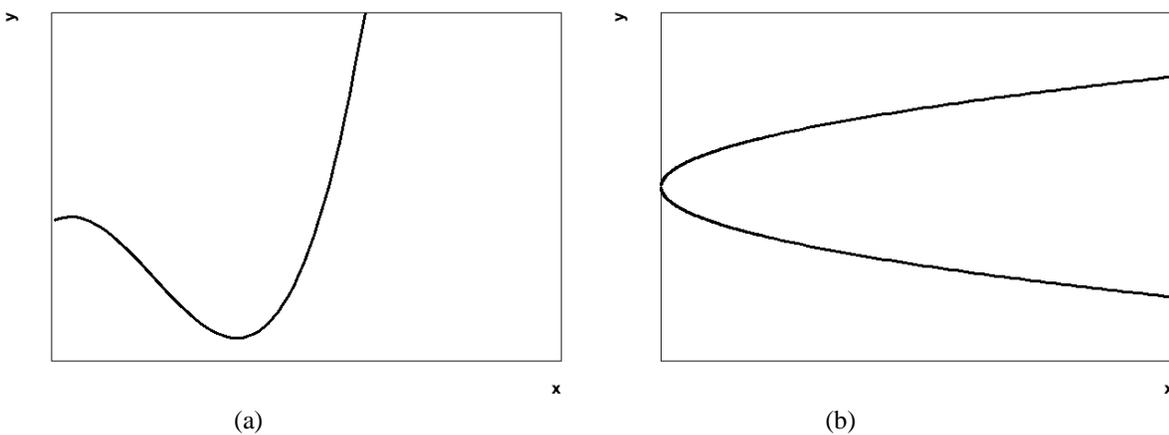
Figure 2: Graphs of a function (a) and of a relation which is not a function (b). Note that the latter does not pass the vertical line test.

Data, Uncertainties, and Fits

When we plot empirical data, we are still plotting relations; it is just not necessarily obvious that we are doing so. Our data will typically come as a set of ordered pairs (x, y); this can be seen as a relation from a small, discrete domain to a small, discrete range. Instead of plotting a curve, we just draw dots or some other kind of marker at each ordered pair.

Empirical data also typically comes with some uncertainty in the independent and dependent variables of each ordered pair. We need to show these uncertainties on our graph; this helps us to interpret the region of the plane in which the true value represented by a data point might lie. To do this, we attach error bars to our data points. Error bars are line segments passing through a point and representing some confidence interval about it.
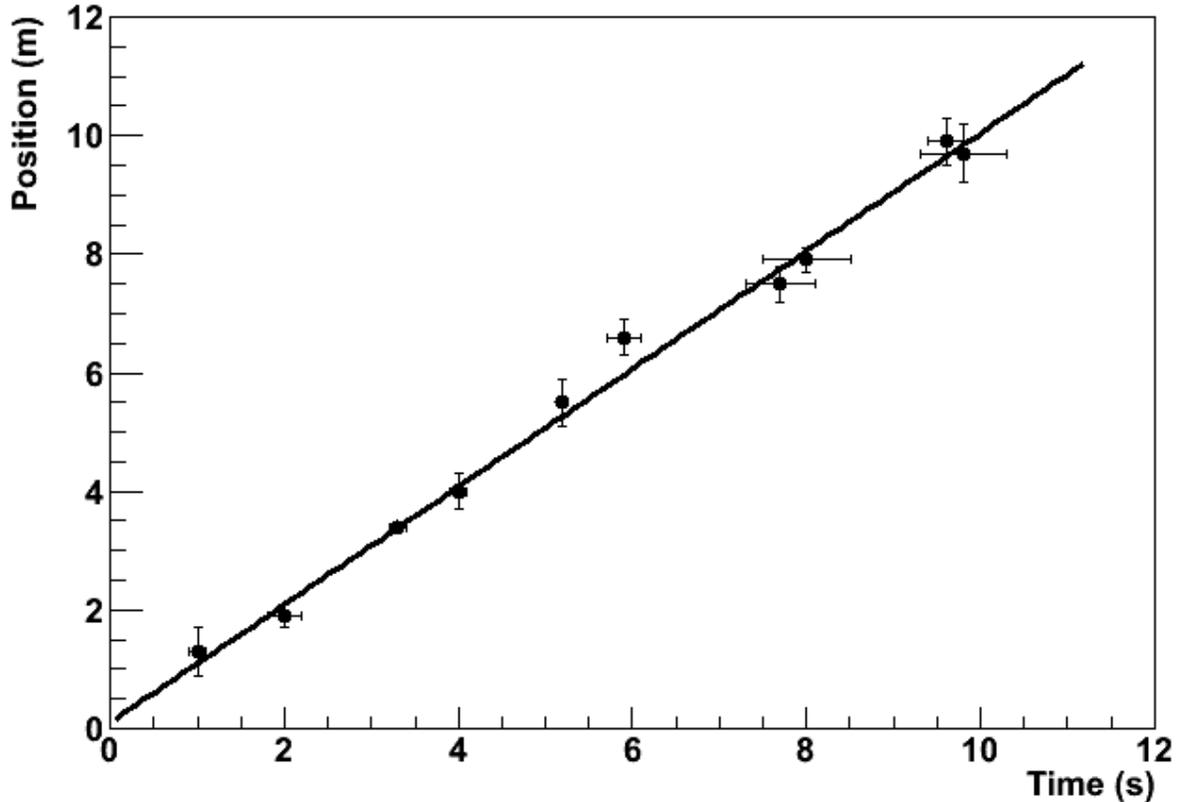
Figure 3: An empirical data set with associated uncertainties and a best-fit line.

After we have plotted data, we often need to try to describe that data with a functional relationship. We call this process "fitting a function to the data" or, more simply, "fitting the data." There are long, involved statistical algorithms for finding the functions that best fit data, but we won't go into them here. The basic idea is that we choose a functional form, vary the parameters to make it look like the experimental data, and then see how it turns out. If we can find a set of parameters that make the function lie very close to most of the data, then we probably chose the right functional form. If not, then we go back and try again. In this class, we will be almost exclusively fitting lines because this is easiest kind of fit to perform by eye. Quite simply, we draw the line through the data points that best models the set of data points in question. The line is not a "line graph;" we do not just connect the dots (That would almost never be a line, anyway, but a series of line segments.). The line does not need to pass through any of the data points. It usually has about half of the points above it and half of the points below it, but this is not a strict requirement. It should pass through the confidence intervals around most of the data points, but it does not need to pass through all of them, particularly if the number of data points is large. Many computer programs capable of producing graphs have built-in algorithms to find the best possible fits of lines and other functions to data sets; it is a good idea to learn how to use a high-quality one.

Making Graphs Say Something

So we now know what a graph is and how to plot it; great. Our graph still doesn't say much; take the graph in Figure 4(a). What does it mean? Something called q apparently varies quadratically with something called τ, but that is only a mathematical statement, not a physical one. We still need to attach physical meaning to the mathematical relationship that the graph communicates. This is where labels come into play.

Graphs should always have labels on both the horizontal and vertical axes. The labels should be terse but sufficiently descriptive to be unambiguous. Let's say that q is position and τ is time in Figure 4. If the problem is one-dimensional, then the label "Position" is probably sufficient for the vertical axis (q). If the problem is two-

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dimensional, then we probably need another qualifier. Let's say that the object in question is moving in a plane and that q is the vertical component of its position; then "Vertical Position" will probably do the trick.


(a)

(b) Position q with respect to time τ for a mass of 3kg. The acceleration is constant.
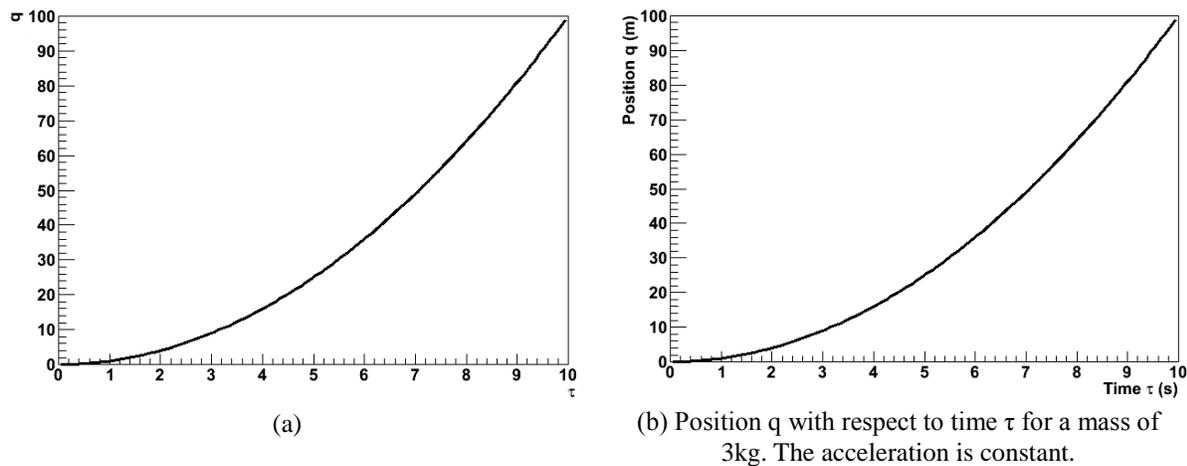
Figure 4: Poorly- versus well-labeled and -captioned graphs. The labels and caption make the second graph much easier to interpret.

There's still a problem with our axis labels. Look more closely; where is the object at $\tau = 6s$? Who knows? We don't know if the ticks represent seconds, minutes, centuries, femtoseconds, or even some nonlinear measure of time, like humans born. Even if we did, the vertical axis has no units, either. We need for the units of each axis to be clearly indicated if our graph is really to say something. We can tell from Figure 4(b) that the object is at $q = 36m$ at $\tau = 6s$. A grain of salt: our prediction graphs will not always need units. For example, if we are asked to draw a graph predicting the relationship of, say, the acceleration due to gravity of an object with respect to its mass, the label "Mass" will do just fine for our horizontal axis. This is because we are not expected to give the precise functional dependence in this situation, only the overall behavior. We don't know exactly what the acceleration will be at a mass of $10g$, and we don't care. We just need to show whether the variation is increasing, decreasing, constant, linear, quadratic, etc. In this case, it might be to our advantage to include units on the vertical axis, though; we can probably predict a specific value of the acceleration, and that value will be meaningless without them.

Every graph we make should also have some sort of title or caption. This helps the reader quickly to interpret the meaning of the graph without having to wonder what it's trying to say. It particularly helps in documents with lots of graphs. Typically, captions are more useful than just titles. If we have some commentary about a graph, then it is appropriate to put this in a caption, but not a title. Moreover, the first sentence in every caption should serve the same role as a title: to tell the reader what information the graph is trying to show. In fact, if we have an idea for the title of a graph, we can usually just put a period after it and let that be the first sentence in a caption. For this reason, it is typically redundant to include both a title and a caption. After the opening statement, the caption should add any information important to the interpretation of a graph that the graph itself does not communicate; this might be an approximation involved, an indication of the value of some quantity not depicted in the graph, the functional form of a fit line, a statement about the errors, etc. Lastly, it is also good explicitly to state any important conclusion that the graph is supposed to support but does not obviously demonstrate. For example, let's look at Figure 4 again. If we are trying to demonstrate that the acceleration is constant, then we would not need to point this out for a graph of the object's acceleration with respect to time. Since we did not do that, but apparently had some reason to plot position with respect to time instead, we wrote, "The acceleration is constant."

Lastly, we should choose the ranges of our axes so that our meaning is clear. Our axes do not always need to include the origin; this may just make the graph more difficult to interpret. Our data should typically occupy most of the graph to make it easier to interpret; see Figure 5. However, if we are trying to demonstrate a functional form, some extra space beyond any statistical error helps to prove our point; in Figure 5(c), the variation of the dependent with respect to the independent variable is obscured by the random variation of the data. We must be careful not to abuse the power that comes from freedom in plotting our data, however. Graphs

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can be and frequently are drawn in ways intended to manipulate the perceptions of the audience, and this is a violation of scientific ethics. For example, consider Figure 6. It appears that Candidate B has double the approval of Candidate A, but a quick look at the vertical axis shows that the lead is actually less than one part in seventy. The moral of the story is that our graphs should always be designed to communicate our point, but not to create our point.


