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Kenneth & Patricia Heller

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. We are surrounded by the products resulting from the application of that understanding, technological inventions including clocks, cars, and computers. You have already developed your own physical theories to understand the world around you. Some of these ideas are consistent with the accepted theories of physics while others are not. This laboratory is designed to focus your attention on your interactions with the world so that you can recognize where your ideas agree with those accepted by physics and where they do not.

You are presented with contemporary physical theories in lecture and in your textbook. The laboratory is where you can apply those theories to problems in the real world by comparing your application of those theories with reality. This course is rare in the University for that property. In very few departments are you able to test and see if what was heard in lecture is actually truth. Relish this opportunity to be free from interpretation and relative perspective. If you think the TA, the professor, and the book are incorrect, this is your opportunity to demonstrate it conclusively. The laboratory setting is a good one to clarify your ideas through discussions with your classmates. You will also get to clarify these ideas through writing in a report to be read by your instructor. Each laboratory consists of 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 that the goal is not to make a lot 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 - each serve a different purpose. The laboratory is where physics ideas, often expressed in mathematics, come to grips with the real world. Because different lab sections meet on different days of the week, sometimes you will deal with concepts in the lab before meeting them in lecture. In that case, the lab will serve as a good introduction to the lecture. In other cases, when the lecture about a topic precedes the lab, 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 warm-up 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 G. 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 learn what is true!

WHAT TO DO TO BE SUCCESSFUL IN THIS LAB:



Safety always comes first in any laboratory.

If in doubt about any procedure, or if it seems unsafe to you, do not continue.
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. As such, your lab journal is a legal document; consequently you should **never** tear pages from it. For this reason, your lab journal **must** be bound, for example, University of Minnesota 2077-S, and **not** of the varieties that allow pages to be easily removed, for example 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, you should carefully read the Introduction, Objectives and Preparation sections. Read the sections of the text specified in the *Preparation* section.
2. Each lab contains several different experimental problems. Before you come to a lab, be sure you have completed the assigned *Prediction* and *Warm-Up Questions*. The warm-up questions will help you build a prediction for the given problem. It is usually helpful to answer the warm-up 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 more dull or 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 not be happy 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 is not to be copied or fabricated. To do so constitutes Scientific Fraud. To make sure no one gets in that habit, such behavior will be treated in the same manner as cheating on a test: **A failing grade for the course and possible expulsion from the University.** Your lab report should describe your predictions, your experiences, your observations, your measurements, and your conclusions. A description of the lab report format is discussed at the end of this introduction. **Each lab report is due 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 grade of F for the entire course.* The laboratory grade makes up 15% of your final course grade. 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. Again, a rewrite must be handed in within two days of the return of the report to you by the instructor, in order to obtain an acceptable grade.

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 reasoned mistake. It is in fact, one of the more 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 speech, 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 acceptable to copy the work of others. Helping others is encouraged because it is one of the best ways for you to learn, but copying someone else's work and claiming it as your own is completely inappropriate and immoral. 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 using the Problem Report Form found on the desktop. To use the Problem Report Form you will have to login using your University ID and password. 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.

WHAT IS EXPECTED IN A LAB REPORT? HOW IS IT HANDLED?

1. Before you leave the laboratory, have the instructor assign the problem you will write up and initial your cover sheet.
2. A cover sheet for each problem must be placed on top of each problem report handed in to the instructor. A cover sheet can be found at the end of every lab. *It gives you a general outline of what to include in a report.*
3. A problem report is always due **within two days of the end of the lab.**
4. **A lab report should be an organized, coherent display of your thoughts, work, and accomplishments.** It should be written *neatly* (word processor recommended) in English that is **clear, concise, and correct.** It may help you to imagine that hundreds of people will read your report and judge you by it. **Communication is the goal of the report.** In many cases, communication can be aided greatly by use of tables and graphs.
5. A sample report is included in Appendix G. Listed below are the major headings which most laboratory reports use.

MAJOR PARTS OF A LABORATORY REPORT:

COVER SHEET

See the end of this introduction for a sample cover sheet.

STATEMENT OF THE PROBLEM

State the problem you were trying to solve, and how you went about it. Describe the general type of physical behavior explored, and provide a short summary of the experiment.

PREDICTION

This is a part of the lab where you try to predict the outcome of the experiment based on the general knowledge of Physics. Generally, you start from fundamental laws or principles and derive the theoretical expression for the measured quantity. Later you are going to use your prediction to compare with experimental results.

EXPERIMENT AND RESULTS

Following the problem statement is a Data and Results section, containing a detailed description of how you made your measurements and what results you obtained. This usually involves an organized and coherent display of labeled diagrams, tables of measurements, tables of calculated quantities, and graphs. Explanations of all results must occur in correct grammatical English that would allow a reader to repeat your procedure.

Mathematical calculations connecting fundamental physics relationships to the quantities measured should be given. Any interesting behavior should be explained. Difficulties performing the experiment should be described as well as any subtleties in the analysis.

All data presented must be clearly identified and labeled. Calculated results should be clearly identified. Anybody should be able to distinguish between quantities you measured, those you calculated, and those you included from other sources. Clearly assign uncertainties to **ALL** measured values -- **without uncertainties, the data is nearly meaningless.**

CONCLUSIONS

The Conclusions section should include your answers to the following questions: What generalized behavior did you observe? Was it different from what you expected? Why? (e.g. What were the possible sources of uncertainties? Did you have any major experimental difficulties?) How do your results compare with the theory presented in your textbook or during lectures? Can you think of any other ways to check your theory with your data?

SAMPLE COVER SHEET

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 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 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 $g = 9.8 \text{ m/s}^2$.) 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 Fishbane: Chapter 3, section 4; Chapter 22.

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.

SIMULATION 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 EM Field.

PREDICTION

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

WARM-UP QUESTIONS

Read: Fishbane Chapter 22 Section 1. It also might be a good idea to review Chapter 1 Section 6.

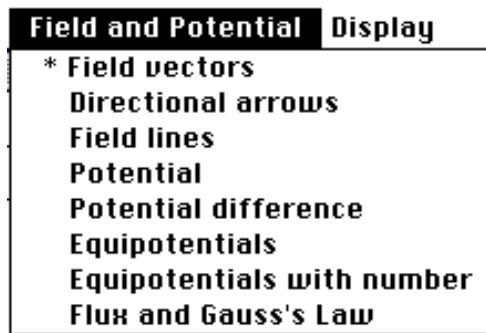
1. Draw a positively charged point object.
2. Consider a point in space some distance from that object. What is the direction of the electric field vector at this point? Remember that you can understand the electric field by considering the electric force on a positive “test charge” placed at that point.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

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

On the desktop, open EM Field 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 EM Field. Select *Field vectors* from the *Field and Potential* pull-down menu (as shown).



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 may want to use the *Show grid* and *Constrain to grid* features in the *Display* pull-down menu to position your dipole. Using your favorite electric field representation, make a map of the electric field caused by a dipole. Make sure that you carefully 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 (select *Print Screen* from the *File* pull-down menu).

Look at the electric field diagram for your dipole. Where is the electric field the greatest? The least?

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?

CONCLUSIONS

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 in the diagram?

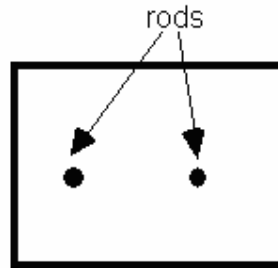
Suppose you placed a positively charged point object near the dipole. If the object began at rest, how would it move? Be careful not to confuse the acceleration of an object (determined by the total force on that object) with the velocity of the object. Try placing your object at several different points.

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.

EQUIPMENT

You will be using the conductive paper setup described in Appendix D. There is a coordinate grid drawn 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 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 grid similar to the grid on the conducting paper is useful for recording the field (do not write on the conductive paper).



Overhead view of
conductive paper for this
problem.

PREDICTION

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

WARM-UP QUESTIONS

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. To understand electric field you can imagine a positively charged object at that point and consider the force on that “imaginary” charged object. 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?

EXPLORATION

You can compare your prediction with a field map of *2D charged rods* produced by the [EM Field](#) simulation program, located on the desktop. 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 power supply. 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 center of the probe stays in the same spot. 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?

MEASUREMENT

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.

<p style="text-align: center;">CONCLUSIONS</p>

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?

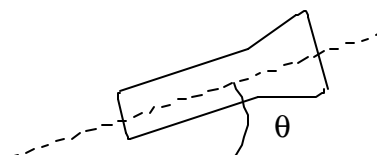
PROBLEM #3

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 QUESTIONS

Read: Fishbane Chapter 22 Section 4 and review Chapter 3 Section 4.

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 battery or power supply creates an applied electric field. A high voltage power supply supplies the energy used to give the electron its initial velocity.

PREDICTION

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

WARM-UP QUESTIONS

For this problem, review Projectile Motion [Fishbane, 3-4], Motion of a Charge in a Field [Fishbane, 22-4] and Appendix D [lab Manual]:

These questions are similar to those for Problem #5. If you have already completed Problem #5, 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 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.

If you have already learned about potential differences, you may not need the following hint <based on Fishbane section 24-2; also see problem 24-24>: the magnitude of the work done on the electron by the accelerating voltage equals V_{acc} times the electron charge.

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.

If you have already learned about potential differences, you may not need the following hint <from Fishbane 24-5>: 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.

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

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.

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.

CONCLUSIONS

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 QUESTIONS

For this problem, review Projectile Motion [Fishbane, 3-4], Motion of a Charge in a Field [Fishbane, 22-4] and *Appendix D* [lab Manual].

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.

If you have already learned about potential differences, you may not need the following hint <based on Fishbane section 24-2; also see problem 24-24>: the magnitude of the work done on the electron by the accelerating voltage equals V_{acc} times the electron charge.

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. If you have already learned about potential differences, you may not need the following hint <from Fishbane 24-5>: 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

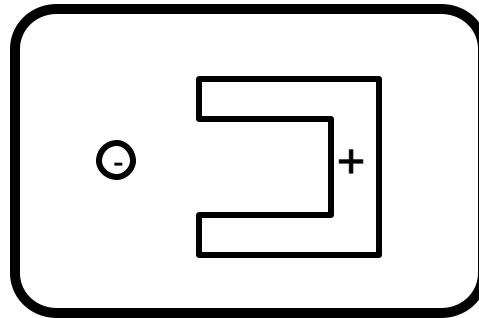
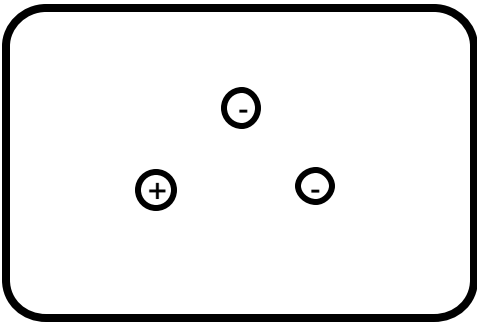
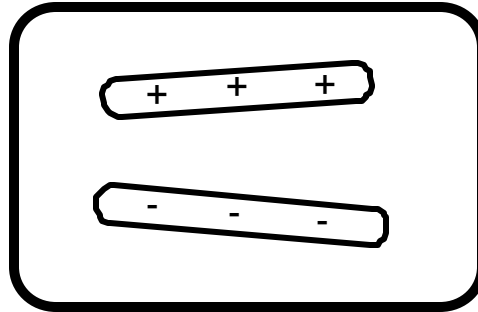
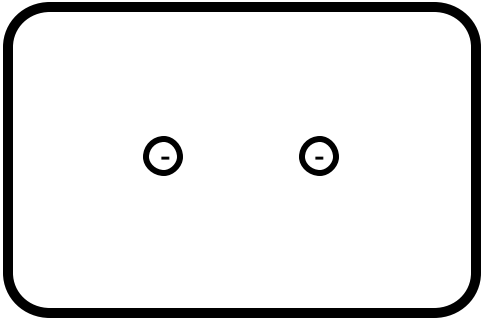
Draw a graph of your average measurements of the deflection of the electron beam as a function of the initial electron velocity. How do your uncertainties affect your graph?

CONCLUSIONS

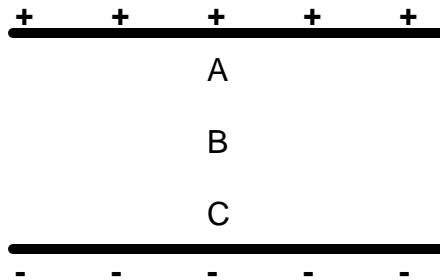
Did your data agree with your prediction of how the electron beam would deflect due to the initial electron velocity? If not, why? How does the deflection of the electron beam vary with initial electron velocity? State your results in the most general terms supported by your data.

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 V_x plate to the fluorescent screen is 10 cm and the distance from the center of the V_y plate to the screen is 8 cm. If V_{acc} is 300V, $V_x = -8V$ and $V_y = 3V$, 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.



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 rewrite that section only 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: Fishbane Chapters 22, 24.

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.

SIMULATION 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 EM Field 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?

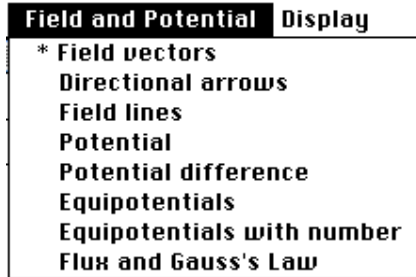
WARM-UP QUESTIONS

Read: Fishbane Chapter 22. Read carefully Sections 22-1 and 22-2 and Examples 22-3 and 22-4.

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

On the desktop, open EM Field 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 EM Field. From the *Field and Potential* pull-down menu (shown to the right), select *Field vectors*.



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 *Clean 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; besides, keep in mind that you will be adding a positive charge of $1/3$ the magnitude.) Add the positive charge. 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.

CONCLUSIONS

Did the result of your calculations using the 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.

SIMULATION 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.

EQUIPMENT

The computer program [EM Field](#) 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 QUESTIONS

Read: Fishbane Sections 22-1, 22-2, and 22-3.

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 $d\mathbf{E}$ 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. The integral(s) from the previous step are conceptually

straightforward but cannot be evaluated directly; the integrand(s), including dq , must be re-written in terms of a different integration variable. What is an appropriate integration variable in this case? Determine appropriate limits for the new integration variable. 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 EM Field 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 EM Field 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.

SIMULATION 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 [EM Field](#) 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 QUESTIONS

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

From the desktop, open [EM Field](#) 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 EM Field. 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.



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 button. 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 you used in the data that you took, 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 should in each case?

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.

SIMULATION 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.

EQUIPMENT

The computer program EM Field and a ruler.

PREDICTION

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

WARM-UP QUESTIONS

Read: Fishbane Chapter 24. Pay particular attention to Sections 24-2 and 24-5 and Examples 24-9, 24-10 and 24-11.

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. The integral from the previous step is conceptually straightforward but cannot be evaluated directly; the integrand, including dq , must be re-written in

terms of a different integration variable. What is an appropriate integration variable in this case? Determine appropriate limits for the new integration variable. 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.

EXPLORATION

On the desktop open EM Field. 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.

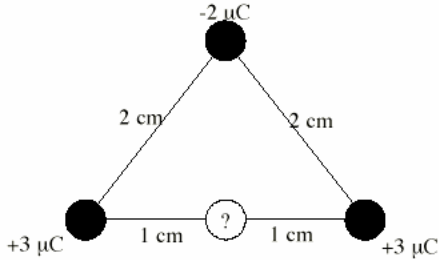
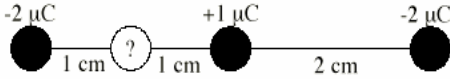
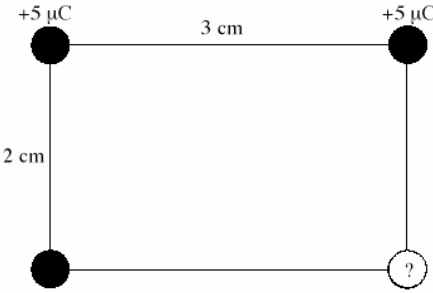
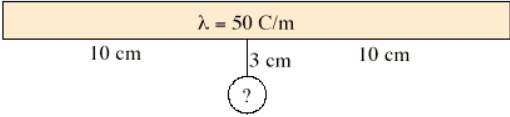
CONCLUSION

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 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 “?”.

 <p>Configuration 1</p>	 <p>Configuration 2</p>
 <p>Configuration 3</p>	 <p>Configuration 4</p>

TA Name: _____

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 Fishbane: Chapter 6, section 1 and section 5; Chapter 25, sections 1-4.

Before coming to lab you should be able to:

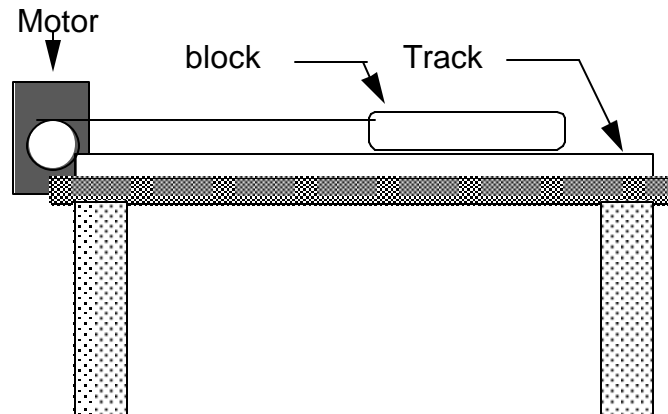
- Calculate the work done by a force exerted on a moving object.
- Calculate the relationship between power and energy.
- Write the equation for the energy stored in a single capacitor and understand the meaning of all the quantities involved.

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. 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 for a motor that drags a block of wood across a table. You calculate how far the block will move as a function of the capacitance of the capacitor, the efficiency of the system, and other properties of the block and table. You assume that you know the initial voltage on the capacitor.

EQUIPMENT

A block of wood, an aluminum track, a motor, 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 QUESTIONS

Read: Fishbane Chapter 25 Sections 1 and 2. Also review Chapter 5 Section 2.

1. Draw pictures of the situation before the block moves, while the block is in motion, and after the block 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. Indicate interactions that transform energy from one form to another or from one object to another.
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. Draw a force diagram for the block while it is in motion. Are there any relevant forces with magnitudes you *can* calculate, in terms of quantities you can measure in the lab? Write equations for those forces. Are there any relevant forces you *can't* calculate in terms of easily measured quantities? Indicate which forces those are.
5. Use the work-energy theorem to write an equation for the net work done on the block. Use this equation and equations from previous steps to write the amount of energy transferred from the capacitor to the block, during the entire process, as a function of the distance the block slides and properties of the block and track.
6. 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 block slides.
7. 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.
8. Sketch a graph of the distance the block slides 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 handle connected wires by their metal ends. **Always discharge a capacitor with a wire 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 block 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 block pulled along the track? Try it for 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? Choose a range of capacitors to give you a good range of distances.

Write down your measurement plan.

MEASUREMENT

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

ANALYSIS

Graph the distance the block is pulled versus the capacitance of the capacitor. 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?

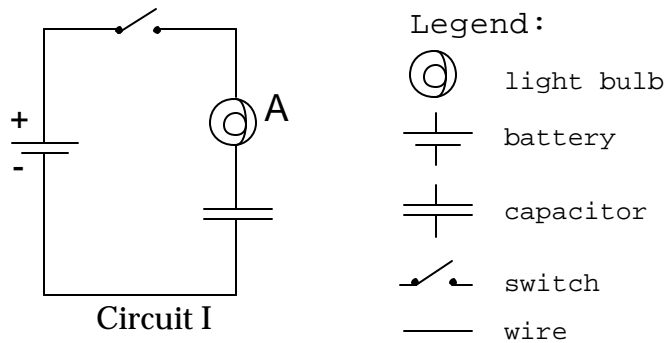
You have heard that energy is always conserved. Is it appropriate to say that energy was conserved in this situation? Why or why not?

EXPLORATORY 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).



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 with a wire 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 over the same time? 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.

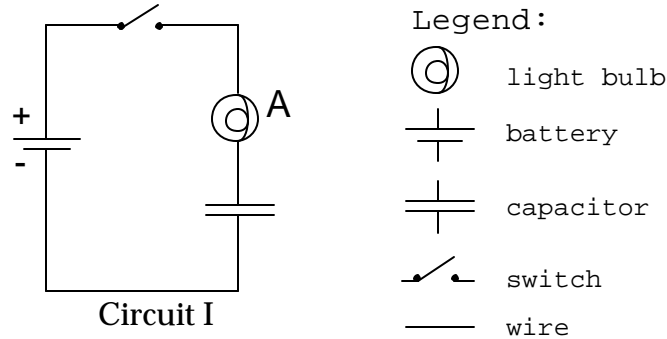
Sketch a qualitative graph of the brightness of the bulb as a function of time after you complete the circuit consisting of the *initially charged* capacitor, NO battery and light bulb. Sketch a qualitative graph of the charge on the capacitor as a function of time for this situation. Describe how this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

EXPLORATORY 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.

EQUIPMENT

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



PREDICTION

Restate the problem. What is the variable you will be measuring and what is the variable 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 after 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

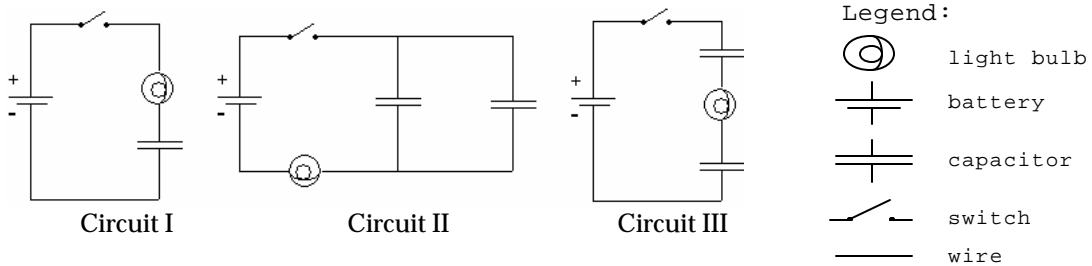
How did your measurement compare with your prediction? Using conservation of charge, conservation of energy, and the model of a capacitor as two plates separated by a short distance, explain how the capacitance affects the time it takes for the bulb to turn off.

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.



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. 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 QUESTIONS

Read: Fishbane Chapter 25 Section 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 only 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?

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.

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

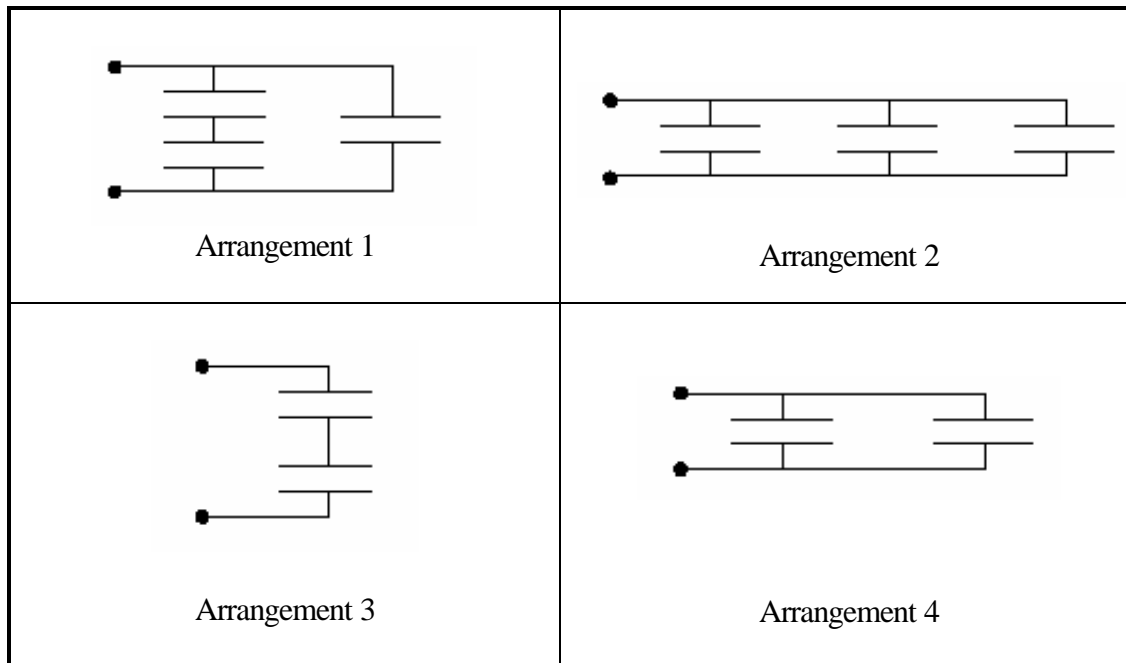
How did your initial ranking of the time it would take for the bulbs to go out compare with what actually occurred? Use conservation of charge, conservation of energy, and the concept of potential difference to explain your results.

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 $10 \mu\text{C}$.
- 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 $10 \mu\text{C}$.



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, the most familiar 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 ubiquitous 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 Fishbane: Chapter 24 section 1; Chapter 25, sections 1, 2, 4; Chapter 26,27. 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.




EXPLORATORY PROBLEM #1 SIMPLE CIRCUITS

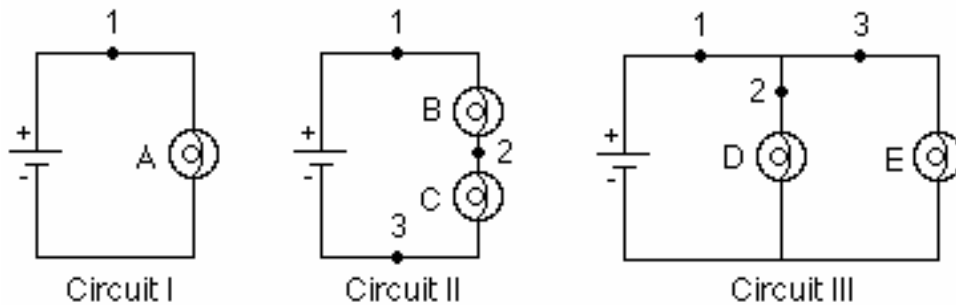
You need more light in your workroom, so you decide to add another light fixture to your track lighting. However, you are concerned that adding another light may dim the lights that are already in the track. When you proceed with the addition of another light, you notice that none of the lights are dimmer 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 bulb
 battery
 wire



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, 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.

PROBLEM #1: SIMPLE CIRCUITS

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?