(a)

(b)

(c)
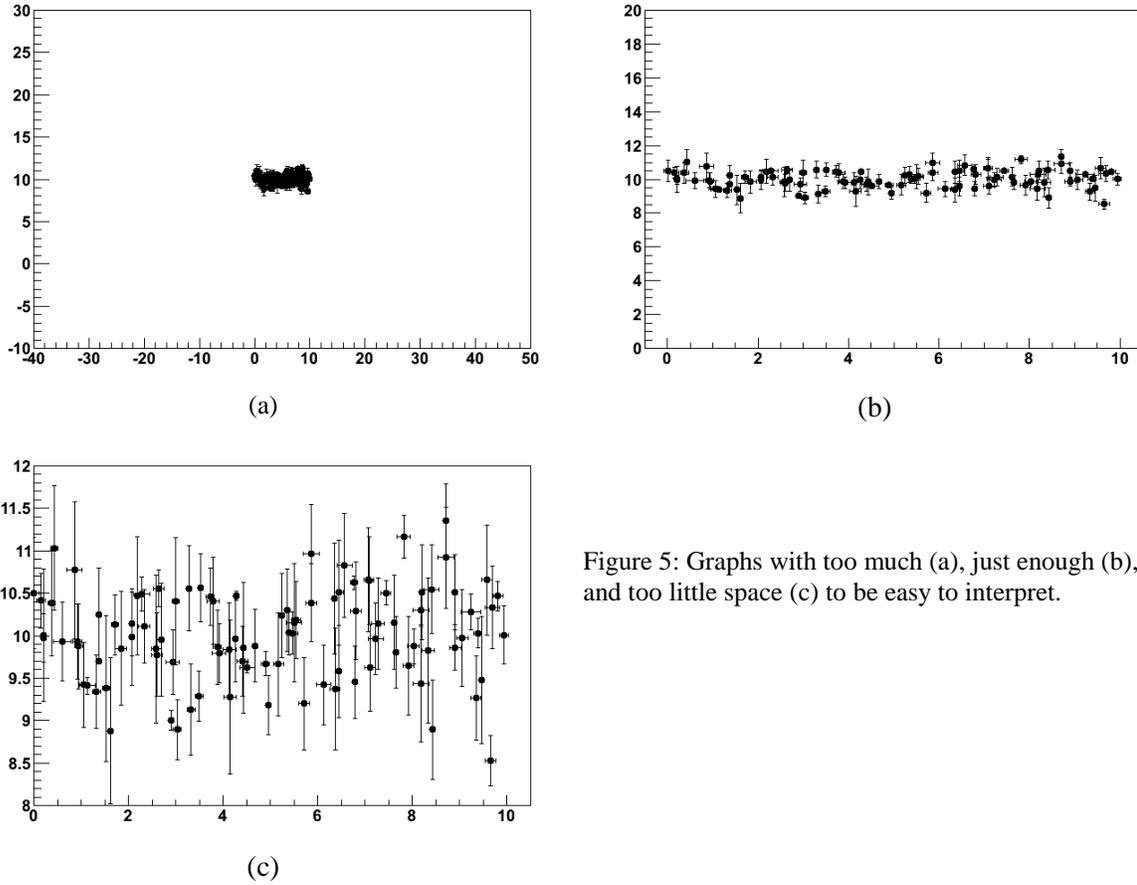
Figure 5: Graphs with too much (a), just enough (b), and too little space (c) to be easy to interpret.
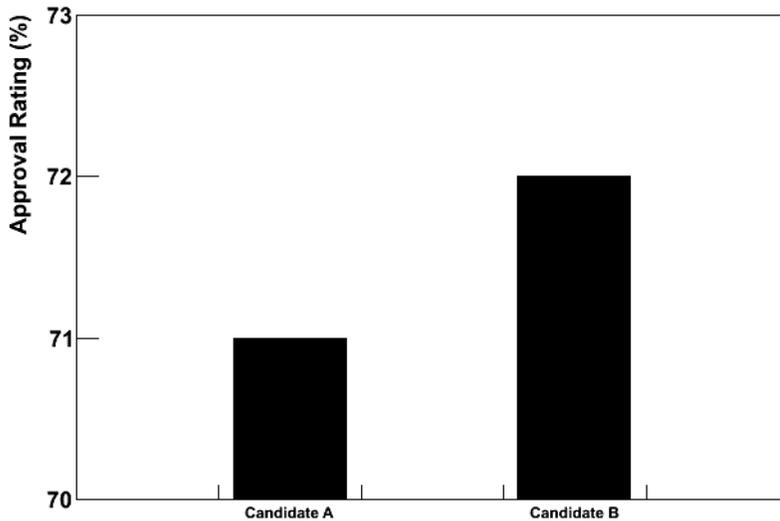
Figure 6: Approval ratings for two candidates in a mayoral race. This graph is designed to mislead the reader into believing that Candidate B has a much higher approval rating than Candidate A.

Using Linear Relationships to Make Graphs Clear

The easiest kind of graph to interpret is often a line. Our minds are very good at interpreting lines. Unfortunately, data often follow nonlinear relationships, and our minds are not nearly as good at interpreting those. It is sometimes to our advantage to force data to be linear on our graph. There are two ways that we might want to do this in this class; one is with calculus, and the other is by cleverly choosing what quantities to graph.

The "calculus" method is the simpler of the two. Let's say that we want to compare the constant accelerations of two objects, and we have data about their positions and velocities with respect to time. If the accelerations are very similar, then it might be difficult to decide the relationship from the position graphs because we have a hard time detecting fine variations in curvature. It is much easier to compare the accelerations from the velocity graphs because we then just have to look at the slopes of lines; see Figure 7. We call this the "calculus" method because velocity is the first derivative with respect to time of position; we have effectively chosen to plot the derivative of position rather than position itself. We can sometimes use these calculus-based relationships to graph more meaningful quantities than the obvious ones.

The other method is creatively named "linearization." Essentially, it amounts to choosing non-obvious quantities for the independent and/or dependent variables in a graph in such a way that the result graph will be a line. An easy example of this is, once again, an object moving with a constant acceleration, like one of those in Figure 7. Instead of taking the derivative and plotting the velocity, we might have chosen to graph the position with respect to $t^2/2$; because the initial velocity for this object happened to be 0, this would also have produced a graph with a constant slope.


(a)

(b)

(c)

(d)
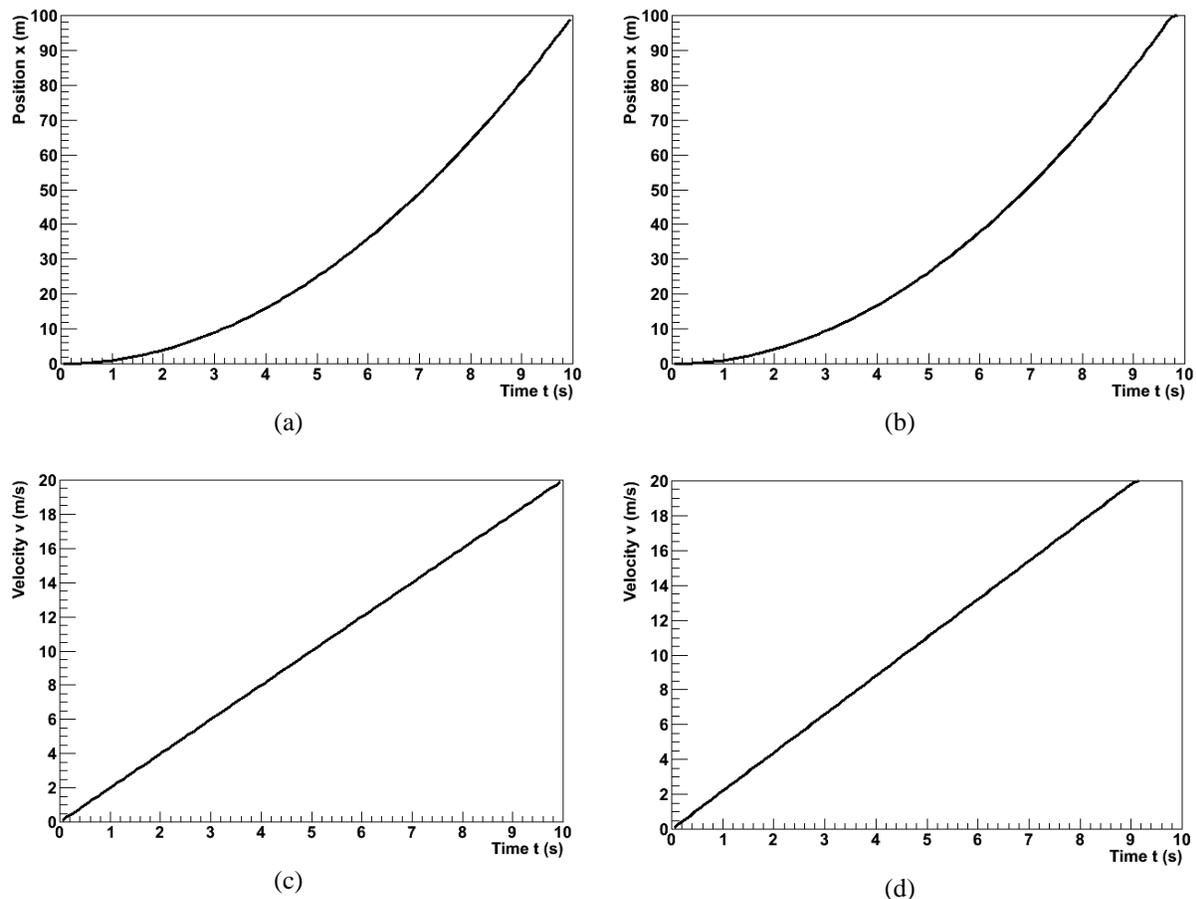
Figure 7: Position and velocity with respect to time for an objects with slightly different accelerations. The difference is easier to see in the velocity graphs.
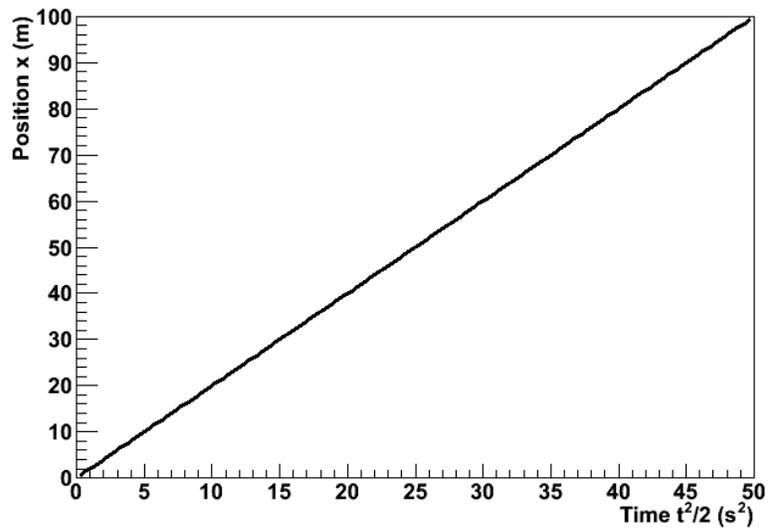
Figure 8: The position of the first object from Figure 7 plotted with respect to t2 /2. The relationship has been linearized.

The Bottom Line

Ultimately, graphs exist to communicate information. This is the objective that we should have in mind when we create them. If our graphs can effectively communicate our point to our readers, then they have accomplished their purpose.

Appendix D: Equipment

ELECTROSTATIC PAPER AND ACCESSORIES:

To investigate electric fields with the electrostatic paper, you need to do the following:
- Lay the electrostatic paper flat. .
- Distribute the pieces of metal (called "electrodes") on the paper, in the configuration whose field you wish to examine. The tips of the long brass rods may also be used as electrodes, to create point-like charges.
- Connect the electrodes to a source of charge. This is done by connecting a wire from the positive ("+") side of the battery or power supply to one electrode and the wire from the negative ("–") side to the other as shown in Figure 1.
- You may wish to place a wooden block on top of the brass rods to increase contact pressure with the paper. This can increase the magnitude of the electric field created on the paper. It also helps to place an extra sheet of paper under the electrostatic paper.

Figure 1: Electrostatic paper Setup   Figure 2: Electric Field Probe
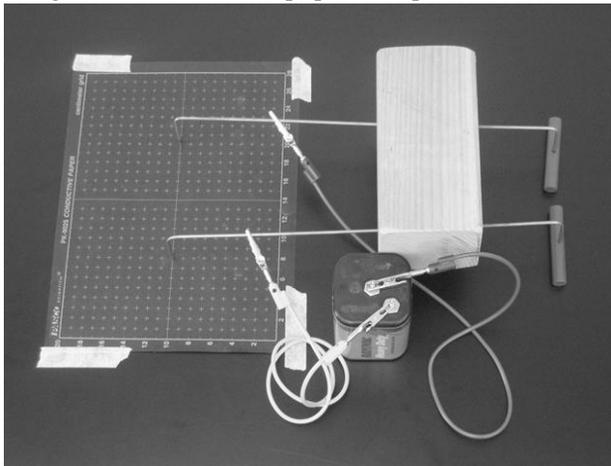
To measure the electric field from the charged electrodes, you will use a probe connected to a digital Multimeter set to measure volts (see Figure 2). For best results, turn the DMM to measure in the two-volt DC range, as indicated in Figure 2.

THE DIGITAL MULTIMETER (DMM)

The DMM is a common piece of lab equipment that can be used to measure various electrical quantities, most often current, resistance, and potential. The DMM's you will be using are capable of measuring both "direct current" (DC) and "alternating current" (AC) circuits. Be careful about knowing which type of measurement you need to make, then set your DMM accordingly. Some DMM's might be slightly different from the one pictured to the right.
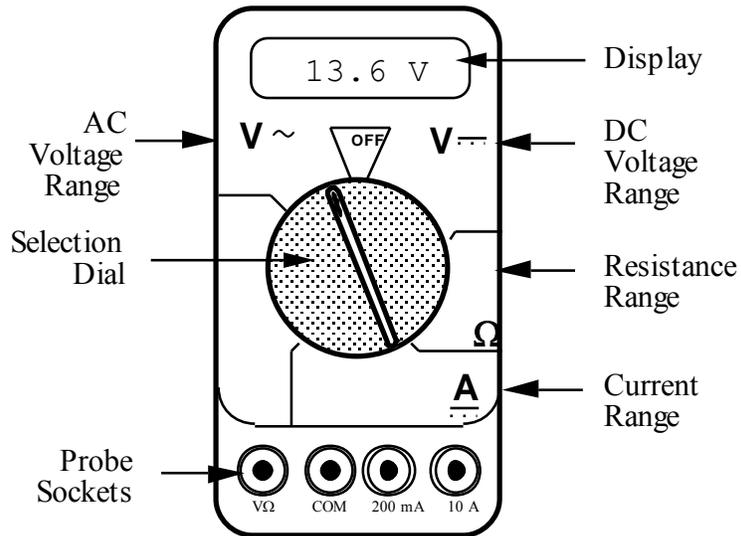
The DMM can measure currents anywhere from 10 amps to a microamp (10^{-6} amps). This versatility makes the DMM fragile, since measuring a large current while the DMM is prepared to measure a small one will certainly harm the DMM. For example, measuring a 1 ampere current while the DMM is on the 2 milliamp scale will definitely blow a fuse! If this happens, your instructor can change the fuse. However, if you damage the DMM beyond repair, you will have to finish the lab without the DMM.

Measuring Current:

1. Set the selection dial of the DMM to the **highest** current measurement setting (10 amps). Insert one wire into the socket labeled '10A' and a second wire into the socket labeled 'COM'.

2. Attach the DMM into the circuit as shown below:
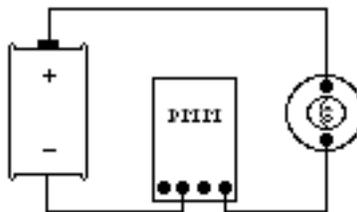
To measure current, the DMM must be placed in the circuit so that all the current you want to measure goes **through** the DMM.

3. If no number appears while the DMM is at the 10A setting, move the wire from the 10A socket to the 200mA socket and then turn the selection dial to the 200 milliamp (200m) setting. If there is still no reading, change the dial to the 20 milliamp setting, etc.

4. When you have taken your measurement, return the DMM selection dial to the highest current setting (10 amps) and move the wire back to the 10A socket.

Measuring Voltage:

1. Set the DMM selection dial to read DC volts. Insert one wire into the socket labeled 'V' and a second wire into the socket labeled 'COM'.

2. Set the selection dial of the DMM to the **highest** voltage measurement setting. Connect the two wires from the DMM to the two points between which you want to measure the voltage, as shown below.
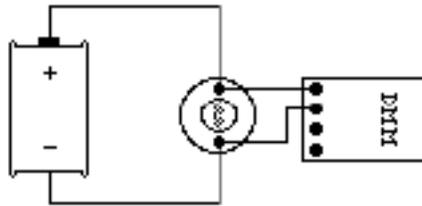
To measure voltage, the DMM must be placed in the circuit so that the potential difference across the circuit element you want to measure is **across** the DMM.

3. If no number appears, try a different measurement scale.   Start at the highest voltage scale and work your way down the scales until you get a satisfactory reading.

Measuring Resistance:

*The element whose resistance you are measuring **must** be free from all other currents (due to other batteries, power supplies, etc.) for the DMM to work.* That means you must **remove** it from a circuit.

To measure resistance:

1. Set the DMM selection dial to measure ohms (Ω). Insert one wire into the socket labeled 'VΩ' and a second wire into the socket labeled 'COM'.

2. *Make sure that the circuit element whose resistance you wish to measure is free of any currents.*

3. Attach the wires across the circuit element, as shown in the example below.
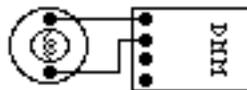
4. If no number appears, try a different measurement scale. Use a logical method that covers all scales, such as beginning at the largest scale (20 MΩ) and working your way down.

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CATHODE RAY TUBE (CRT) AND ACCESSORIES:

Use of the cathode-ray tube and its relatives is widespread. It is the heart of many familiar devices, from older computer monitors to televisions. The following is a sketch of the tube you will be using and its connections.

Figure 3:
Cathode Ray Tube.

$D = 7.4$ cm
$L = 2.0$ cm
$S = 0.30$ cm
$D_{tot} = 9.6$ cm
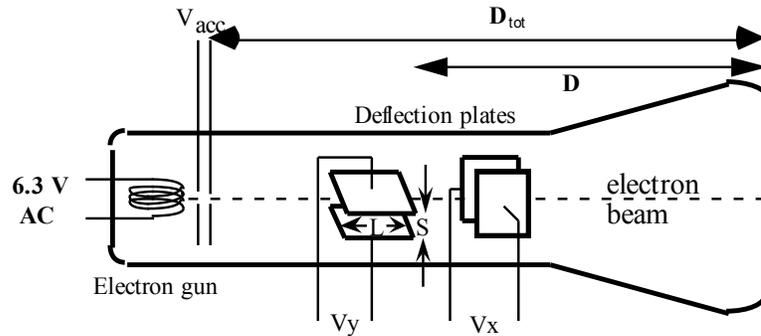
How the CRT works:

Within the electron gun:
- A thin filament (represented above as a coil of wire), similar to a light-bulb filament, is heated by a current. When the CRT is operating, this filament can be seen as an orange, glowing wire. This hot filament ejects slow-moving electrons.
- Some slow electrons drift toward the high-voltage "acceleration plates." These plates are labeled as Vacc in Figure 3. The electric field between the charged plates accelerates the electrons to high velocities in the direction of the fluorescent screen. The final velocity of an accelerated electron is much greater than its initial "drift" velocity, so the initial electron velocity can be ignored in calculations.

After the electron gun:
- Before hitting the screen, the high-velocity electrons may be deflected by charged plates along the length of the CRT. These charged plates are usually called the "x-deflection" and "y-deflection" plates.
- When the electrons reach the end of the tube, their energy causes the material that coats the end of the tube to glow. This material is similar to the material inside fluorescent light bulbs. The end of the CRT is called the fluorescent screen.

To supply the necessary electric potentials to the CRT you will use a power supply. The power supply provided has the proper potential differences to heat the CRT filament and to accelerate the electrons. The power supplies we use also have built-in circuit breakers. Should you attempt to draw too much current from your power supply, it will shut itself off with an audible "click." If this happens, check to make sure all of your wires are connected properly, then press in the small white button on the side of the power supply.

Note that the CRT and power supply come as a set, and many of the connections are color-coordinated to avoid potentially damaging misconnections. You will also have an assortment of batteries, which will be used to control the electric field between the CRT x- and y-deflection plates.

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply.

To properly connect the CRT to the power supply:
1.   Turn the power supply off.
2.   Connect the power supply ports marked "AC 6.3V" (they are green; the voltage differs slightly from one supply to another, but should be clearly marked) to the ports marked "HEATER" or "FILAMENT" on the CRT (these are also green).
3.   Connect the appropriate accelerating potential across the cathode and anode. For instance, if your experiment calls for a 500 volt accelerating potential, connect the cathode to the port marked "–250 V" (which may be black or white) and the anode to the port marked "+ 250 V" (which is red). This gives a total potential difference of 500 volts.
4.   Turn the power supply on.

RESISTOR CODES

A resistor is a circuit element manufactured to have a constant resistance. The resistance is coded onto the side of the resistor in colored bands, where the color and position of the bands tell you what the resistance is.

$$R = \underline{}\,\underline{} \times 10^{-}\ \Omega$$
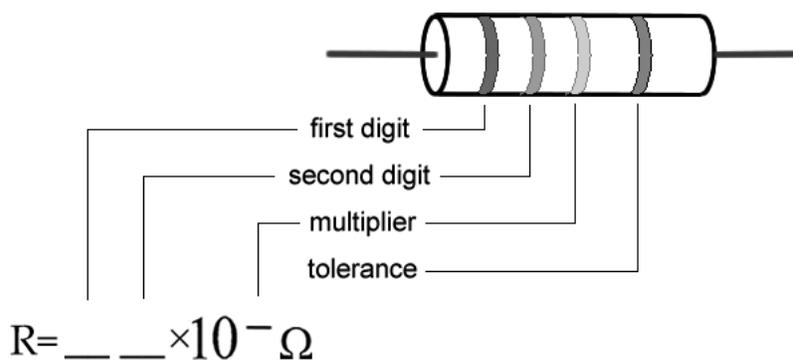
To read the color bands on the resistor, begin by finding the gold or silver band on one end of the resistor; this is the back of the resistor. You begin reading from the other end. Most resistors (including those you will use in lab) are coded to two significant digits. The first two color bands correspond to these two significant digits.

The third color band is called the multiplier. The number coded by this band represents a power of ten which you multiply by the number from the first two bands to get the total resistance.

The fourth color band tells you the tolerance, or error bounds for the coded resistance: gold means ±5% tolerance, silver means ±10% tolerance and no fourth band means ±20%.

Some resistors have a fifth color band, which represents the reliability of the resistor, and can just be ignored for the purposes of these labs.

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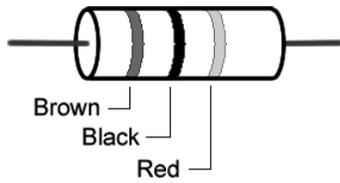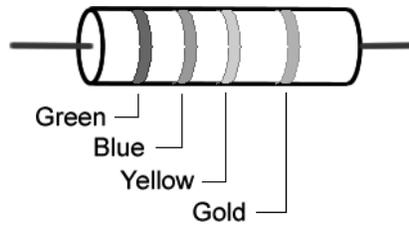
Color	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Brown —
Black —
Red —

Green —
Blue —
Yellow —
Gold —

$$R = 10 \times 10^2 \, \Omega \pm 20\%$$

$$R = 56 \times 10^4 \, \Omega \pm 5\%$$

SORENSEN POWER SUPPLIES

The Sorensen power supply is an all-purpose power supply for the production of constant currents and voltages.

At the top is the main display that reads either current in Amperes or voltage in Volts. There is a switch there that allows you to switch between them.