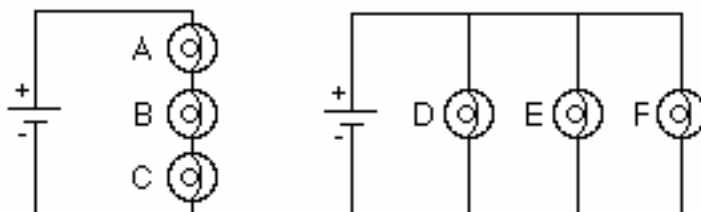
Comparing the three circuits, does the amount of current at point 1 appear to remain constant or to depend on the number of bulbs and how they are connected?

CONCLUSIONS

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.

EXPLORATORY PROBLEM #2 MORE COMPLEX CIRCUITS

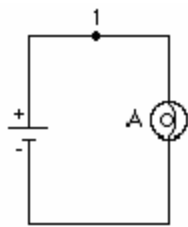
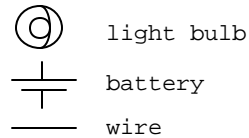
It is the holiday season once again so you have decided to put up your decorations. You have three strings of decorative lights and only one electrical outlet between the tree and your doorway. To have enough lights to cover the tree, you will need to connect two of your light strings together end to 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

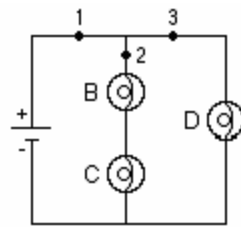
You will build four simple circuits shown below out of wires, bulbs, and batteries.

Use the accompanying legend to build the circuits.

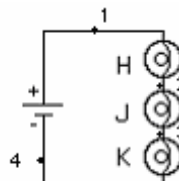
Legend:



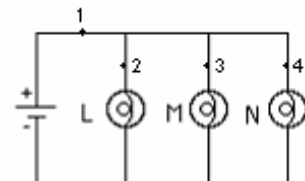
Circuit I



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?

CONCLUSIONS

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?




EXPLORATORY PROBLEM #3 SHORT CIRCUITS

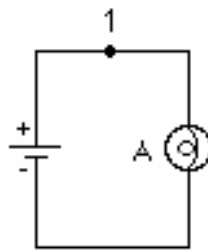
A friend of yours who manages a movie theater is having a problem with the lights that surround the marquee. Some of the light bulbs don't light up. But when he takes out the bulbs and checks them individually, they all work. You tell him he must have a short circuit. You explain that you have a short 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

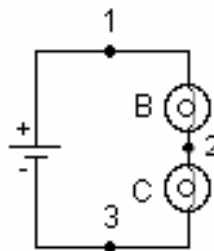
You will build three simple circuits shown below out of wires, bulbs, and batteries.

Use the accompanying legend to build the circuits.

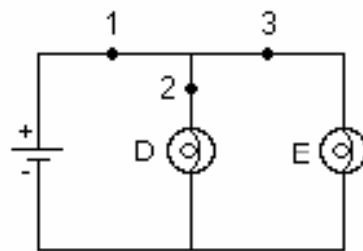
Legend:
 light bulb
 battery
 wire



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).



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 QUESTIONS

Read: Fishbane Section 27-5.

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.

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 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.

CONCLUSIONS

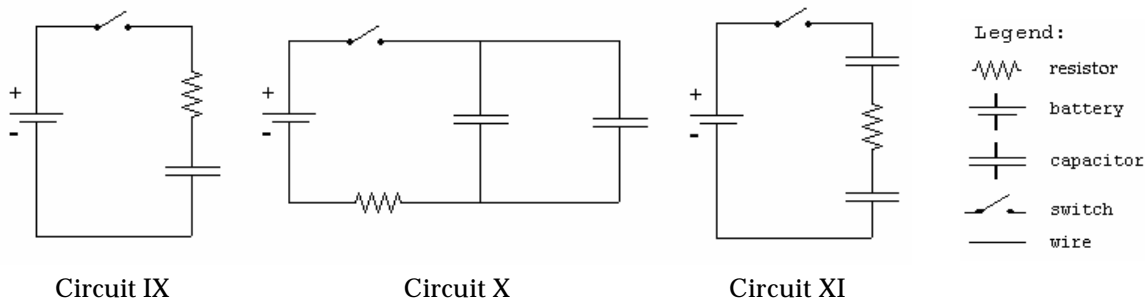
Describe which of your predictions were confirmed by experiments and draw conclusions accordingly. To continue conclusions, explain what was incorrect in those of your predictions that your laboratory observations or measurements did not support (or what went wrong with the experiment that failed to 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 is 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.



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 QUESTIONS

Read: Fishbane, Sections 25-4 and 27-5.

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.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Review your exploration from Problem #4.

PROBLEM #5: CIRCUITS WITH TWO CAPACITORS

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.

CONCLUSIONS

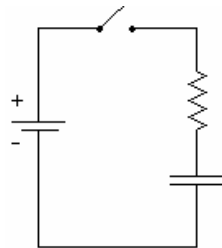
How well did your graphs drawn from your data compare to those in your predictions? Explain any differences. How did your predicted rankings of the time each bulb would remain lit compare to your measurements? Explain any differences.

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

Legend:

~ ~ ~	Resistor
+ -	Battery
— —	Capacitor
—	Wire
/ \	Switch

PREDICTION

In a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series, calculate the dependence of 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 $\frac{1}{2}$, $\frac{1}{4}$, ? ... of its initial value).

WARM-UP QUESTIONS

Read: Fishbane, Sections 25-4 and 27-5.

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?

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.

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 $\frac{1}{2}$, $\frac{1}{4}$, ? ... of its initial value.

CONCLUSIONS

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

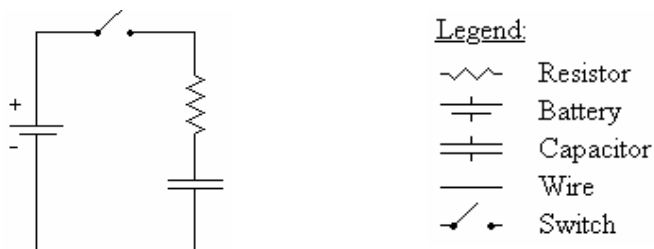
Using these times for successive halving of the current, can you determine how long it would take for the current to fall to zero? Does this agree with your experimental evidence?

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.

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

For a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series, how does the time taken 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 taken for the current to fall to half its initial value against the resistance of the resistor.

WARM-UP QUESTIONS

Read: Fishbane, Sections 25-4 and 27-5.

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. Sketch a graph of this time against the resistance of the resistor.

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 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

Using the measured value of the capacitance of the capacitor, construct a graph showing how the time it takes the current to halve should depend on resistance in the circuit. This is based on the theory, as you use a formula. Now construct a graph of the measured times against resistance, using your experimental data.

CONCLUSIONS

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 QUESTIONS

Read: Fishbane section 26-3.

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?

CONCLUSIONS

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.

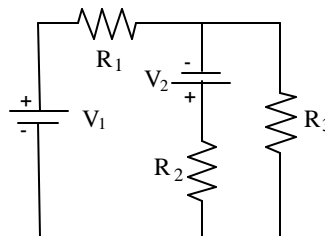
PROBLEM #9 QUANTITATIVE CIRCUIT ANALYSIS (PART A)

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 them 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 QUESTIONS

Read: Fishbane, Section 27-3. Pay attention to the examples 27-55, 27-6, and 27-7.

1. Draw and label a circuit diagram, showing all voltages and resistors. You may need to redraw the given circuit to see which resistors are in series and which are in parallel. For this problem, the voltages and the resistors 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.

CONCLUSIONS

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.

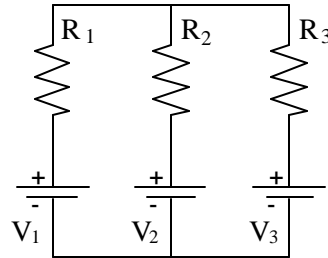
PROBLEM #10 QUANTITATIVE CIRCUIT ANALYSIS (PART B)

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 QUESTIONS

1. Draw and label a circuit diagram showing all voltages and resistors. Sometimes you may need to redraw the given circuit to help yourself see which resistors are in series and which are in parallel. For this problem, the voltages and the resistors 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.

CONCLUSIONS

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

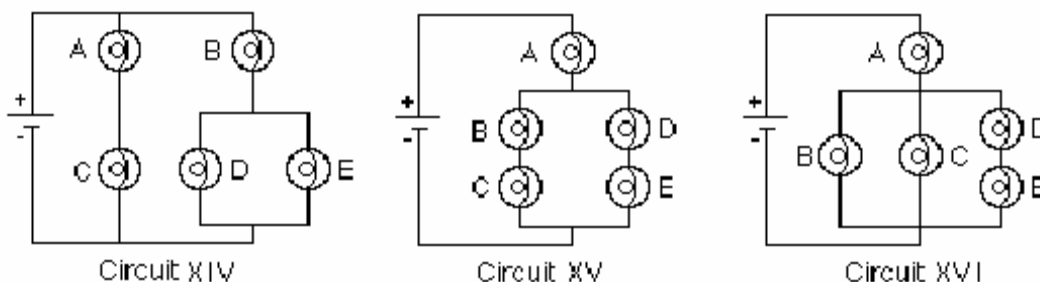
As a check for the consistency of your measurements, calculate the potential difference across each resistor using the currents that you measured. Compare these values with the potential difference across each resistor that you measured with the DMM.

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.



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 does the brightness of a bulb depend on? Then derive 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 text book 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.

CONCLUSIONS

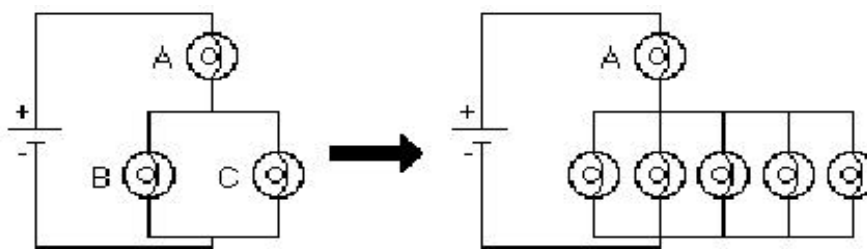
Qualitative circuit analysis is very useful for quickly checking the results of the algebra that come from quantitative circuit analysis. It is a great way to catch mistakes before you fry expensive circuits.

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).

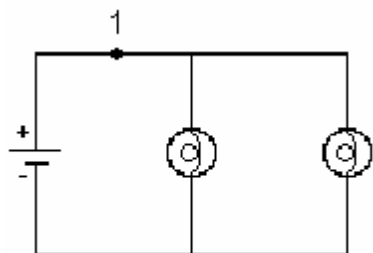
☑ CHECK YOUR UNDERSTANDING

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?

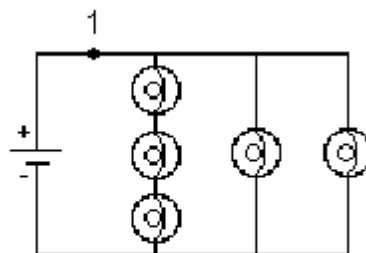


1b. In household circuits, a fuse or circuit breaker is in the position occupied by bulb A, why?

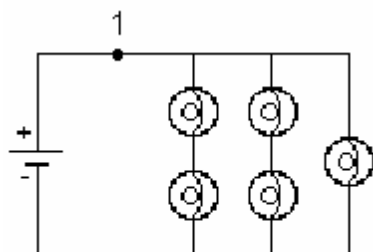
2. In circuits I through IV below, the four batteries supply the same voltage and all bulbs are identical. Rank the circuits from the largest current at point 1 to the smallest current at point 1. Explain your reasoning.



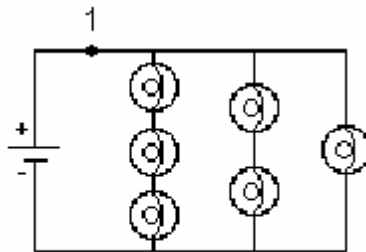
Circuit I



Circuit II

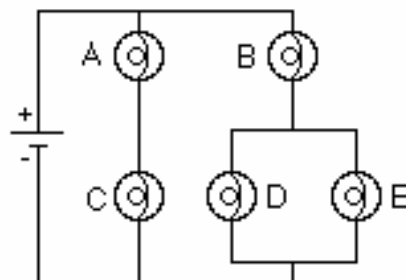


Circuit III



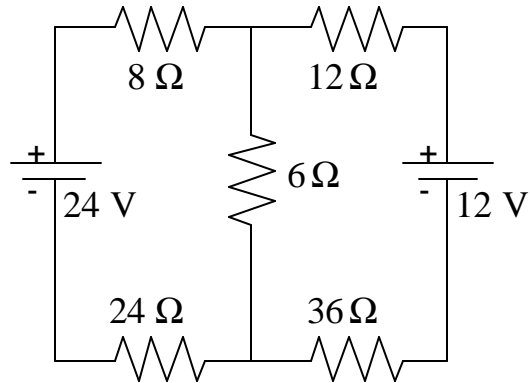
Circuit IV

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.

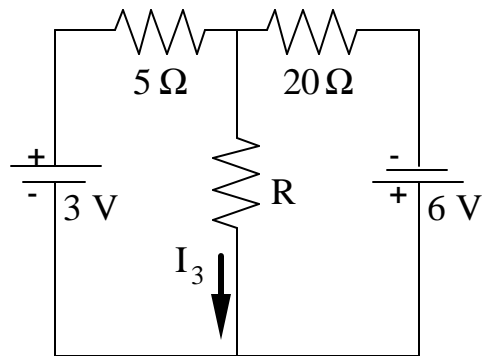


CHECK YOUR UNDERSTANDING

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 I_3 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 Fishbane: Chapter 28, sections 1-5. Review your notes from the first lab (Electric Fields and Forces).