The current and voltage controls are located in the middle.   In between the constant current and constant voltage knobs is a switch that allows you to toggle from high currents to low currents. **It is highly recommended that you use only the low current mode.**

This power supply normally operates in the constant voltage mode. As such, you can only change the voltages by using the constant voltage knobs. **In the event that too much is being pulled from the power supply (as in a short), it will automatically switch to the constant current mode, where the amount of current flowing is greatly reduced.** This is a signal that something is amiss with your circuit.

There is a *mater-slave* switch on the back of the power supply. This should always be set to master for the DMM to function properly. If you experience any problems, this is the first place to check.

THE MAGNETIC FIELD SENSOR (HALL PROBE)

To measure magnetic field strength, you will need a measurement probe (the magnetic field sensor) that connects to a computer through the Vernier *SensorDAQ* lab interface..
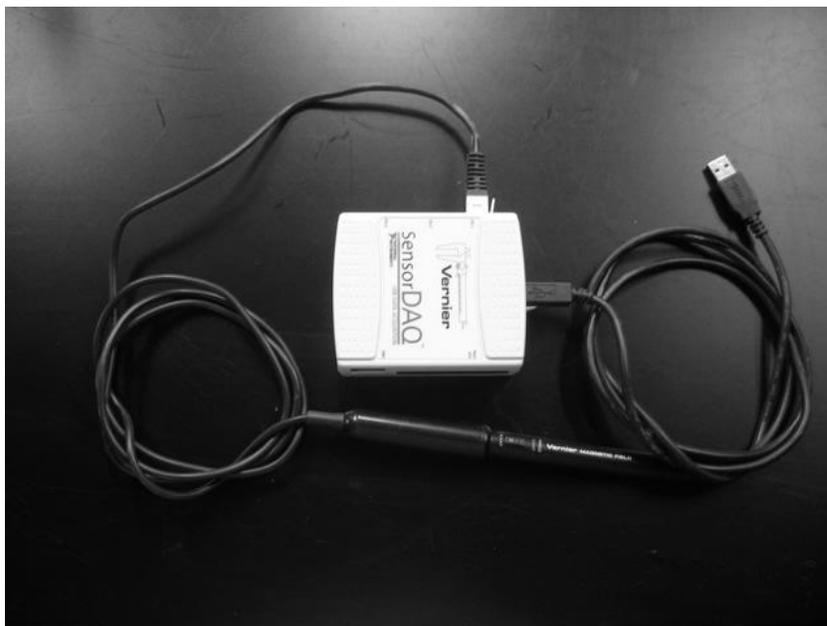
The tip of the measurement probe is embedded with a Hall Effect transducer chip (shown below as the white dot on the end of the probe). The chip produces a voltage that is linear with the magnetic field. The maximum output of the chip occurs when the plane of the white dot on the sensor is perpendicular to the direction of the magnetic field, as shown below:
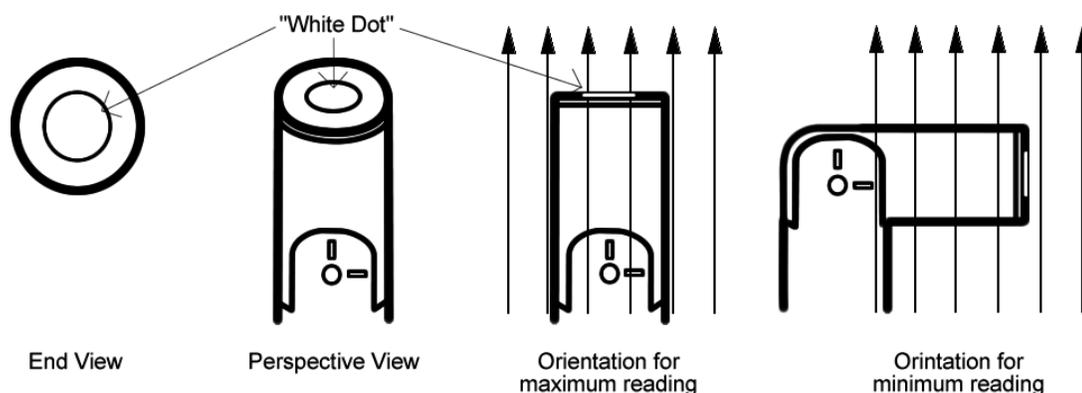
The *SensorDAQ* allows the computer to communicate with the probe. In order to measure magnetic fields, the wire leading out of the probe must be plugged into the *SensorDAQ* port labeled "CH 1". The *SensorDAQ* itself should be plugged into the USB port of the computer.

The Range switch on the side of the probe is to allow you to measure a greater range of magnetic field strengths. Each setting represents the maximum field strength that the probe can measure: either ±6.4mT or ±0.3mT. When measuring stronger magnetic fields, you should use the 6.4mT setting, but for fields weaker than 0.3mT the lower setting will give you a more accurate reading.

The measurement probes have swiveling tips to allow for more convenient data collection. Note: **these tips are only meant to swivel in one direction. They will break of they are bent in the wrong direction, and they are very fragile, so it does not take much to do this.** Please be very careful as these are costly to replace.

Appendix E: Software

## MAGNETLAB - MEASURING CONSTANT MAGNETIC FIELD

Application Basics

Before you begin, you should ensure that you have read the relevant sections of Appendix A to familiarize yourself with the equipment.

The software package that works in tandem with your magnetic field sensor is written in LabVIEW™. It allows you to measure and record magnetic field strength as a function of a number of different variables.

After logging into the computer, execute the application by double clicking the "MAGNETLAB" icon located in the PhysLab folder on the desktop.

Before you start using the program, you should take a moment to identify several key elements. The two most important of these are the Command Panel, shown to the right, and the Guide Box, shown below.

MagnetLab Guide Box

Amplification switch on the Magnetic Field Sensor should be set to the "6.4mT" position. If not, change it, and press Abort/ Restart button to re-initialize the SensorDAQ.

When switch is in correct position, select "Calibrate Probe" to begin.

○ Calibrate Probe
○ Accept Prediction
○ Acquire Data

○ Erase Data Points
○ Analyze Data
○ Accept Fit

○ Import Data
○ Print Results (anytime)
○ Abort / Restart

● Quit Program
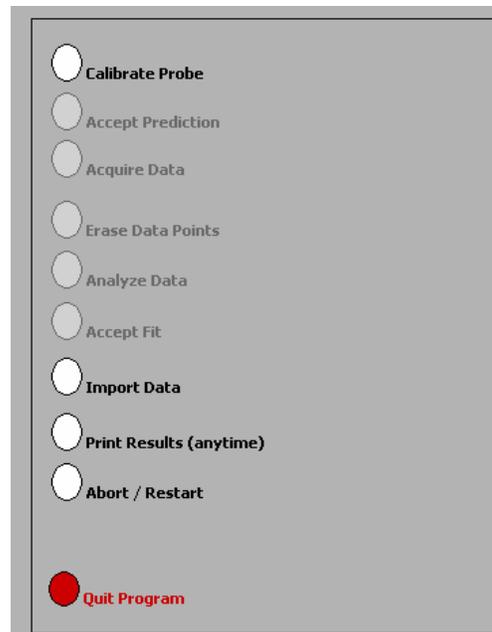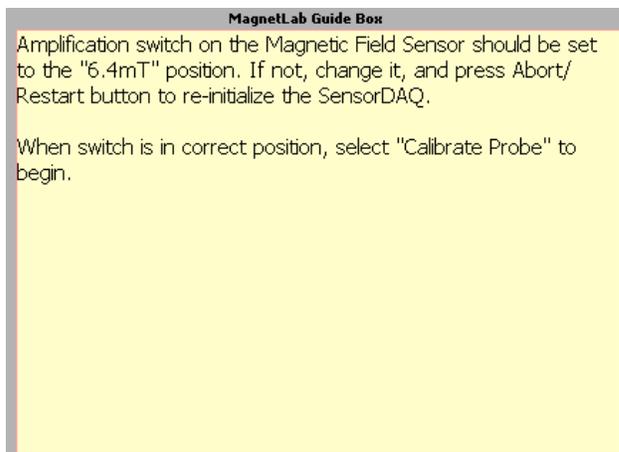
The Guide Box will give you directions and tasks to perform. It will also tell you when to select a command in the Command Panel. After selecting a command, it will "gray out" and the next command will become available.

You can also print and/ or quit from the Command Panel or abort your analysis and try again.

The primary data output you get is by generating pdf files of your results, so be careful not to quit without printing pdf files or exporting your data to be emailed amongst your lab group.

Calibration

The first command is to calibrate the Magnetic Field Sensor. Before selecting this command, you need to set the probe to the 6.4mT setting.

After selecting the "Calibrate Probe" command, you will be asked to do *two* tasks. Firstly, you will need to choose the quantity on the x-axis of your data graph. This is accomplished by moving the mouse cursor over to the word "meter" in the red-colored area (shown below) and then pressing the mouse button.
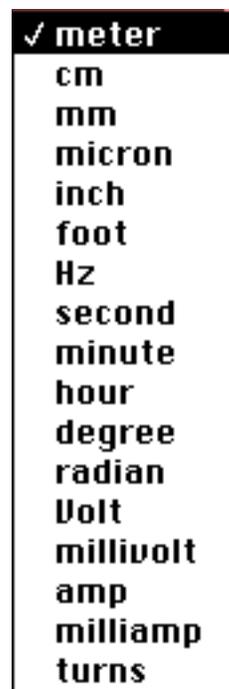
You should get a list of choices as shown to the right. By selecting any of these units, you will be making a choice about what you wish to measure. For example, if you choose to use "cm", you will make a graph of magnetic field strength as a function of distance (B vs. x). It is likely you will want to choose a small unit (cm's or mm's) to measure the distance in, since many magnetic fields are not very strong over long distances Selecting "degree" will make a plot of magnetic field strength as a function of angle (B vs. θ). Click "OK" when you are ready to proceed.

Secondly, you will need to eliminate the effect of the background magnetic fields. This process is called "zeroing the Hall probe" in the Guide Box. **Place the magnetic field sensor wand in the position you would like to take your measurement, but be sure that there are no magnets nearby.** Note that power supplies and computers generate magnetic fields, so it is a good idea to keep away from them! When you are ready, select the "Set Probe Zero" as shown below.
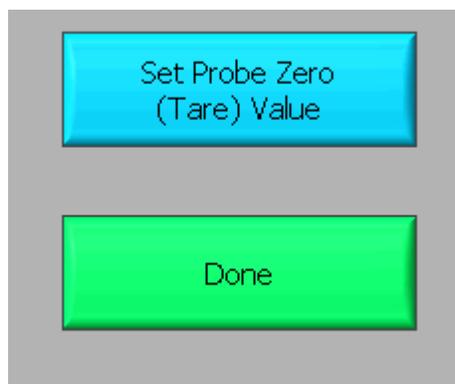
Then select the "Done" button. The calibration process is now complete.

Predictions

This type of analysis relies on your graphical skills to interpret the data. You should be familiar with both Appendix D: *Graphing,* and Appendix C: *Uncertainties.*

The first task is to enter your prediction of the mathematical function you expect to represent your data. Making a prediction before taking data is the best way to determine if anything is going wrong (remember Murphy's Law). It's also a good way to make sure you have learned something, but only if you stop to think about the discrepancies or similarities between your prediction and the results.

In order to enter your graphical prediction, you first need to decide on your coordinate axes and scale (units) for your measurements. *Record these in your lab journal.*

Next, you will need to select the generic equation, u(x), which describes the graph you expect for the data. Clicking the equation currently showing in the box will bring up a list of equations to choose from; see the diagrams to the right.

After selecting your generic equation, you next need to enter your best approximation for the parameters A, B, C, and/or D. These values should come directly from your prediction equation you did for class. As you enter these values, you should see the red line in the "Plot" box changing.

```
u(x) = A + Bx                          Fit
0.000        A                         Equation
0.000        B
0.000        C
0.000        D                         Prediction
```

```
✓ u(x) = A + Bx
  u(x) = A + Bx + Cx^2
  u(x) = A + Bx + Cx^2 + Dx^3
  u(x) = A + B sin(Cx + D)
  u(x) = A + B cos(Cx + D)
  u(x) = A + B exp(-Cx)
  u(x) = A + B{1 - exp(-Cx)}
  u(x) = A + B / (x + C)^D
  u(x) = A + B / (x^2 + C)^D
  u(x) = A + B / (x^2 + Cx)^D
```

Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes or use the *AutoScale* feature (see Finding Data below). When you are satisfied, select the *Accept Prediction* option from the Command Panel. Once you have done this you cannot change your prediction except by starting over.

Exploration

After you have entered your prediction, you can explore the limitations of your magnetic field sensor before you take data. The value of the magnetic field strength is displayed directly under the Guide Box. When you are ready to take data, select *Acquire Data* from the Command Panel.

Data Acquisition

Collecting data requires that you enter the x-axis data each time the computer reads in a value for the magnetic field strength. You enter this data using the panel shown. For every x-axis data value you enter, the analysis program will record the magnetic field strength in gauss on the y-axis of the "Plot". Press "OK" to collect the next data point. Each data point should appear on the graph on the computer screen as you take it. If it doesn't, adjust the scales of your graph axes or use the *AutoScale* feature (see Finding Data below). If you are satisfied with your data, choose *Analyze Data* from the Command Panel.

```
X-Axis Data
1.000        Value

   OK
```

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Finding Data on the Graph

You can find your data on the graph by adjusting the scales of your X-axis and Y-axis plots manually. This scaling is accomplished by entering values into the legend of the graph. Click on the upper or lower legend value and enter a new value, then hit enter. If you cannot locate your data, you can select both "AutoScale Y-axis" and "AutoScale X-Axis" to let the program find the data for you. You can then adjust your axis scales to give you a convenient graph for analysis. Be careful, the AutoScale option will often set the scales in such a way that small fluctuations in the data are magnified into huge fluctuations.

Data Fits

Deciding which equation best fits your data is the most important part of using this analysis program. While the actual mechanics of choosing the equation and parameters is similar to what you did for your predictions, fitting data is somewhat more complicated.

By looking at the behavior of the data on the graph, determine the best possible function to describe this data. After you have decided on the appropriate equation, you need to determine the constants of this equation so that it best fits the data. Although this can be done by trial and error, it is much more efficient to think of how the behavior of the equation you have chosen depends on each parameter. Calculus can be a great help here. *This can be a time-consuming task, so be patient.*

Now you need to estimate the uncertainty in your fit by deciding the range of other lines that *could* also fit your data. This method of estimating your uncertainty is described in Appendix D. Slightly changing the values for each constant in turn will allow you to do this quickly.

After you have computed your uncertainties, return to your best-fit line and use it as your fit by selecting *Accept Fit* in the Command Panel.

Importing / Exporting Data

After you have selected *Analyze Data*, it is possible to save your data to the computer's hard drive. This feature can come in handy if you need to analyze your data at a later date or if you want to re-analyze your data after you have printed it out.

To save your data, simply select *Export Data* (as shown to the right) and follow the instructions in the windows. Your file should be saved in the **LabData** folder. To retrieve this file, restart *MagnetLab* from the desktop and select *Import Data.*

Last Words

These directions are not meant to be exhaustive. You will discover more features as you analyze more data. Be sure to record these features in your lab journal.
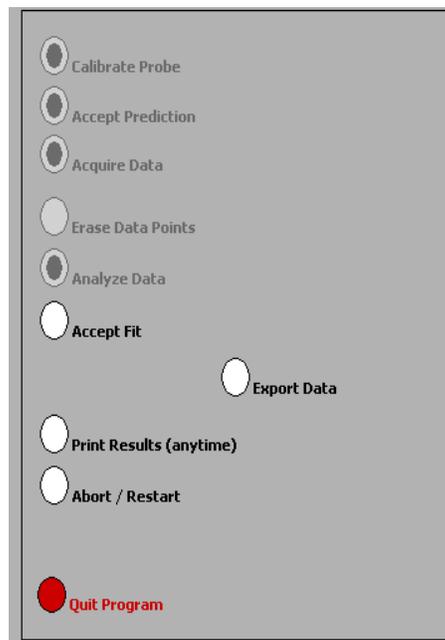
FLUX SIMULATOR

A computer movie called <u>FluxSimulator</u> shows the magnetic flux through a rectangular coil of wire (called a frame in the program). The frame is rotated in a uniform magnetic field changing the magnetic flux passing through it. The screen of this simulation is shown below. The magnetic flux is visualized by a "magic eye" that is always perpendicular to the cross-sectional area of the frame (as shown below). The amount of flux "seen" is indicated by the use of color intensity as the frame rotates. Blue indicates positive flux while red indicates negative flux.
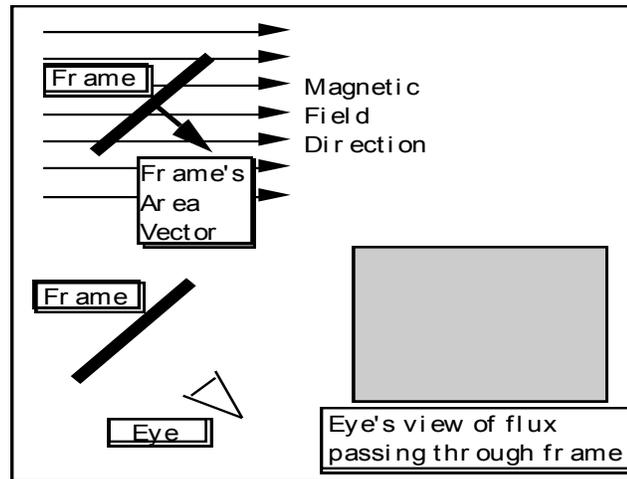
Picture of <u>FluxSimulator</u> Screen

Use the control bar with the slider, as shown below, to control the rotation of the frame.

Slider
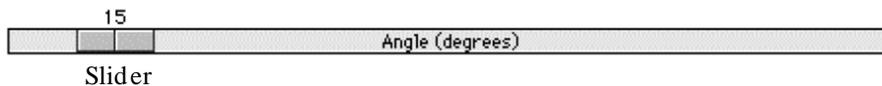
As you rotate the frame, observe both the angle the frame's area vector makes with the magnetic field and the color seen by the eye.

VoltageTimeLAB - MEASURING TIME-VARYING VOLTAGES

The Basics:

This software package, written in LabVIEW™, allows you to measure and record potential differences as a function of time. The software and voltage interface act much like an oscilloscope.

After logging into the computer, execute the application by double clicking the "VoltageTimeLab" icon located in the PhysLab folder on the desktop.

Before you start using the program, you should take a moment to identify several key elements. The two most important of these are the Command Panel, shown to the right, and the Guide Box, shown below.
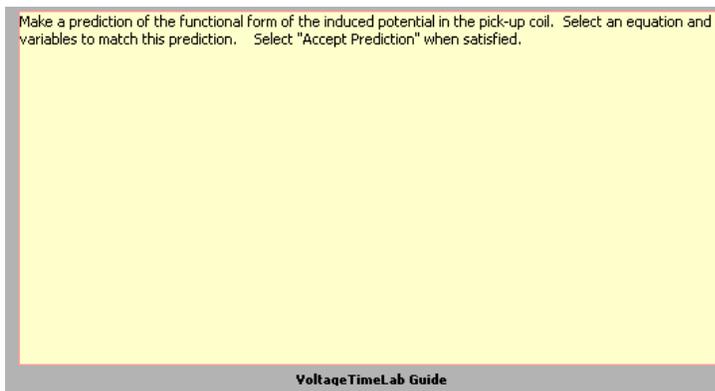
The Guide Box will give you directions and tasks to perform. It will also tell you when to select a command in the Command Panel.

You can also print and/or quit from the Command Panel or abort your analysis and try again.

The primary data output you get is by generating pdf files of your results, so be careful not to quit without printing pdf files or exporting your data to be emailed amongst your lab group.

Since the application to measure time-varying voltage is a slight modification of the application to measure magnetic field, you are already familiar with how to use much of it. The basic difference between the TimeVoltageLab and the MagnetLab applications is an additional display that is much like an oscilloscope. The potential difference versus time display is shown on the next page. The DAQ (Data Acquisition) control buttons are located directly above this display. The "DAQ START" and "DAQ STOP" buttons do as they suggest, stop and start data streaming from the probe to the voltage versus time display. When you first start the application you will need to click the "DAQ START" button to start streaming the probe readings. You will use the "DAQ STOP" to freeze the data screen for taking measurements. A green indicator is used to indicate whether the interface is running or not.
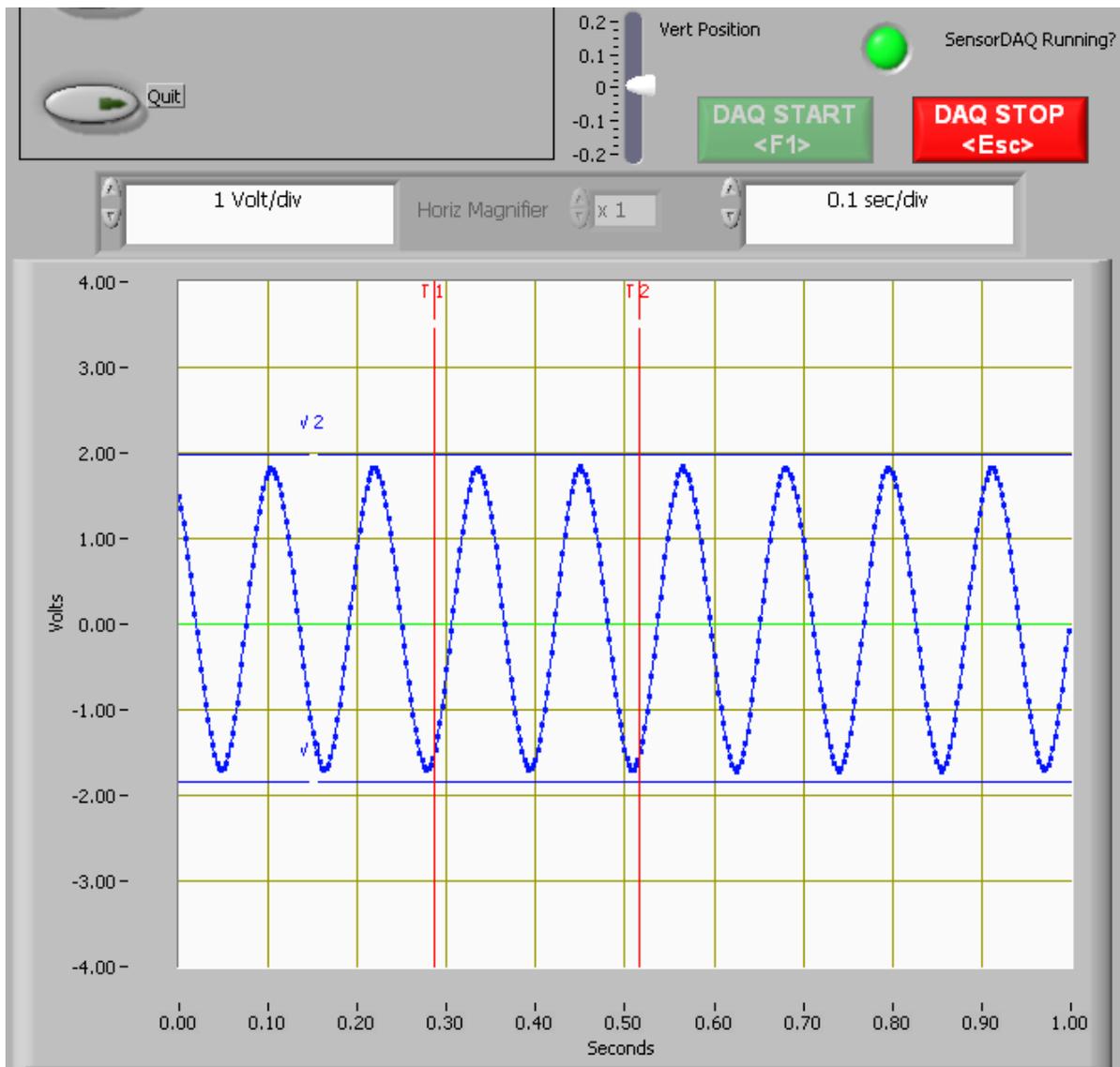
The vertical axis is a measure of the potential difference (voltage) between the two leads of the voltage probe. The horizontal axis measures time. You should also notice that the display has a grid on it. The scale of each axis is shown at the bottom of the display. As you might suspect, it is possible to change the grid size of each axis. To change the scale of the axis, simply click on the highest or lowest number on that axis and type in a new value. The axis will automatically adjust to create even increments over the newly defined range.