Before coming to lab you should be able to:

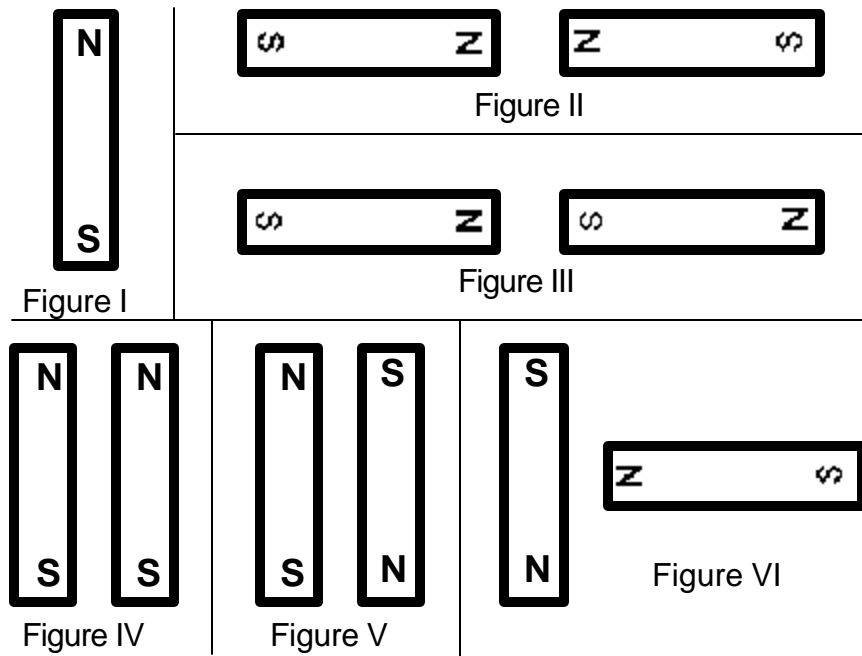
- Add fields using vector properties.
- Use the vector cross product.
- Calculate the motion of a particle with a constant acceleration.
- Calculate the motion of a particle with an acceleration of constant magnitude perpendicular to its velocity.
- Write down the magnetic force on an object in terms of its charge, velocity, and the magnetic field through which it is passing.

PROBLEM #1 PERMANENT MAGNETS

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:



PREDICTION

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

WARM-UP QUESTIONS

Read: Fishbane Chapter 28 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, a length of wire, a meter stick, a power supply, and the EMField application. You will also have a Hall probe and the accompanying software.

PREDICTIONS

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

EXPLORATION

To open the EMField application, just click on the EMField icon on your desktop. 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 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 Hall probe calibration procedure outlined in Appendix E. Be sure the switch on your amplification box agrees with the value on the computer. Why do you rotate the probe 180 degrees for the calibration process? 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 Hall probe 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 FIELDS OF PERMANENT MAGNETS

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 QUESTIONS

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 $\frac{g}{r^2}$ 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 the 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 Hall probe 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.

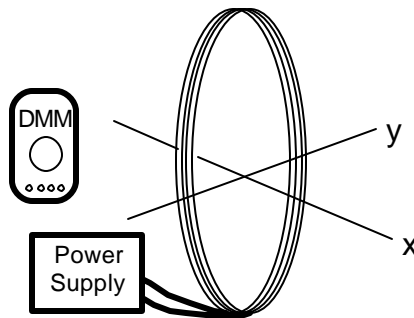
How does the shape of the graph of magnetic field strength versus distance compare to the shape of the graph of electric field strength versus distance, for an electric dipole along each axis? Is it reasonable to assume that the functional form of the magnetic field of a monopole is the same as that 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 coil of 150 turns of wire, 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 [EMField](#) 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 QUESTIONS

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 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?

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 Hall probe 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?

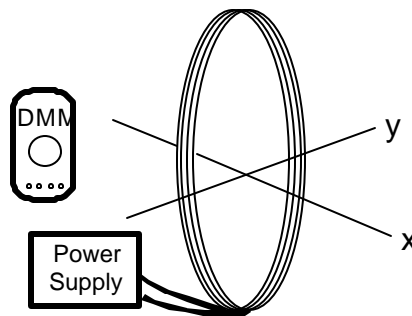
PROBLEM #5 DETERMINING THE MAGNETIC FIELD OF A COIL

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 large, 150 turn 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 QUESTIONS

Read: Fishbane Chapter 29 Section 4.

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 rule out one or more components of the magnetic field at the point of interest?

- 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?

- 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 Hall probe 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

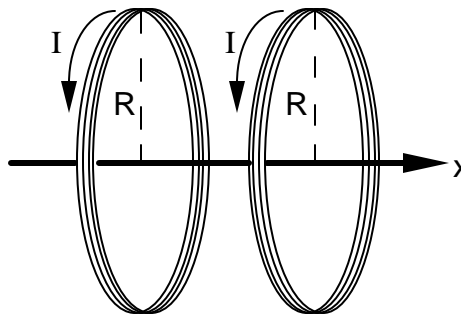
MEASURING THE MAGNETIC FIELD OF TWO PARALLEL COILS

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.

EQUIPMENT

Connect two large coils to a power supply so that each coil has the same current. Each coil has 150 turns.

You will have a digital Multimeter (DMM), a compass, a meter stick, and a Hall probe. A computer is used for data acquisition.



PREDICTION

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

WARM-UP QUESTIONS

Read: Fishbane Chapter 29 Section 4.

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?

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 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 Hall probe 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

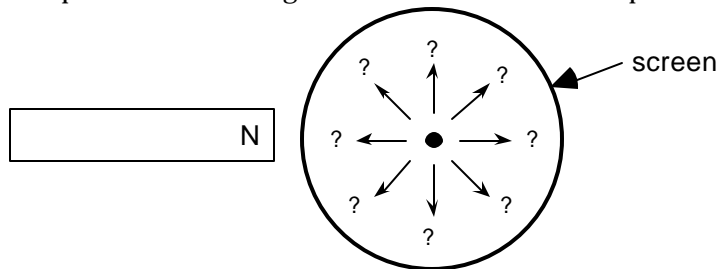
You are leading a technical team at a company that is redesigning the cathode ray tubes (CRT's) used for computer monitors. To introduce this project to a group of stockholders, you need to demonstrate how an electron beam can be moved across a screen by a magnetic field. You decide to use an ordinary 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 variable(s) can you control in the lab? What variables will be fixed for you? Express results in the form of an equation and a graph.

WARM-UP QUESTIONS

Read: Fishbane Chapter 28 Sections 2 and 3.

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, Problem #5 or the Method Questions from that problem.)
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.

EXPLORATION

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.

MEASUREMENT

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.

ANALYSIS

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.

CONCLUSION

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 II

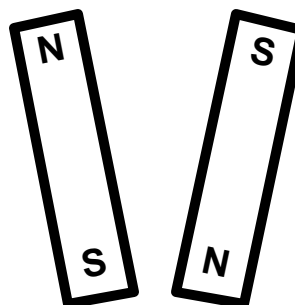


Figure III



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 in the same direction. 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 Fishbane: Chapter 30, sections 1,2.

Before coming to lab you should be able to:

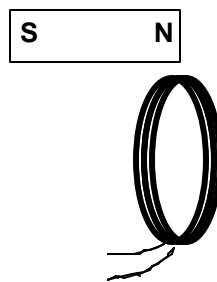
- Use a DMM to measure current, potential difference, and resistance.
- Sketch the magnetic fields from permanent magnets and current carrying coils of wire.
- Use vector addition to combine magnetic fields from several sources.
- Use the right-hand rule to determine the direction of the magnetic fields from circuit loops and wires.
- Use a Hall probe to determine the strength of a magnetic field.
- Use the definition of magnetic flux.

EXPLORATORY 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.

EQUIPMENT

You will have a small coil of wire and a bar magnet. You will use the LabPro interface and the Faraday Probe (*Appendix D*) to convert the potential difference into a digital signal suitable for your computer data acquisition program (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 LabPro interface. Plug the Faraday Probe into the LabPro interface (*Appendix D*). Attach the clips to the two ends of the coil and start the FaradayPROBE 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 .

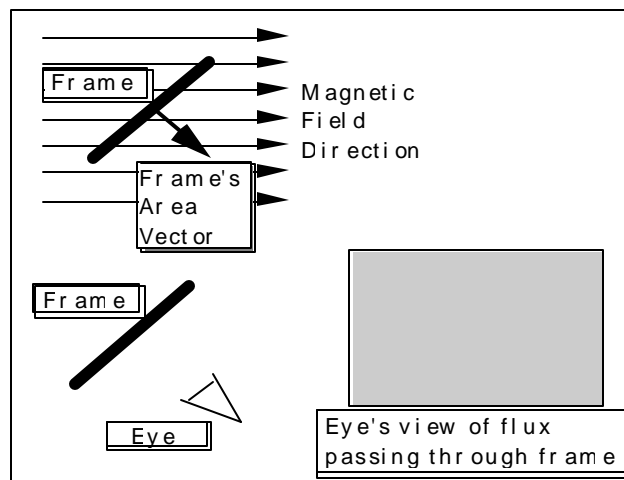
List the important characteristics for inducing a potential difference in the coil of wire. Explain how they are related to the magnitude and sign of the induced potential difference. How do you get the largest potential difference?

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.

EQUIPMENT

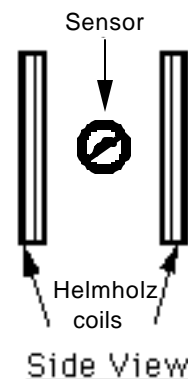
You will use the computer Flux Simulation (see *Appendix E*).



Picture of Flux Simulation Screen

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 (HallPROBE).





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.**

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.

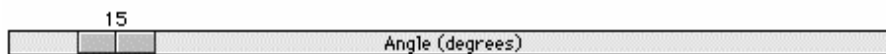
In the simulation program, under what conditions will the “eye see” the most intense blue color? The most intense red color? Will there ever be no color, or white? As the Frame is slowly rotated, will the transitions in intensity be sudden, or gradual? Is the change in intensity linear or something else?

WARM-UP QUESTIONS

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.



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

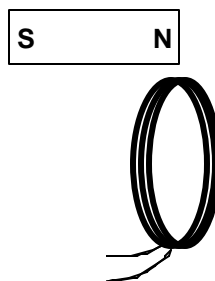
How is the magnetic flux through the coil dependent on the angle it makes with the magnetic field? Is the flux ever zero? When is the flux a maximum? How did the results compare to your prediction?

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 QUESTIONS

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.
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 LabPro interface. Plug the Faraday Probe into the LabPro interface. Attach the clips to the two ends of the coil and start the FaradayPROBE program.

PROBLEM #3: THE SIGN OF THE INDUCED POTENTIAL DIFFERENCE

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.

MEASUREMENT

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.

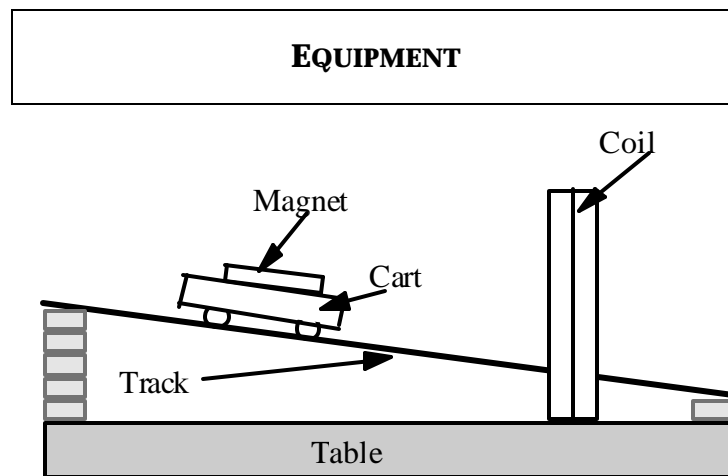
Repeat the measurements, but this time keep the magnet still and move the coil.

CONCLUSION

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.



You will have a large 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 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 QUESTIONS

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. You can 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 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 FaradayPROBE 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 LabPro interface. Plug the Faraday Probe into the LabPro interface. Attach the clips to the two ends of the coil and start the FaradayPROBE 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 FaradayPROBE program update the screen? How much data does it display? You may find that not all of the data captured by the program is displayed; in that case, you will have to time your release of the cart to coincide with the part of the signal being displayed in order to see the signal.

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.

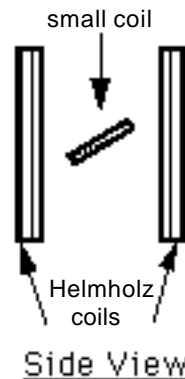
From the computer screen, make a sketch of the shape of the induced potential difference across the ends of the coil as a function of time for one pass of the magnet. Label each feature of the graph and indicate where the magnet is in the coil at that time and why the graph looks like it does at that 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 sits between the Helmholtz coils, as shown to the right. The Helmholtz coils are connected to a power supply. The small coil has 3000 turns of wire, and can be rotated by a motor. The Cenco supply's 0-5volt is used to power the small coil.



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 QUESTIONS

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 as large a magnetic field as you can produce safely with the equipment available. Develop a plan for measuring the magnetic field using the Hall probe. 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.