The red and blue lines that are on the display are movable simply by putting your mouse pointer over one of the lines. When the mouse pointer changes shape, hold the mouse button down and drag the lines to mark a voltage or time as shown. The lines mark the voltage and time boundaries of the data that will be considered for analysis.
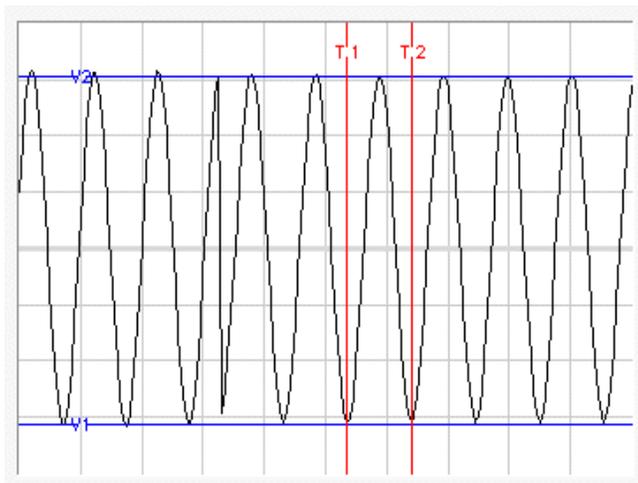
If you are unable to see the lines, it is possible that you changed the axes scale and "zoomed in" too far. Try changing the axes to "zoom out" again, and determine if you can locate the blue and red lines. Move the lines to within the values of the new scale, and they should remain visible on the screen when you zoom in.

Predictions

This type of analysis relies on your graphical skills to interpret the data. You should be familiar with both Appendix D: *Graphing,* and Appendix C: *Uncertainties.*

The first task is to enter your prediction of the mathematical function you expect to represent your data. Making a prediction before taking data is the best way to determine if anything is going wrong (remember Murphy's Law). It's also a good way to make sure you have learned something, but only if you stop to think about the discrepancies or similarities between your prediction and the results.

You will need to select the generic equation, u(x), which describes the graph you expect for the data. Clicking the equation currently showing in the box will bring up a list of equations to choose from; see the diagrams to the right.

After selecting your generic equation, you next need to enter your best approximation for the parameters A, B, C, and/or D. These values should come directly from your prediction equation you did for class. As you enter these values, you should see the red line in the "Plot" box changing.

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Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes (see Finding Data below).   When you are satisfied, select the *Accept Prediction* option from the Command Panel. Once you have done this you cannot change your prediction except by starting over.

Exploration

After you have entered your prediction, you can explore the limitations of your voltage probe sensor before you take data. The value of the voltage is displayed directly on the voltage vs. time display. When you are ready to take data, select *Acquire Data* from the Command Panel.

Data Acquisition

Collecting data requires that you position the moveable red and blue lines on the voltage vs. time display. The blue lines will generate potential difference data and the red lines will generate time/ period data. The data values are shown in the data box.   The data box appears once you have selected "*Acquire Data*" from the Command Panel. Press "*OK*" to collect each data point. Each data point should appear on the graph on the computer screen as you take it. If it doesn't, adjust the scales of your graph axes. If you are satisfied with your data, choose *Analyze Data* from the Command Panel.

Finding Data on the Graph

You can find your data on the graph by adjusting the scales of your X-axis and Y-axis plots manually. This scaling is accomplished by entering values into the legend of the graph. Click on the upper or lower legend value and enter a new value, then hit enter. If you cannot locate your data, you can select both "AutoScale Y-axis" and "AutoScale X-Axis" to let the program find the data for you. You can then adjust your axis scales to give you a convenient graph for analysis. Be careful, the AutoScale option will often set the scales in such a way that small fluctuations in the data are magnified into huge fluctuations.

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Data Fits

Deciding which equation best fits your data is the most important part of using this analysis program. While the actual mechanics of choosing the equation and parameters are similar to what you did for your predictions, fitting data is somewhat more complicated.

By looking at the behavior of the data on the graph, determine the best possible function to describe this data. After you have decided on the appropriate equation, you need to determine the constants of this equation so that it best fits the data. Although this can be done by trial and error, it is much more efficient to think of how the behavior of the equation you have chosen depends on each parameter. Calculus can be a great help here. *This can be a time-consuming task, so be patient.*

Now you need to estimate the uncertainty in your fit by deciding the range of other lines that *could* also fit your data. This method of estimating your uncertainty is described in Appendix D. Slightly changing the values for each constant in turn will allow you to do this quickly.

After you have computed your uncertainties, return to your best-fit line and use it as your fit by selecting *Accept Fit* in the Command Panel.

Appendix F: A Brief Introduction to RMS Measurements

A problem arises when one wishes to measure an alternating current or potential. All measuring instruments sample a signal over some period of time. A device that samples over a time longer than one period of the signal (such as the DMM) essentially measures the average signal. For sine or cosine functions, the average is zero, which doesn't tell you much about the signal strength.

The solution to this difficulty is to use root-mean-square (RMS) averaging. To eliminate the cancellation of the positive and negative parts of the sine function, it is squared, then the average is taken[1], and the square root of this average yields the RMS value.

For example, to find the RMS value of an AC current that has a maximum value of I_O:

$$I(t) = I_0 \sin(\omega t)$$
$$I^2(t) = I_0^2 \sin^2(\omega t)$$

$$\langle I^2 \rangle = \frac{1}{2\pi} \int_0^{2\pi} I_0^2 \sin^2(\omega t) d(\omega t)$$

$$= \frac{I_0^2}{2\pi} \int_0^{2\pi} \sin^2(\omega t) d(\omega t) = \frac{1}{2} I_0^2$$

$$I_{RMS} = \sqrt{\langle I^2 \rangle} = \frac{1}{\sqrt{2}} I_0$$

When in AC mode, your DMM displays the RMS values of current and voltage.

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1 When a quantity that varies with time is averaged, as in this case, the average value is often designated by putting angle brackets around the quantity. For example, the time average of a sinusoidally varying current is:

$$\langle I \rangle = \frac{I_0}{2\pi} \int_0^{2\pi} \sin(t) dt = 0$$

Appendix G: What is a Lab Report?

Glad you asked. A lab report is an analysis of an experiment that you personally performed in this class's lab setting. It is a self-contained document; the reader should not have to consult any other source to understand what you did or why you did it. It should present a cogent, coherent, complete analysis which moves from a statement of a question (expressed in terms of one or more empirical quantities) toward a clear, pre-established goal (an evaluation of those empirical quantities) which answers that question.

This makes a lab report a somewhat unique assignment in the context of science classes you may have taken in the past. To this point, work has always been about finding an answer; to this point, the product of the work has been the answer. Lab reports do seek to answer a question, yes, but the product of a lab report is the *process*. Your purpose in writing a lab report (as an assignment, not as a composition) is to demonstrate to your instructors that you understand the process of science.

Audience

Your audience when writing a lab report is an arbitrary scientifically literate person. You should assume that your audience is well-acquainted with science in general and physics and mathematics in particular, both in theory and in practice. You should also assume that your audience knows absolutely nothing about what specific experiment you have performed, why you have performed it, or what the result ought to be. This means that you can use the language, methods, and writing style of physics without explaining them, but that you must explain your experimental procedure and analysis in detail.

Technical Style

A lab report is a technical document. This means that it is stylistically quite different from documents you may have written in English, history, rhetoric, or other humanities classes. The sample lab reports in this manual, real scientific papers, manuals, design reports, and such things are good examples of technical writing.

A lab report is divided into sections. It does not rely on language to create transitions from one topic to the next, and each section should be comprehensible by itself. This is not to say that the sections should duplicate information; reading the "Procedure" section of a lab report will not tell the reader the goal or the result of the experiment, but it should completely communicate the experimental procedure used.

A lab report does not need to use the active voice. In many kinds of writing, the active voice is encouraged for sounding brief and clear, and the passive voice is discouraged for sounding verbose and distant. In technical writing, the passive voice is often encouraged to shift the focus of the writing to the science rather than the scientist. Either voice is acceptable in your report. You should use whichever feels natural and accomplishes your intent, but you should be consistent.

A lab report presents much of its information with media other than prose. Tables, graphs, diagrams, and equations frequently can communicate far more effectively than can words. Technical writing embraces these media. You should integrate them smoothly into your report.

A lab report is a persuasive document, but it does not express opinions. Your predictions should be expressed as objective hypotheses. Your experiment and analysis should be a disinterested effort to confirm or deny your predictions, not an attempt to convince your audience that they are correct. Please note that your thesis, which your report should always confirm, will not necessarily coincide with your predictions. Whether or not your report supports your predictions, it should support your thesis objectively.

A lab report does not entertain. If you read the sample reports, you will probably find them boring. A lab report *ought* to be boring. Your audience is not reading your report to have a good time; he is

reading your report to learn. The science in your report should be able to stand for itself. If your report needs to be entertaining, then its science is lacking.

Spelling, Grammar, Mechanics, and So Forth

You should write your lab report in standard, formal, American English. You should use proper grammar, syntax, orthography, and so on. Bad spelling, in particular, is inexcusable; while electronic spelling checkers are not perfect, they are good enough to render spelling mistakes in finished products all but extinct. You are a college student; you ought to be able to do these things properly.

With that said, these linguistic components of the report are the emphasis neither of this course nor of this assignment. If they are sufficiently lacking to compromise the understandability of your report, you will be penalized. Otherwise, they are of secondary importance.

Physical Style

Physical style refers to the visual, as opposed to the logical, attributes of a document. In lab reports, this basic philosophy holds true: content is important; appearance is not. You should therefore consider physical style to be of secondary importance.

This is not to say that you may simply write your lab report by hand on notebook paper. Your report should be typeset using a computer. Your graphs should be produced with a high-grade plotting program, not with a drawing program like Microsoft Paint or Adobe Illustrator. Your headings should stand out. Your equations should be rendered using a tool specifically for typesetting mathematics, not simply typed using a word processor's text mode. It *is* to say that your specific choices of fonts, heading sizes, paragraph delimitation, etc. are up to you. Ultimately, the physical style is subservient to the logical style. It should serve to communicate information. Your headings should be obvious, your mathematics should be unambiguous, your graphs should be accurate, and so forth.

When in doubt, your best practice is to ask your TA. He may or may not have specific desires in this area, and he can always provide an acceptable suggestion. If you need to see something personally, this lab manual, particularly the sample reports, is a good example of physical style done well.

Graphs, Tables, Diagrams, Math

A lab report utilizes a variety of media to communicate its message. An old cliché tells us, "A picture is worth a thousand words;" you should embrace this sentiment when you write your reports, but you should not limit yourself to pictures. Your goal should be to make your point to your reader as clearly and tersely as possible. When a graph will do better than words, use a graph. When a table will do better than a listing, use a table. When a diagram will do better than a long description, use a diagram.

You should label these media when you write your report. Graphs, diagrams, and other pictures should be labeled with "Figure *X*," wherein *X* is an identifying integer. Tables should be labeled similarly, with "Table." Equations typically only receive a number; convention places the numbers at the right end of the line, and the word "Equation" is omitted for space. However, you should still refer to an equation as "Equation *X*" in the text.

You should caption every table and figure you include in your report. Your goal in the caption, at the very least, is to accomplish what a title otherwise would: to declare to the reader what information the object is presenting. Depending on the circumstance, you should also explain any relevant, non-obvious details, such as assumptions or important numerical quantities not presented in the object itself. For example, if you include a graph of the position of a ball with respect to time in a report where you measured this quantity for balls of several masses, your caption should indicate the mass

of the ball for which the data is presented. Finally, if the object is intended to demonstrate some derived piece of information, such as a conclusion or a fit to a graph, you should include this in your caption.

As valuable as these media are, they do not contain enough information to stand without context. You should not merely add these sorts of objects without addressing them in the text of your report. They should be naturally integrated into the discussion. When you come to a point that you wish to make with a graph, state that the information is contained in Figure X. When you reference data that is included in a table, tell your reader to refer to Table Y. Be sure to state and explain the salient conclusion that the reader should draw from the object that she has just examined. Sometimes, these two functions can even be combined into a single sentence.