Before connecting the motor to a power supply (or batteries), disconnect the Hall probe from the LabPro interface (if necessary). Plug the Faraday Probe into the LabPro interface and attach the clips to the two ends of the small coil. The ends of the small coil are attached to terminals (small wires sticking up) located near the bearings on opposite ends of the axle about which the coil spins. Use the time varying voltage LabVIEW™ 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 moving the small coil so that its area vector is perpendicular to the field.

Now connect the motor to a battery (or 0-5 V DC variable voltage on a power 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 connecting it to a different number of batteries or increasing the power supply voltage. 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.

From the computer display of potential difference as a function of time, 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. How can you check your computer display to ensure that the coil is rotating at constant speed?

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?

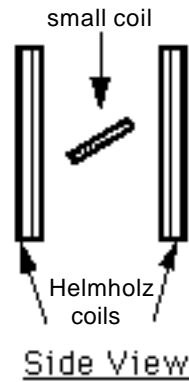
PROBLEM #6 TIME-VARYING MAGNETIC FIELDS

You have been hired by a research team at the University of Minnesota that is developing a new method to electronically detect cancer cells in the lining of a patient's intestine. The patient swallows a small probe, which gathers data as it works its way through the intestine. You can't attach the probe to an external power source, and you decide against asking the patient to swallow a magnet. Instead, 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.

EQUIPMENT

A small "pick-up coil" is mounted between Helmholtz coils, as shown to the right. The small coil has 4000 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 only frequencies of less than 100 Hz.*



You will have a DMM, a magnetic compass, a meter stick, and a protractor. 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 the problem. What do you need to calculate?

WARM-UP QUESTIONS

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 changing current through the Helmholtz coils.)
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 to graph the maximum potential difference vs. the angle.

EXPLORATION

Use the function generator to drive a low frequency alternating current through the large parallel coils of the Helmholtz coils:

- Set the function generator to create a sinusoidal voltage.
- Use the output labeled LO Ω on the function generator to drive the current through the coils.
- Connect the Helmholtz coils in series so that they carry the same current. Should the current go in the same direction or the opposite direction in the two parallel coils to give the most uniform magnetic field between them?

Set the frequency from the function generator to less than 1 Hertz. 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?

Orient the small coil so that the largest magnetic flux passes through it. Attach the DMM to the small coil to read the potential difference across it. Set the DMM to read AC voltage. Slowly change the orientation of the small coil to get the maximum potential difference.

Adjust the amplitude of the signal generator to give the maximum reading on the DMM. At the lowest frequency compare the AC voltage reading to the DC voltage reading. Slowly increase the frequency and observe the results for both AC and DC settings. Decide on the best frequency to use.

Use a Hall probe and the LabVIEW™ application to determine how the magnetic field between the Helmholtz coils varies as a function of time at the frequency you have selected. Note how much time it takes for the computer display to react to any adjustment you make. Try different data sampling times on computer display and select the best one for your situation.

Adjust the amplitude of the function generator to give a magnetic field reading that looks like a sine (or cosine) function. Select the best amplitude for your measurements. How does the magnetic field period on the computer display compare to the frequency of the function generator? What happens to the amplitude of the magnetic field as you change the frequency of the function generator?

Select a range of angles to use in your measurement and note the range of magnetic field amplitudes you expect for the signal generator frequency and amplitude you have chosen to use.

The magnetic field is just the Hall probe reading (a voltage) times a calibration constant. Determine this calibration constant.

MEASUREMENT

For a fixed function generator output, measure how the potential difference across the pick up coil varies with time 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 potential difference across the pick up coil compare to the output of the function generator?

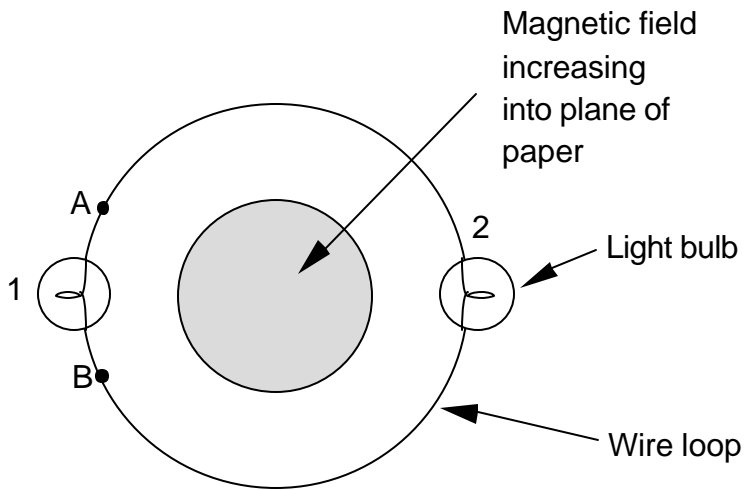
Graph the maximum potential difference across the pick up coil as a function of the angle the coil's area vector makes with the magnetic field.

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.



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 9Ω 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?

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: _____

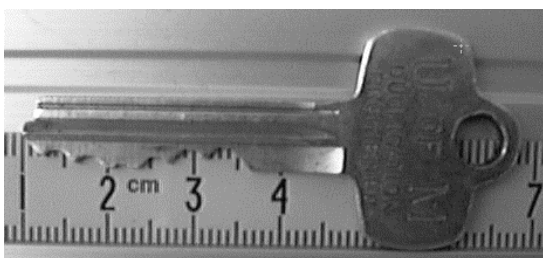
Grading Checklist	Points*
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up questions completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM 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 rewrite that section only 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 5.8142712 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 5.81 cm. Since you estimated the 1, 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 5.8 cm, but it is clear that 5.81 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
6.242	5.875
+4.23	<u>-3.34</u>
<u>+0.013</u>	2.535
10.485	
10.49	2.54

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	
15.84	17.27
<u>x 2.5</u>	<u>x 4.0</u>
7920	69.080
<u>3168</u>	
39.600	
40	69

Division	
<u>117</u>	<u>25</u>
23)2691	75)1875
<u>23</u>	<u>150</u>
39	375
<u>23</u>	375
161	
161	
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 $5' 6" \pm \frac{1}{2}"$. This $\pm \frac{1}{2}"$ 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?

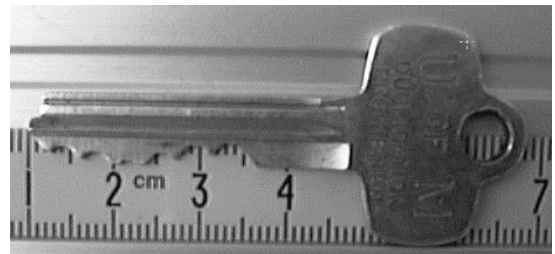
This Appendix will discuss two basic techniques for determining the uncertainty: **estimating the uncertainty** and measuring the **average**

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 6cm, 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 5.81cm. 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 5.81 ± 0.03 cm.

Another time you may need to estimate uncertainty is when you analyze video data. Figures B2 and B3 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

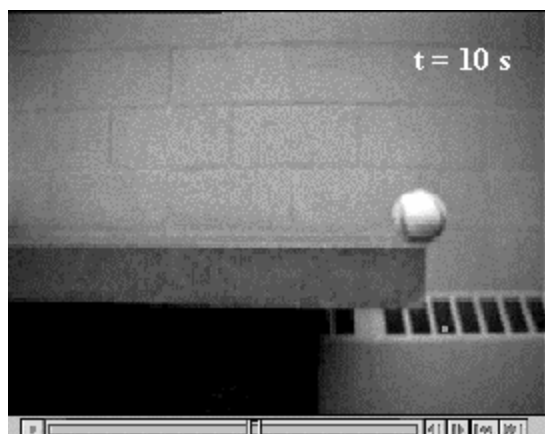
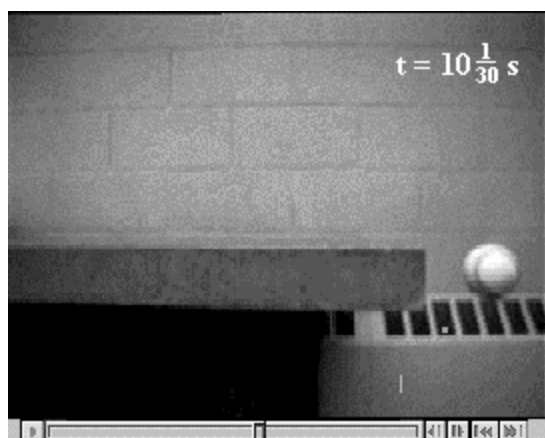


Figure B-3



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 uncertainty by making several measurements 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 measurements 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
<u>3.120</u>
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
<u>3.125</u>
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

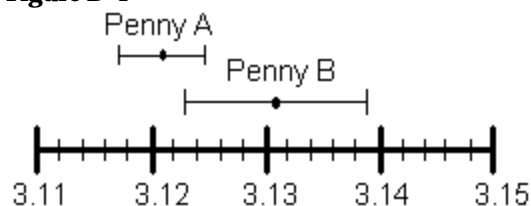
However you choose to determine the uncertainty, you should always state your

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:
 $(0.004 \text{ g} \div 3.121 \text{ g}) \times 100\% = 0.1 \%$
 Precision of Class 2's value:
 $(0.008 \text{ g} \div 3.131 \text{ g}) \times 100\% = 0.3 \%$

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 $3.556 \pm 0.004 \text{ g}$. 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:

<p>Addition:</p> $(3.131 \pm 0.008 \text{ g}) + (3.121 \pm 0.004 \text{ g}) = ?$ <p>First, find the sum of the values:</p> $3.131 \text{ g} + 3.121 \text{ g} = 6.252 \text{ g}$ <p>Next, find the largest possible value:</p> $3.139 \text{ g} + 3.125 \text{ g} = 6.264 \text{ g}$ <p>The uncertainty is the difference between the two:</p> $6.264 \text{ g} - 6.252 \text{ g} = 0.012 \text{ g}$ <p>Answer: $6.252 \pm 0.012 \text{ g}$.</p> <p><i>Note: This <u>uncertainty</u> can be found by simply adding the <u>individual uncertainties</u>:</i></p> $0.004 \text{ g} + 0.008 \text{ g} = 0.012 \text{ g}$	<p>Multiplication:</p> $(3.131 \pm 0.013 \text{ g}) \times (6.1 \pm 0.2 \text{ cm}) = ?$ <p>First, find the product of the values:</p> $3.131 \text{ g} \times 6.1 \text{ cm} = 19.1 \text{ g-cm}$ <p>Next, find the largest possible value:</p> $3.144 \text{ g} \times 6.3 \text{ cm} = 19.8 \text{ g-cm}$ <p>The uncertainty is the difference between the two:</p> $19.8 \text{ g-cm} - 19.1 \text{ g-cm} = 0.7 \text{ g-cm}$ <p>Answer: $19.1 \pm 0.7 \text{ g-cm}$.</p> <p><i>Note: The <u>percentage uncertainty</u> in the answer is the sum of the <u>individual percentage uncertainties</u>:</i></p> $\frac{0.013}{3.131} \times 100\% + \frac{0.2}{6.1} \times 100\% = \frac{0.7}{19.1} \times 100\%$
<p>Subtraction:</p> $(3.131 \pm 0.008 \text{ g}) - (3.121 \pm 0.004 \text{ g}) = ?$ <p>First, find the difference of the values:</p> $3.131 \text{ g} - 3.121 \text{ g} = 0.010 \text{ g}$ <p>Next, find the largest possible difference:</p> $3.139 \text{ g} - 3.117 \text{ g} = 0.022 \text{ g}$ <p>The uncertainty is the difference between the two:</p> $0.022 \text{ g} - 0.010 \text{ g} = 0.012 \text{ g}$ <p>Answer: $0.010 \pm 0.012 \text{ g}$.</p> <p><i>Note: This <u>uncertainty</u> can be found by simply adding the <u>individual uncertainties</u>:</i></p> $0.004 \text{ g} + 0.008 \text{ g} = 0.012 \text{ g}$ <p><i>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.</i></p>	<p>Division:</p> $(3.131 \pm 0.008 \text{ g}) \div (3.121 \pm 0.004 \text{ g}) = ?$ <p>First, divide the values:</p> $3.131 \text{ g} \div 3.121 \text{ g} = 1.0032$ <p>Next, find the largest possible value:</p> $3.139 \text{ g} \div 3.117 \text{ g} = 1.0071$ <p>The uncertainty is the difference between the two:</p> $1.0071 - 1.0032 = 0.0039$ <p>Answer: 1.003 ± 0.004</p> <p><i>Note: The <u>percentage uncertainty</u> in the answer is the sum of the <u>individual percentage uncertainties</u>:</i></p> $\frac{0.008}{3.131} \times 100\% + \frac{0.004}{3.121} \times 100\% = \frac{0.0039}{1.0032} \times 100\%$ <p><i>Notice also, the largest possible value for the numerator and the smallest possible value for the denominator gives the largest result.</i></p>

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) $g = 10.4 \pm 1.1 \text{ m/s}^2$

$g = 9.8 \text{ m/s}^2$

b) $T = 1.5 \pm 0.1 \text{ sec}$

$T = 1.1 \text{ sec}$

c) $k = 1368 \pm 45 \text{ N/m}$

$k = 1300 \pm 50 \text{ N/m}$

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 $5.37 \pm 0.05 \text{ cm}$. The width was found to be $3.42 \pm 0.02 \text{ cm}$. What is the area and the average deviation?

Answer: $18.4 \pm 0.3 \text{ cm}^2$

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: $299.3 \pm 1.6 \text{ g}$.

Cart and set 2: $297.0 \pm 1.2 \text{ g}$.

Cart and both sets: $395.1 \pm 1.9 \text{ g}$.

Appendix C: Graphing

One of the most powerful tools used for data presentation and analysis is the graph. Used properly, graphs are an important guide to understanding the results of an experiment. They are an easy way to make sense out of your data. Therefore, it is important to graph your data as you take it.

LabVIEW™ will often provide you with a graph, but on occasion you will have to make your own. Good graphing practice, as outlined below, is a way to save time and effort while solving a problem in the laboratory.

How do I make a graph?

1. Accurate graphs are drawn on graph paper. Even if you are just making a quick sketch for yourself, it will save you time and effort to use graph paper. That is why every page of your lab journal is a piece of graph paper. Make sure to graph your data as you take it. Never put off drawing a graph until the end.
2. Every graph should have a title to indicate the data it represents. In a large collection of graphs, it is difficult to keep one graph distinct from another without clear, concise titles.
3. The axes of the graph should take up at least half a page. Give yourself plenty of space so that you can see the pattern of the data as it is developing. Both axes should be labeled to show the values being graphed and their appropriate units.
4. The scales on the graphs should be chosen so that the data occupies most of the space of your graph. You do not need to include zero on

your scales unless it is important to the interpretation of the graph.

5. If you have more than one set of data on a set of axes, be sure to label each set to avoid confusion later.

How do I plot data and uncertainties?

Another technique that makes data analysis easier is to record all your data in a table.

A useful data table will always include a title and column headings, so that you will not forget what all the numbers mean. The column headings should include the units of the quantities listed, and usually serve as the labels for the axes of your graph. For example, look at Table C-1 and Graph C-1 on the next page. This is a position-versus-time graph drawn for a hypothetical situation.

The uncertainty for each data point is shown on the graph as a line representing a range of possible values with the principal value at the center. The lines are called **error bars**, and they are useful in determining if your data agrees with your prediction. Any curve (function) that represents your data should pass through your error bars.

Table C-1: Position vs. Time: Exercise 3, Run 1

Time, sec	Position, cm
0.1	10 ± 5
0.2	20 ± 5
0.3	30 ± 5
0.4	39 ± 5
0.5	49 ± 5
0.6	59 ± 5
0.7	69 ± 5
0.8	79 ± 5
0.9	89 ± 5
1.0	98 ± 5

What is a best fit straight line?

If your data points appear to lie on a straight line, then use a clear straight edge and draw a line through all the error bars, making sure the line has as many principal values beneath it as above it. The line does not need to touch any of the principle values. **Do not connect the dots.** When done correctly, this straight line represents the function that best fits your data. You can read the slope and intercept from your graph. These quantities usually have important physical interpretations. Some computer programs, such as Excel or Cricket Graph, will determine the best straight line for your data and compute its slope, intercept, and their uncertainties. You should check with your lab instructor, before you use a graphing program to see if it is appropriate. As an example, look at Graph C-1. The dashed lines are possible linear fits, but the solid line is the best fit. Once you have found the best-fit line, you should determine the slope from the graph and record its value.

How do I find the slope of a line?

The slope of a line is defined as the ratio of the change in a line's ordinate (vertical axis) to the change in the abscissa (horizontal axis), or the "rise" divided by "run." Your text explains slope. For Graph C-1, the slope of the best-fit line will be the change in the position of the object divided by the time interval for that change in position. To find the value of the slope, look carefully at your best-fit line to find points along the line that have coordinates that you can identify. It is usually not a good idea to use your data points for these values, since your line might not pass through them exactly. For example, the best-fit line on Graph C-1 passes through the points (0.15 sec, 15 cm) and (1.10 sec, 110 cm). This means the slope of the line is

$$\begin{aligned}\text{Slope} &= \frac{110\text{cm} - 15\text{cm}}{1.10\text{sec} - 0.15\text{sec}} = \frac{95\text{cm}}{0.95\text{sec}} \\ &= 100 \frac{\text{cm}}{\text{sec}}\end{aligned}$$

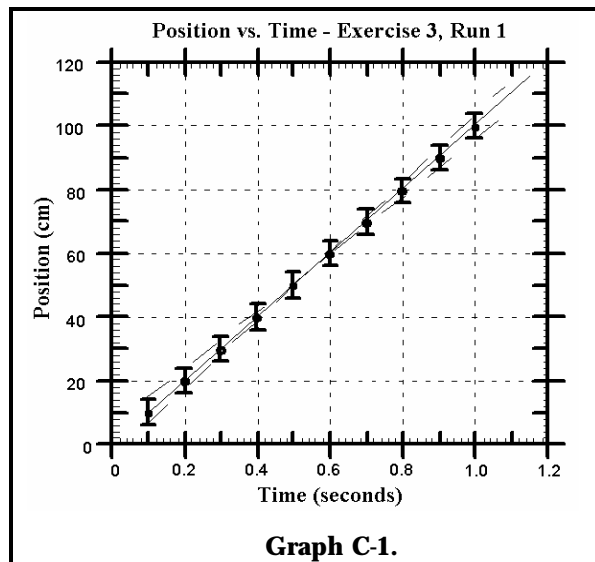
Note that the slope of a position-versus-time graph has the units of velocity.

How do I find the uncertainty in the slope of a line?

Look at the dashed lines in Graph C-1. These lines are the largest and smallest values of the slopes that can realistically fit the data. The lines run through the extremes in the uncertainties and they represent the largest and smallest *possible* slopes for lines that fit the data. You can extend these lines and compute their slopes. These are your uncertainties in the determination of the slope. In this case, it would be the uncertainty in the velocity.

How do I get the slope of a curve that is not a straight line?

The tangent to a point on a smooth curve is just the slope of the curve at that point. If the curve is not a straight line, the slope will change from point to point along the curve.



To draw a tangent line at any point on a smooth curve, draw a straight line that only touches the curve at the point of interest, without going inside the curve. Try to get an equal amount of

space between the curve and the tangent line on both sides of the point of interest.

The tangent line that you draw needs to be long enough to allow you to easily determine its slope. You will also need to determine the uncertainty in the slope of the tangent line by considering all other possible tangent lines and selecting the ones with the largest and smallest slopes. The slopes of these lines will give the uncertainty in the slope of the tangent line. Notice that this is exactly like finding the uncertainty of the slope of a straight line.

How do I "linearize" my data?

A straight-line graph is the easiest graph to interpret. By seeing if the slope is positive, negative, or zero you can quickly determine the relationship between two measurements. But not all the relationships in nature produce straight-line graphs. However, if we have a theory that predicts how one measured quantity (e.g., position) depends on another (e.g., time) for the experiment, we can make the graph be a straight line. To do this, you make a graph with the appropriate function of one quantity on one axis (e.g., time squared) and the other quantity (e.g., position) on the other axis. This is called "linearizing" the data.

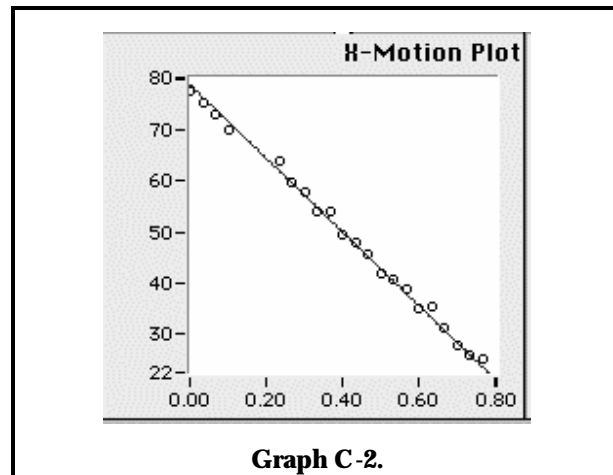
For example, if a rolling cart undergoes constant acceleration, the position-versus-time graph is curved. In fact, our theory tells us that the curve should be a parabola. To be concrete we will assume that your data starts at a time when the initial velocity of the cart was zero. The theory predicts that the motion is described by $x = \frac{1}{2}at^2$. To linearize this data, you square the time and plot position versus time *squared*. This graph should be a straight line with a slope of $0.5a$. Notice that you can only linearize data if you know, or can guess, the

relationship between the measured quantities involved.

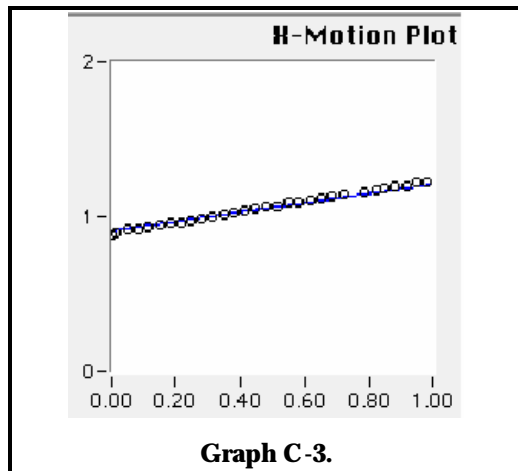
How do I interpret graphs from LabVIEW™?

Graphs C2 through C4 were produced with LabVIEW™. They give the horizontal position as a function of time. Even though LabVIEW™ draws the graphs for you, it usually does not label the axes and never puts in the uncertainty. You must add these to the graphs yourself.

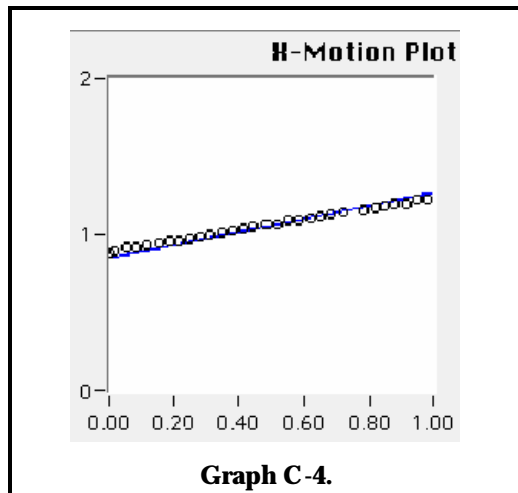
One way to estimate the uncertainty is to observe how much the data points are scattered from a smooth behavior. By estimating the average scatter, you have a fair estimate of the data's uncertainty. Graph C2 shows position versus time for a moving cart. The vertical axis is position in cm and the horizontal axis is time in seconds. See if you can label the axes appropriately and estimate the uncertainty for the data.



Finding the slope of any given curve with LabVIEW™ should be easy after you have chosen the mathematical equation of the best-fit curve. Graphs C3 and C4 each show one possible line to describe the same data. From looking at these graphs, the estimate of the data's uncertainty is less than the diameter of the circles representing that data.



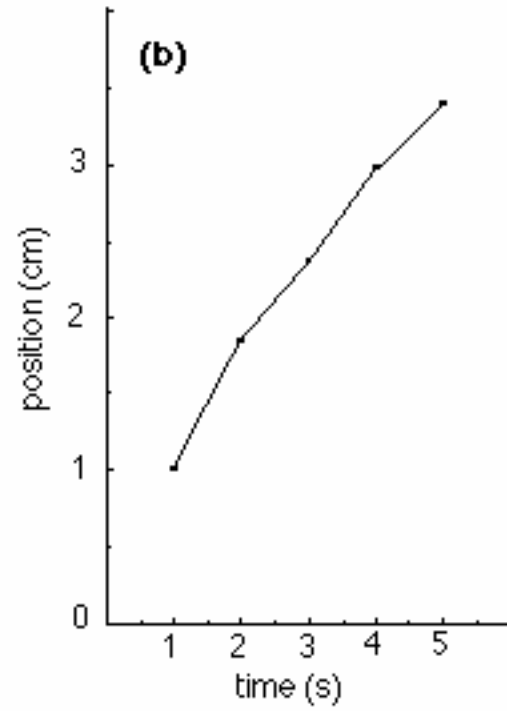
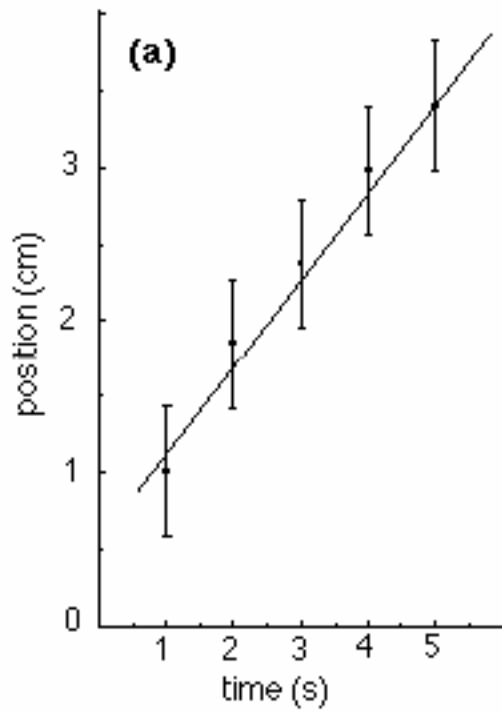
The line touching the data points in Graph C-3 has a slope of 0.38 m/sec. This is the **minimum** possible slope for a line that fits the given data.



The line touching the data points in Graph C-4 shows a slope of 0.44 m/sec. This is the **maximum** possible slope for a line that fits the given data. You can estimate the uncertainty by calculating the average difference of these two slopes from that of the best-fit line. Therefore the uncertainty determined by graphs C-3 and C-4 is ± 0.03 m/sec.