These media are powerful tools, and they are at your disposal to help you make your case in your report. You should use them whenever you can make your argument more elegantly by doing so than by not. If you find yourself in a situation where trying to use one only makes things more confusing, it is best to stick with tried-and-true prose. Use your best judgment.

Quantitativeness

A lab report is quantitative. Quantitativeness is the power of scientific analysis. It is objective, and it allows us to know precisely how well we know something. Your report is scientifically valid only insofar as it is quantitative.

You must follow one, simple rule to make your report quantitative: give numbers. Give numbers for everything. You should report the numerical values of every relevant quantity that you measure or calculate. You should report some numerical evaluation of every result you derive and every conclusion you draw. You should report the numerical errors in every quantity you measure, and you should propagate the numerical errors in every quantity you compute. If you find yourself using words like "big," "small," "close," "similar," and etc., then you are probably not being sufficiently quantitative. Try to replace vague statements like these with precise, quantitative ones.

If there is a single "most important part" to quantitativeness, it is error analysis. This lab manual contains an appendix about error analysis; read it, understand it, and take it to heart.

Making an Argument

The single most important part of any lab report is the argument. You need to be able communicate and demonstrate a clear point. If you can do this, and do it in a scientifically valid manner, your report will be a success. If you cannot, your report will be a failure.

You have certainly written a traditional five-paragraph essay at some point. Recall its structure:
1. An opening paragraph stating a thesis.
2. A middle paragraph explaining a first supporting point.
3. A middle paragraph explaining a second supporting point.
4. A middle paragraph explaining a third supporting point.
5. A closing paragraph restating the thesis.

A lab report is not so trite and formulaic a document as this, but you can, nevertheless, learn an important lesson from it. Good technical writing states a thesis, supports it with argument, and then restates the thesis. By "giving away the ending," so to speak, you accomplish two things. First, you entice the audience to finish reading the report. Second, you let the audience know where the report is about to take her, an act which will help her to keep track of her train of thought as she reads. Once this is done, you must defend your thesis through logical, scientific argument. Your audience is trained to react to anything you say with skepticism, so you must rigorously justify it. Finally, by

restating the thesis with which you opened, you emphasize the point, remind your audience what she just learned, and give your audience a sense of closure.

In science, this is typically implemented by structuring a report in four basic sections: introduction, methodology, results, and discussion; this is sometimes called the "IMRD method." You should state your thesis, along with enough background information to explain it and a brief preview of the succeeding sections, in your introduction. You should defend that thesis in the methodology and results sections. You should restate your thesis, this time with an evaluation of its veracity and its implications, in your discussion. N.B.: Your report does not need to have exactly four sections entitled "Introduction," "Methodology," "Results," and "Discussion;" this is just the logical progression by which you should structure it. Several more specific, more finely divided sections are recommended below.

An Example Format

We here present an example of how to structure your report. You should not interpret this as a strict, required format. It is, however, one possible good implementation of the IMRD method. Any format that you choose should be such a good implementation and should include all of the information presented in the format below. Much of the advice given below is useful in general.

Abstract

You should think of the abstract as your report in miniature. It should be only a few sentences long, but should emulate the IMRD method. You should state the question you are trying to answer. You should then state the method you used to answer that question. You should finally summarize your results and conclusion.

The abstract serves the same purpose for your report that a teaser serves for a film. It is the first thing that your audience will encounter, and it is what will convince her that reading the rest of your report is worth her time.

Although the abstract is first piece of your report, it can be helpful to write it last. After you have written the rest of the report is when you best understand it and can best summarize it.

Your abstract should not be an integrated component of your report as a whole; it should not replace any other part of the report, and the report should be complete and comprehensible in its absence.

Introduction

You should do three things in your introduction. First, you should provide enough context so that your audience can understand the question that your report tries to answer. This typically involves a brief discussion of the hypothetical, real-world scenario presented at the beginning of the experiment's prompt in the lab manual. Second, you should clearly state the question. Third, you should provide a brief statement of how you intend to go about answering it.

Students sometimes balk at hypothetical scenarios used in the lab manual to provide context to the experiment. There is some fairness to the objections; the stories are often awkward and far-fetched. That is not really the point. You should include the discussion of context in your report. Think of it as the part where you justify yourself to your oversight committee or funding agency. The realism you perceive in the story is not important; the skill that it helps to develop is.

Predictions

You should include the same predictions in your report that you made prior to the beginning of the experiment. They do not need to be correct. If they do turn out to be correct, then you must prove that they are so by means of your analysis. If they do not, then you must prove that, too, and explain the reality exposed by your analysis. Either way, you will be doing the same work; only a few words will change. You will receive far more credit for an incorrect, well refuted prediction than you will for a correct, poorly supported one.

The lab manual will often ask you for an equation or a graph as your prediction. Just as they cannot in any other part of the report, these things cannot stand by themselves. You must discuss them in prose.

Your prediction will often be expressible as an equation that you can derive from the physical principles and formulas that you will learn in the lecture portion of this class. If so, then you should include a brief, mathematical derivation of that prediction. You should not include every step in the calculation, but only the ones which constitute important, intermediate results.

Procedure

You should explain what your actual, experimental methodology was in the procedure section. You should discuss the apparatus and techniques that you used to make your measurements.

You should exercise a little conservatism and wisdom when deciding what to include in this section. You should include all of the information necessary for someone else to repeat the experiment, but only in the important ways. It is important that you measured the time for a cart to roll down a ramp through a length of one meter; it is not important who released the cart, how you chose to coordinate the person releasing it with the person timing it, or which one meter of the ramp you used. You should also omit any obvious steps. If you performed an experiment using some apparatus, it is obvious that you gathered the apparatus at some point. If you measured the current through a circuit, it is obvious that you hooked up the wires. One aspect of this which is frequently problematic for students is that a step is not necessarily important or non-obvious just because they find it difficult or time-consuming. Try to decide what is scientifically important, and then include only that in your report.

Students approach this section in more incorrect ways than any other. You should not provide a bulleted list of the equipment. You should not present the procedure as a series of numbered steps. You should not use the second person or the imperative mood. You should not treat this section as though it is more important than the rest of the report. You should rarely make this the longest, most involved section.

Data

This will be your easiest section. You should record your empirical measurements here: times, voltages, fits from MotionLab, etc.

You should not use this as the report's dumping ground for your raw data. You need to think about which measurements are important to your experiment and which are not. For example, consider a lab wherein you measure acceleration by fitting position and velocity as functions of time. You probably will have estimated some of the coefficients in the fits by making measurements with a meter stick and stopwatch. However, because those "by hand" measurements do not contribute to values of the acceleration that you actually used in your analysis, you should not record them in your report. You may not even need to record the fit functions themselves; it would be appropriate for you just to include the corresponding values of acceleration.

You should also only include data in processed form. Use tables, graphs, and etc. with helpful captions, not long lists of measurements without any logical grouping or order.

Remember to include the uncertainties in all of your measurements.

There is some exception to the "smoothly integrate figures and tables" rule in this section. You should actually include little to no prose in the Data section; most of the discussion of this information actually belongs in the Analysis section. The distinction between the Data and Analysis sections exists largely to make the interpretation of your report easier on your TA.

Analysis

You should do the heavy lifting of your lab report in the Analysis section. This is where you should take the empirical data that you included in the Data section, perform some kind of scientific analysis on it, present your results, and finally answer the question that you posed in your Introduction. You *must* do this quantitatively. This is arguably the most important section of your report, and it has any scientific meaning only if it is quantitative.

Your analysis will almost always amount to quantifying the errors in your experimental measurements and in any theoretical calculations that you made in the Predictions section. You should then answer the following question: are the error intervals in my measurements and predictions consistent with one another? If you are measuring some quantity, say a voltage V, then you need to see whether the error intervals for the experimental value V_e and the theoretical value V_t overlap. If you are trying to confirm some functional form, say, $x(t) = 3t + 12$, then you need to determine whether or nor your fit function passes through the error regions for your experimental data points (t_e, x_e). This manual contains an appendix about error analysis: read it, understand it, and take it to heart.

If your prediction turns out to be incorrect, you should show that it is incorrect as the first part of your analysis. You should then propose the correct result, which your TA should have helped you determine before you left lab, and show that it is, in fact, correct as the second part of your analysis.

You should finally discuss any shortcomings of your procedure or analysis. This includes sources of systematic error for which you did not account, approximations that are not necessarily valid, etc. You should try to decide how badly these shortcomings affected your result. If you confirm your prediction to a high degree, then you can probably dismiss them as insignificant. If you cannot, then you should estimate which are the most important and how they might be addressed in the future.

Conclusion

You should consider your conclusion as the wrapping paper and bow tie, the finishing touches, of your report. At this point, all of the important things ought to have already been said, but this is where you collect them together in one place. You should remind your audience of the important points of your report: what you did and what your result was. You should leave her with a sense of closure.

A good way to go about doing this is to quote your result from the Analysis section and to interpret it in the context of the hypothetical scenario that you discussed in your Introduction. If you determined that there were any major shortcomings in your experiment, you might also propose future work in which the experiment could be done so as to overcome them. If the Introduction included your attempt to justify your funding, then the Conclusion includes your attempt to secure more for the future.

One way to evaluate whether or not your Introduction and Conclusion work well together is to read them in the absence of the intermediate sections. Imagine that you are the person who hired you to perform this work, and that you are so busy that you don't have time to read the whole report. If you can tell what the purpose of the experiment was and what question it was trying to answer in the Introduction, and if you can tell what the answer to that question was in the Conclusion, then chances are good that you have written a solid report.

What Now?

You should now read the sample reports included in this manual. There are two; one is an example of the advice in this document implemented well, and the other is an example of the advice in this document implemented poorly. Hopefully, they should help to clear up any lingering questions about what any of this means. It might be helpful to read the sample reports, then re-read this document, examining the relevant parts of the samples as they are discussed herein.

You should then talk to your TA. She can answer any remaining questions you have and can tell you her preferences about how you should write your report for her, specifically. She can tell you when something written above might not quite apply to a particular experiment. At the end of the day, she determines what is right and what is wrong, so communication is important — and by communication, we do not mean one frantic email that you write to her at 11:30 the night before the report is due.

There is a lot of information here, so implementing it and actually writing your lab report might seem a little bit overwhelming. If so, then go back to the idea that the most important part of the report is the argument. Go back to the idea that the lab report seeks to answer a question. Go back to the idea that the product of the lab report is not so much the answer but the process by which you find it. You should complete your analysis and answer the question before you ever sit down to write your report. At that point, the hard part of the writing should be done: you already know what the question was, what you did to answer it, how the analysis was performed, and what the answer was. You then just need to put that on paper.

GOOD SAMPLE LAB

Lab II, Problem 1: Mass and Acceleration of a Falling Ball
John Porthos
July 13, 2011
Physics 1301W, Professor Matthew, TA Caspar

Abstract

The mass dependence of the acceleration due to gravity of spherical canisters was determined. Balls of similar sizes but varying masses were allowed to fall freely from rest, and their accelerations were measured. The mass independence of acceleration due to gravity was confirmed by the X^2 goodness-of-fit test.

Introduction

The National Park Service is currently designing a spherical canister for dropping payloads of flame-retardant chemicals on forest fires. The canisters are designed to support multiple types of payload, so their masses will vary with the types and quantities of chemicals with which they are loaded. To ensure accurate delivery to the target and desired behavior on impact, the acceleration of the canisters due to gravity must be understood. This experiment therefore seeks to determine the mass dependence of that acceleration.