PRACTICE EXERCISES

Explain all graphing mistakes (if any) on the plots below.



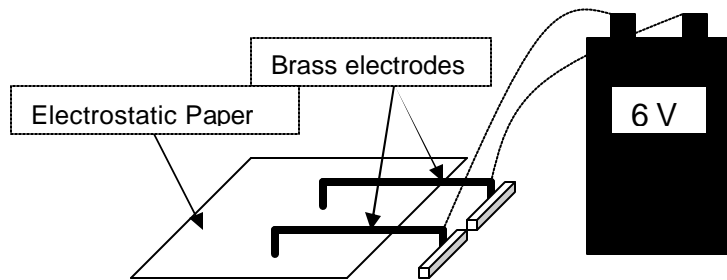
Appendix D: Equipment

ELECTROSTATIC PAPER AND ACCESSORIES:

To investigate electric fields with the electrostatic paper, you need to do the following:

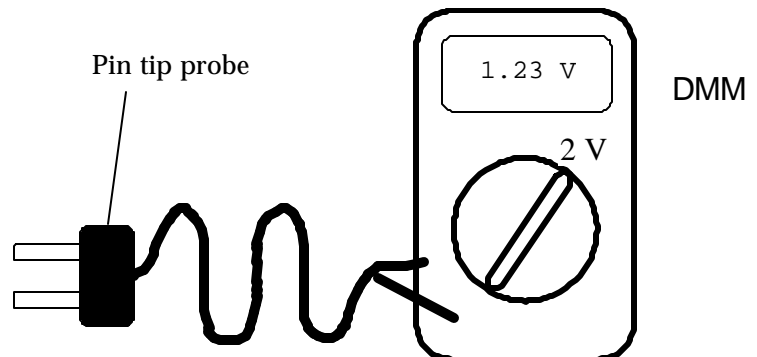
- Lay the electrostatic paper flat.
- Distribute the pieces of metal (called “electrodes”) on the paper, in the configuration whose field you wish to examine. The tips of the long brass rods may also be used as electrodes, to create point-like charges.
- Connect the electrodes to a source of charge. 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

Figure 1: Electrostatic paper Setup
(wooden block not shown)



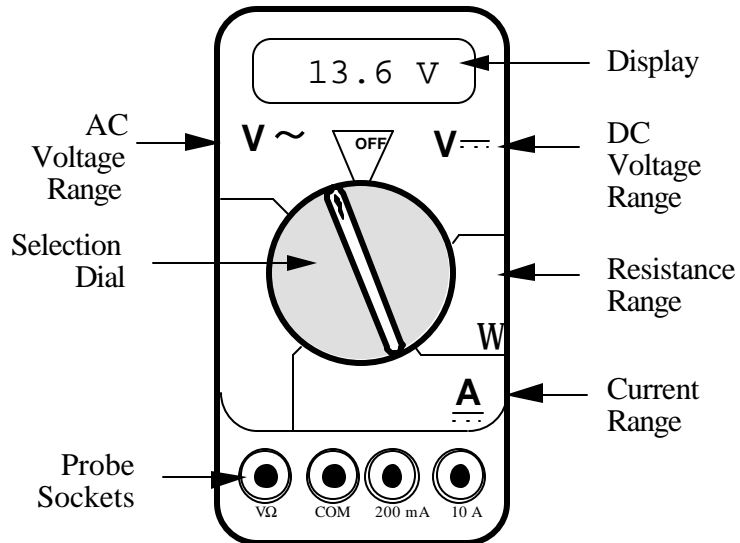
To measure the electric field from the charged electrodes, you will use a probe connected to a digital Multimeter set to measure volts (see Figure 2, below). For best results, turn the DMM to measure in the two-volt DC range, as indicated in Figure 2.

Figure 2: Electric Field Probe



THE DIGITAL MULTIMETER (DMM)

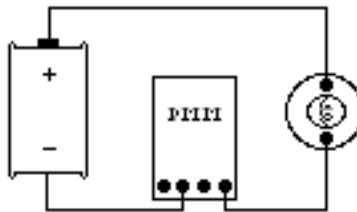
The DMM is a common piece of lab equipment that can be used to measure various electrical quantities, most often current, resistance, and potential. The DMM's you will be using are capable of measuring both "direct current" (DC) and "alternating current" (AC) circuits. Be careful about knowing which 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:

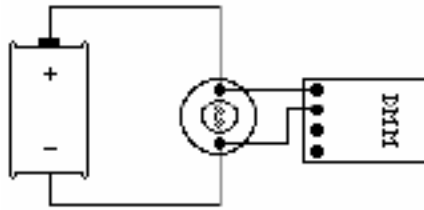


To measure current, the DMM must be placed in the circuit so that all the current you want to measure goes **through** the DMM.

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 ($V\text{-}$). 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.

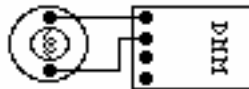
3. If no number appears, try a different measurement scale. Start at the highest voltage scale and work your way down the scales until you get a satisfactory reading.

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 'V Ω ' 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.



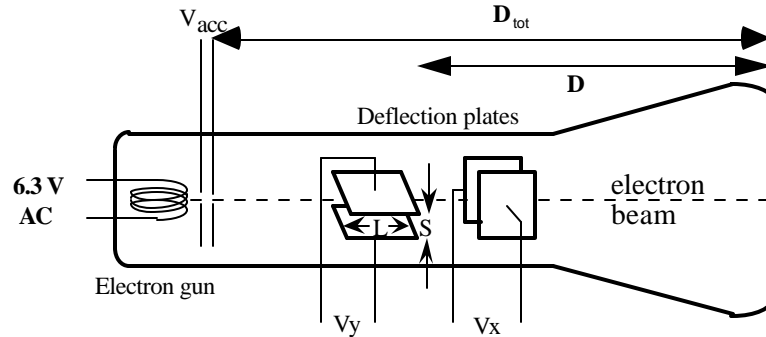
4. If no number appears, try a different measurement scale. Use a logical method that covers all scales, such as beginning at the largest scale (20 M Ω) and working your way down.

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 your computer monitor to your television. The following is a sketch of the tube you will be using and its connections.

Figure 3:
Cathode Ray Tube.

$D = 7.4 \text{ cm}$
 $L = 2.0 \text{ cm}$
 $S = 0.30 \text{ cm}$
 $D_{\text{tot}} = 9.6 \text{ cm}$



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 V_{acc} 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

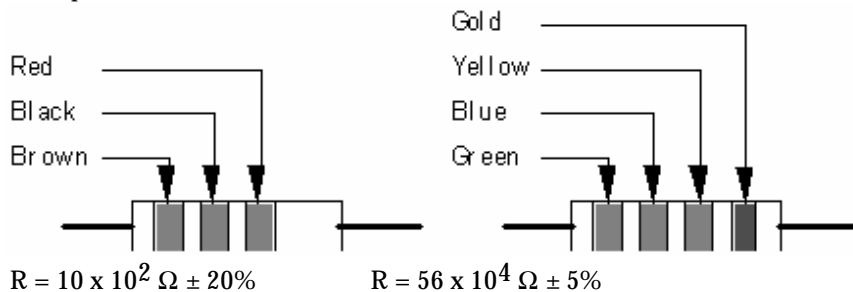
A resistor is a circuit element manufactured to have a constant resistance. The resistance of a resistor can be determined by the color bands (see the chart below) printed on the resistor according to the following rule:

$$R = (\text{first color number})(\text{second color number}) \times 10^{(\text{third color number})} \Omega$$

The fourth color band tells you the tolerance of the resistor: gold means $\pm 5\%$ tolerance, silver means $\pm 10\%$ tolerance and no fourth band means $\pm 20\%$.

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.

Examples:



Color	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

SORENSEN POWER SUPPLIES

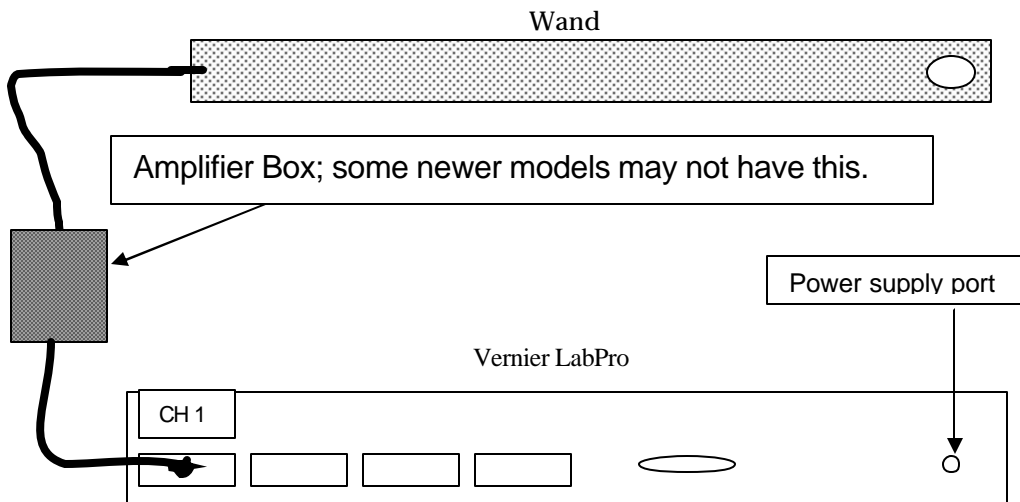
The Sorensen power supply is an all-purpose power supply for the production of constant currents and voltages. The front area consists of 3 areas, the top, middle and bottom. At the top is the main display that reads either current in Amperes or voltage in Volts. There is a switch there that allows you to switch between them. The current and voltage controls are located in the middle. On the right side is the voltage controls for constant voltage (C. V.) mode, and on the left are the current controls for the constant current (C. C.) mode. For each mode there are two knobs, a coarse control knob for large changes and a fine control knob for smaller, more precise changes. 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.** At the bottom of the front is the green power button, and the outputs (positive, negative, and ground).

This power supply normally operates in the constant voltage mode. As such, you can only change the voltages by using the constant voltage (C. V.) 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, which you should attempt to rectify.

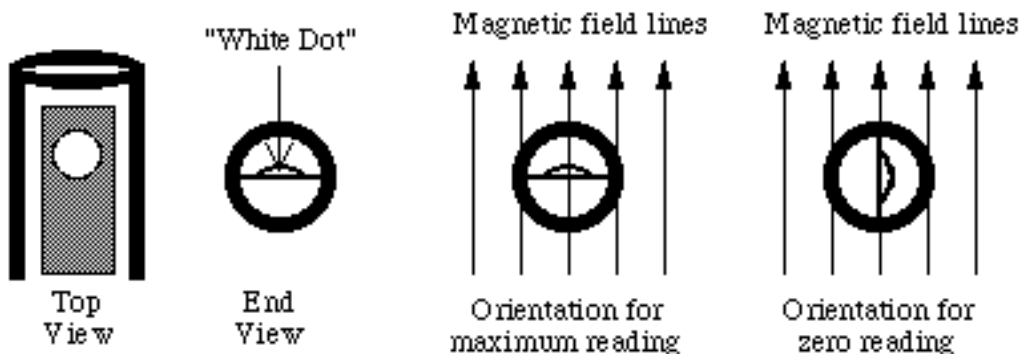
THE MAGNETIC FIELD SENSOR (HALL PROBE)

To measure magnetic field strength, you will need a measurement probe (the magnetic field sensor) and an interface to the computer. Each of these components is described below.

The magnetic field sensor is composed of the wand, the amplifier, and the Vernier LabPro. These parts are sketched below.



The **Wand** is a hollow plastic tube with a Hall effect transducer chip at one end (shown above as the circle on the right hand end of the wand). The chip produces a voltage that is linear with the magnetic field. The maximum output of the chip occurs when the area vector of the white dot on the sensor points directly toward a magnetic south pole, as shown below:



The **LabPro** allows the computer to communicate with the wand. In order to measure magnetic fields, the wire leading out of the wand must be plugged into the LabPro port labeled "CH 1". The LabPro itself should be plugged into the modem port of the computer. The LabPro turns on automatically when its power supply is plugged in. A green light on the top of the LabPro indicates that it is on.

The **Amplifier** is contained in a small box and allows you to measure a greater range of magnetic field strengths. The switch on the box is used to select the desired amplification. The **low** amplification setting is used to measure *strong* magnetic fields. The range of the sensor in low mode is about ± 64 gauss. The **high** amplification setting is used to measure *weak* fields. The range of the sensor in high mode is around ± 3.2 gauss. The actual range will vary from one magnetic field sensor to another. Note: 1 tesla = 10^4 gauss, the magnetic field of the earth is approximately half a gauss. **Some newer models do not have an amplifier box. In these cases there is a switch on the wand itself with the ranges labeled. Also note that on newer models, the "White Dot" is in a different location. This means you will have to hold the wand differently to make sure that the dot is perpendicular to the magnetic field.**

Appendix E: Software

MEASURING CONSTANT MAGNETIC FIELD (THE HALL PROBE APPLICATION)

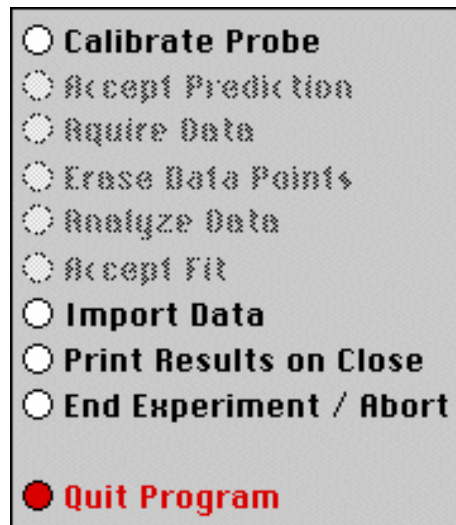
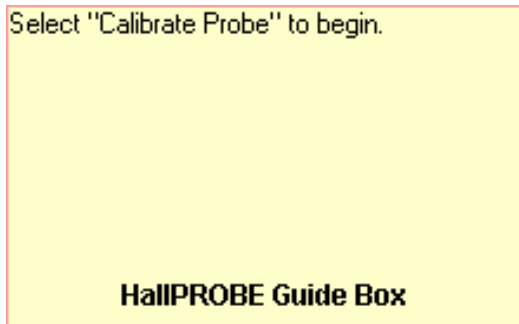
Basics

Before you begin, you should ensure that you have read the relevant sections of *Appendix D* 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 “HallPROBE” icon 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. 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.