Prediction

It is predicted that the acceleration of a spherical canister in free fall is mass- independent, as illustrated in Figure 1. The acceleration due to gravity of any object near the surface of Earth is assumed to be local g, and there is no reason to expect anything else in these circumstances. Mathematically,

$$\frac{d\vec{a}}{dm} = \vec{0}$$

Procedure

Spherical balls were dropped a height of 1m from rest. Their sizes were approximately the same, and their masses varied from 12.9g to 147.6g. Their free-fall trajectories were recorded with a video camera; MotionLab analysis software was used to generate (vertical position, time) pairs at each frame in the trajectories and, by linear interpolation, (vertical velocity, time) pairs between each pair of consecutive frames in the trajectories. A known 1-meter length was placed less than 5cm behind the balls' path for calibration of this software. The position and velocity of each ball as functions of time were fit by eye as parabolas and lines, respectively. The acceleration of each was then taken to be the acceleration as determined from velocity, as this was deemed more reliably fittable by eye than quadraticity.
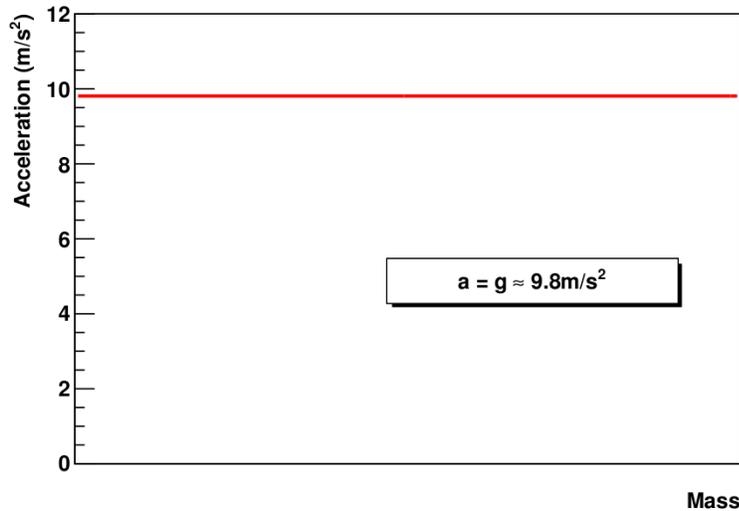
Figure1: Magnitude of acceleration due to gravity with respect to mass of a spherical container near Earth's surface; the dependence is predicted to be trivial.

Data

M(g)	a(m/s^2)
12.9	9.6
48.8	10.2
55.8	9.8
56.7	9.9
57.7	10.0
143.0	9.7
147.6	9.7

Table 1: The masses and magnitudes of acceleration of the 7 balls tested in this experiment. The uncertainties in all of the masses are 0.3g. The uncertainties in the accelerations are unknown; see the Analysis section for more information.

Analysis

The accelerations as measured by the velocity fits are given in Table 1 in the Data section. The errors therein were difficult to determine because of the by-eye fitting procedure used by MotionLab. In principle, errors could have been assigned to the fits by finding the maximal and minimal values of the parameters which yield apparently valid fits, but not all groups performed such an analysis, and this group did not have access to the raw data necessary to do so themselves. A method of analysis which does not rely on the errors in the individual accelerations was therefore attempted. In keeping with the hypothesis, the empirical accelerations were treated as independent measurements of local g. A constant was then fit to the data, and the X^2 goodness-of-fit test was used to determine the validity of the hypothesis. The fit is depicted in Figure 2. This yielded a minimal X^2/NDF = 0.042 at $a = (9.84 \pm 0.08)$m/s. The associated p-value is $p = 0.9997$.

Several potentially important sources of error have not yet been addressed. One is the distortion effect of the camera; data was taken only from the center-most portion of the field of view to limit this effect. Another is air resistance; this was assumed to be negligible. Yet another is improper alignment of the calibration object and camera with the balls' trajectories and with one another; this was minimized by the use of a plumbob. Another is the likely nonzero velocity imparted during release; this was intentionally minimized and then assumed to be negligible. Ultimately, it is not believed that these have significantly affected the result because of the very high p-value of the resulting fit. There is possibly significant systematic error in the mean of the fit acceleration, but the confidence interval is greater than the deviation of this value from the predicted result($0.08 >| 9.81 - 9.84 |= 0.03$), and this does not affect the first derivative, which is constrained to be 0 by the analysis.
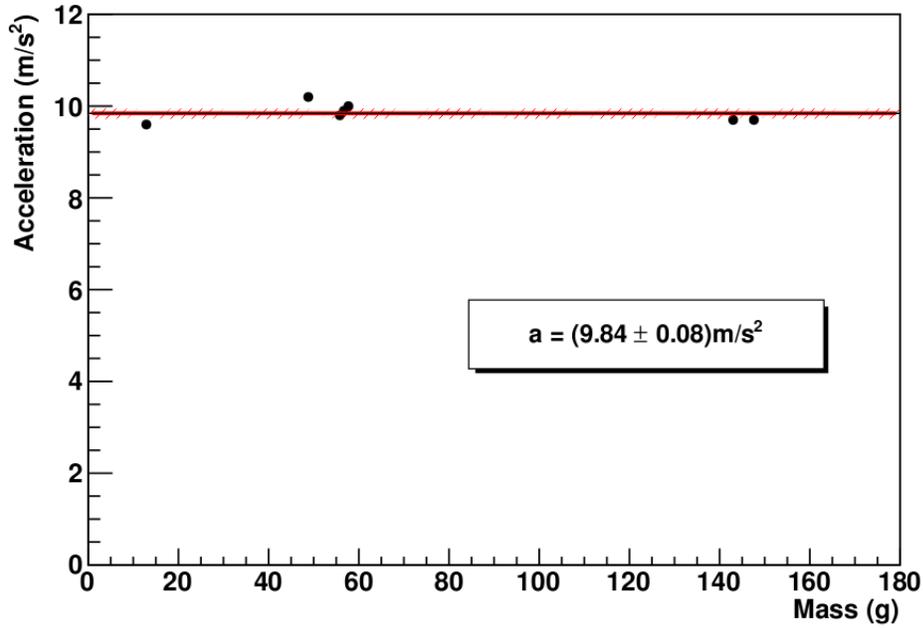
Figure 2: The measured magnitudes of acceleration versus the respective masses, and the constant fit derived therefrom.

Conclusion

Spherical canisters in free-fall were modeled with dropped balls. The mass- independence of the acceleration was confirmed to $p = 0.9997$. This result implies that the National Park Service need not concern themselves with the payload masses of the canisters insofar as gravity is concerned. This result is not to be taken to imply that mass is totally irrelevant, as it may still have significant effects on acceleration due to wind, etc.

BAD SAMPLE LAB

Lab II, Problem 1
Clotho Alecto
July 13, 2011
Physics 1301W, Professor Matthew, TA Caspar

Introduction
We seek to determine how mass affects the acceleration due to gravity of spherical canisters filled with chemicals to fight fires. To do this, we dropped balls from a known height. We used VideoRecorder to record videos of them falling, being as careful as possible to simulate the falling canisters accurately and to minimize errors. We analyzed the videos with MotionLab, taking several data points for each ball.

Prediction
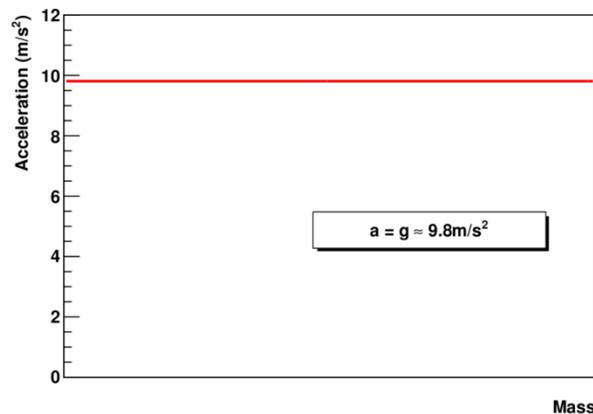
Procedure
We performed this experiment by a scientific procedure. We first made a prediction; then, we performed the experiment; then, we analyzed the data; then, we drew a conclusion.

We began by gathering the materials. They included:
- meter stick
- several balls of similar size but different masses
- video camera on tripod
- computer
- tape

We taped the meter stick to the wall for the calibration of MotionLab. We faced the camera toward the wall. We dropped a street hockey ball with a mass of 57.7g and recorded its video using VideoRecorder. We then analyzed its motion using MotionLab. This began with calibration. We first set time zero at the exact time when we dropped the ball. We then had to calibrate the length. We put the meter stick in the frame of the video, so we used it to do this. We then defined our coordinate system so that the motion of the ball would be straight down.

We then made predictions about the motion. We predicted that the x would not change and that the y would be a parabola opening down with C=-4.9m/sˆ2. The predicted equations were x(z)=0 and y(z)=-4.9zˆ2.

We then had to acquire data. We measured the position of the ball at each frame in the video, starting at t=0. We put the red point at the center of the ball each time for consistency. This was important to keep from measuring a length that changed from frame to frame based on where we put the data point on the ball. We also did not use some of the frames at the end of the video, where the ball was at the edge where the camera is susceptible to the fisheye effect and where the ball was not in the frame.

When this was finished, we fit functions to the data points. The functions did not fit the points exactly, but they were acceptably close. We fit x(z)=0 for the x position and y(z)=-5z^2 for the y position. These were close to our predictions.

It then came time to make predictions of the velocity graphs. We predicted that the Vx graph would be a straight line with Vx(z)=0 and that the Vy graph would be a linear line with Vy(z)=-10z.

Next, we fit the functions to the data points for the velocity graphs. We got the predictions exactly right.

We then printed our data for the street hockey ball and closed MotionLab.

We repeated this process for a baseball with a mass of 143.0g. It was mostly the same, with some exceptions. The y(z) fit was y(z)=-4.85z^2 instead of y(z)=-5z^2. The Vy(z) prediction was Vy(z)=-9.7z instead of Vy(z)=-10z. These were also exactly right, so the Vy(z) fit was the same.

At the end of the lab, everybody put their data on the board so we would have enough to do the analysis. We copied it down. Then we were finished, so we started the next experiment.

Data

Ball 1

mass: 12.9+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-4.8z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-9.6z
Vy fit: Vy=-9.6z

Ball 2

mass: 48.8+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-5.1z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-10.2z
Vy fit: Vy=-10.2z

Ball 3

mass: 55.8+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-4.9z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-9.8z
Vy fit: Vy=-9.8z

Ball 4

mass: 56.7+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-4.95z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-9.9z
Vy fit: Vy=-9.9z

Ball 5

mass: 57.7+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-5.0z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-10.0z
Vy fit: Vy=-10.0z

Ball 6

mass: 143.0+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9z^2
y fit: y=-4.85z^2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-9.7z
Vy fit: Vy=-9.7z

Ball 7
mass: 147.6+/-0.05g
x prediction: x=0z
x fit: x=0z
y prediction: y=-4.9zˆ2
y fit: y=-4.8zˆ2
Vx prediction: Vx=0z
Vx fit: Vx=0z
Vy prediction: Vy=-9.6z
Vy fit: Vy=-9.7z

Analysis

We can calculate the acceleration from the MotionLab fit functions. To do this, we use the formula x = x0+v0t+1/2atˆ2. Then a is just 2 times the coefficient of zˆ2 in the position fits. This gives us
        Ball 1: a=-9.6
        Ball 2: a=-10.2
        Ball 3: a=-9.8
        Ball 4: a=-9.9
        Ball 5: a=-10.0
        Ball 6: a=-9.7
        Ball 7: a=-9.6
The acceleration can also be calculated using the formula v=v0+at. Then
a is just the coefficient of z in the velocity fits. This gives us
        Ball 1: a=-9.6
        Ball 2: a=-10.2
        Ball 3: a=-9.8
        Ball 4: a=-9.9
        Ball 5: a=-10.0
        Ball 6: a=-9.7
        Ball 7: a=-9.7

We know that the acceleration due to gravity is -9.8m/sˆ2, so we need to compare the measured values of the acceleration to this number. Looking at the data from the fits, we can see that they are all close to -9.8m/sˆ2, so the error in this lab must not be significant. Ball 3 actually had 0 error.

We need to analyze the sources of error in the lab to interpret our result. One is human error, which can never be totally eliminated. Another error is the error in MotionLab. This is obvious because the data points don't lie right on the fit, but are spread out around it. Another error is that the mass balance could only weigh the masses to +/-0.05g, as shown in the data section. There was error in the fisheye effect of the camera lens. There was air resistance, but we set that to 0, so it is not important.

Conclusion

We predicted that a would be -9.8m/sˆ2, and we measured seven values of a very close to this. None was off by more than 0.4m/sˆ2, and one was exactly right. The errors are therefore not significant to our result. We can say that the canisters fall at 9.8m/sˆ2. This experiment was definitely a success.