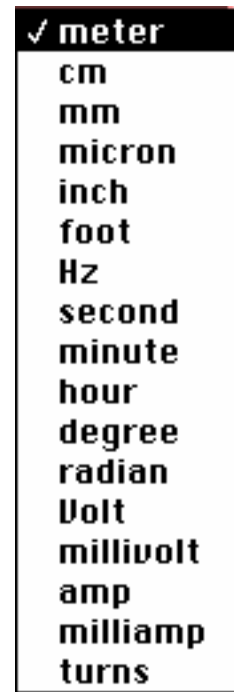
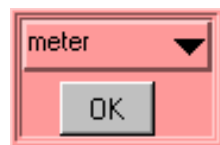
The primary data output you get is by printing your results, so be careful not to quit without printing or exporting your data.

Calibration

The first command is to calibrate the Magnetic Field Sensor. Before selecting this command, you need to decide whether you require high or low amplification. Switch the amplifier box to the appropriate setting also set the amplification switch on the screen to the same setting. The amplification switch on the screen toggles between the two settings by clicking it with the mouse. The two amplification settings are shown below:

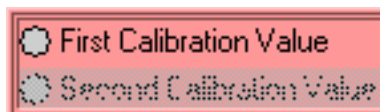


After selecting the "Calibrate Probe" command, you will be asked to do *two* tasks. First, you will need to choose the quantity on the x-axis of your data graph. This is accomplished by moving the mouse cursor over to the word "meter" in the red-colored area (shown below) and then pressing the mouse 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). 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 "First Calibration Value" as shown below. Now rotate the wand 180 degree around its long axis (similar to rolling a pencil) and select "Second Calibration Value." If you have trouble holding the wand in one place you might have good luck rolling it across your lab table.



The calibration process is now complete.

Predictions

This type of analysis relies on your graphical skills to interpret the data, so you should be familiar with both Appendix C: *Graphing*, and Appendix B: *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.

The top screenshot shows a software interface for entering a prediction equation. It features a pink background with a title bar that reads $u(x) = A + Bx$. Below the title bar are four input fields, each with a small green triangle icon above it and a red border. The first field is labeled 'A' and contains the value '0.000'. The second field is labeled 'B' and contains '0.000'. The third field is labeled 'C' and contains '0.000'. The fourth field is labeled 'D' and contains '0.000'. To the right of these fields is the text 'Fit Equation'. At the bottom right of the box is a button labeled 'Prediction'.

The bottom screenshot shows a list of generic equations to choose from. The list is enclosed in a black border with a white background. The first equation, $u(x) = A + Bx$, is selected and has a checkmark to its left. The other equations are:

- $u(x) = A + Bx + Cx^2$
- $u(x) = A + Bx + Cx^2 + Dx^3$
- $u(x) = A + B \sin(Cx + D)$
- $u(x) = A + B \cos(Cx + D)$
- $u(x) = A + B \exp(-Cx)$
- $u(x) = A + B \{1 - \exp(-Cx)\}$
- $u(x) = A + B / (x + C)^D$
- $u(x) = A + B / (x^2 + C)^D$
- $u(x) = A + B / (x^2 + Cx)^D$

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.

Once you are satisfied that the equation you selected and the values of the constants are correct, select the *Prediction* button in the Fit Equation command box. Your prediction equation will then show up 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). If you wish to change your prediction, simply repeat the above procedure. 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.

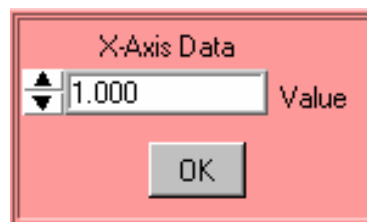
Exploration

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

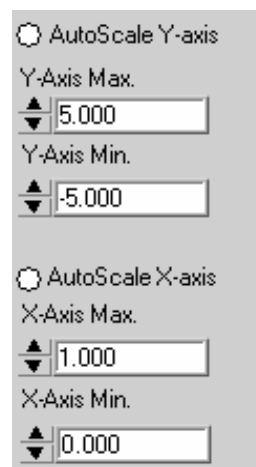
Collecting data requires that you enter the x-axis data each time the computer reads in a value for the magnetic field strength. You enter this data using the panel shown to the right. For every x-axis data value you enter, the analysis program will record the magnetic field strength in gauss on the 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.



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. This scaling is accomplished by entering the appropriate values into the "Y-Axis Max." and "Y-Axis Min." fields (as shown to the right) as well as adjusting the "X-Axis Max." and "X-Axis Min." fields (also shown to the right). 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.*

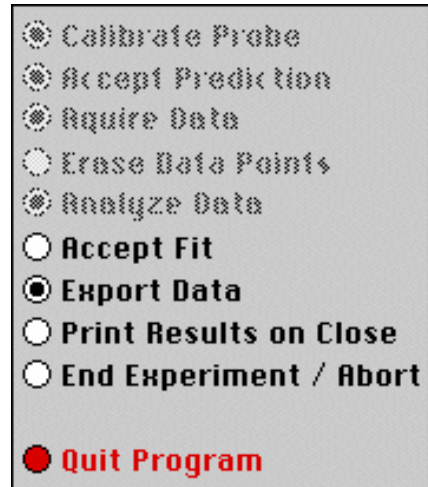
Now you need to estimate the uncertainty in your fit by deciding the range of other lines that *could* also fit your data. This method of estimating your uncertainty is described in Appendix D. Slightly changing the values for each constant in turn will allow you to do this quickly.

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 will be saved to your section's lab folder. To retrieve this file, restart *HallPROBE* from the desktop and select *Import Data*.

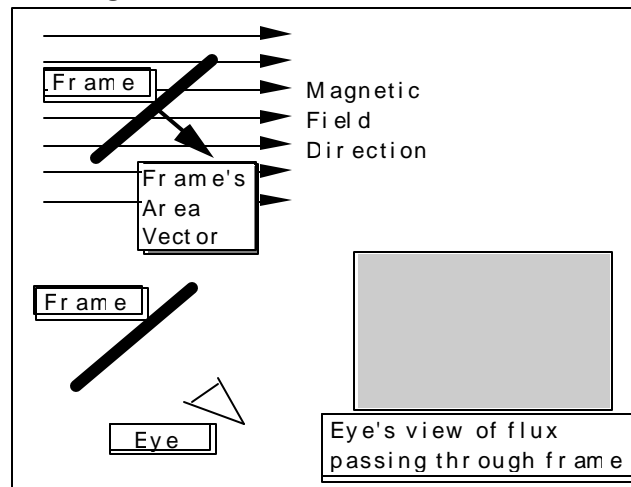


Last Words

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.

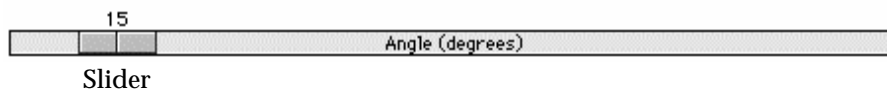
FLUX SIMULATOR

A computer movie called FluxSimulator 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 FluxSimulator Screen

Use the control bar with the slider, as shown below, to control the rotation of the frame.



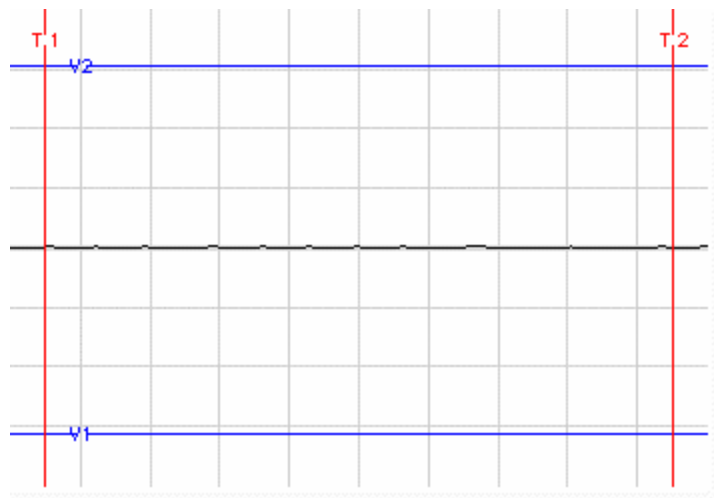
As you rotate the frame, observe both the angle the frame's area vector makes with the magnetic field and the color seen by the eye.

MEASURING TIME-VARYING VOLTAGES (FaradayPROBE)

The Display:

This software package, written in LabVIEW™, allows you to measure and record potential differences as a function of time. 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. These instructions assume a working familiarity with the HallPROBE application.

The basic difference between the FaradayPROBE and the HallPROBE applications is an additional display. The potential difference versus period display is described in these paragraphs. The display itself is shown below.



The vertical axis is a measure of the potential difference (voltage) between the two clips. 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 an 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.



NOTE: Be patient! It takes up to 5 seconds for the display to register a signal.

Measurements:

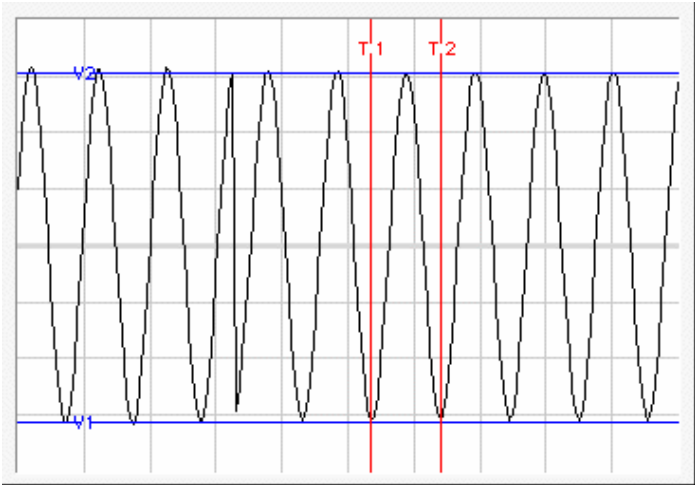
The FaradayPROBE has two modes for acquiring data. The continuous mode acquires data constantly and updates at specified time intervals. There also exists a one shot mode in which one time interval worth of data will be measured after which the program will pause. Talk to your TA for specifics on which mode might work best in the lab problems you are solving.

Voltage and Time cursors

The red and blue lines that are on the display are movable simply by putting your mouse pointer on 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 below. 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.



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 taken¹, 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_0 :

$$I(t) = I_0 \sin(\omega t)$$

$$I^2(t) = I_0^2 \sin^2(\omega t)$$

$$\begin{aligned} \langle I^2 \rangle &= \frac{1}{2p} \int_0^{2p} I_0^2 \sin^2(\omega t) d(\omega t) \\ &= \frac{I_0^2}{2p} \int_0^{2p} \sin^2(\omega t) d(\omega t) = \frac{1}{2} I_0^2 \end{aligned}$$

$$I_{RMS} = \sqrt{\langle I^2 \rangle} = \frac{1}{\sqrt{2}} I_0$$

When in AC mode, your DMM displays the RMS values of current and voltage.

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:

$$\langle I \rangle = \frac{I_0}{2p} \int_0^{2p} \sin(t) dt = 0$$

Appendix G: Sample Laboratory Report

There is no set length for a problem report but experience shows that good reports are typically three pages long. Graphs and photocopies of your lab journal make up additional pages. Complete reports will include the terminology and the mathematics relevant to the problem at hand. Your report should be a clear, concise, logical, and honest interpretation of your experience. You will be graded based on how well you demonstrate your understanding of the physics. Because technical communication is so important, neatness, and correct grammar and spelling are required and will be reflected on your grade.

Note: The double vertical bars indicate an explanation of that part of the report. These comments are not part of the actual report.

Statement of the problem

In a complete sentence or two, state the problem you are trying to solve. List the equipment you will use and the reasons for selecting such equipment.

The problem was to determine the distance the deflection plates (x and y) in the Cathode Ray Tube (CRT) using the deflections recorded on the screen at various potential differences. We connected the CRT as shown in Appendix D and recorded the x-deflection and y-deflection resulting from several different voltages applied to the deflection plates.

Prediction

Next comes your prediction. Notice that the physical reason for choosing the prediction is given. This was an exploratory problem asking for a quantitative prediction, but many predictions ask you to find mathematical relationships between two variables.

Note that the prediction is wrong. The prediction does not need to be correct, it needs to be what you really thought before doing the lab; that is why it is called a prediction. The prediction is supposed to be a complete and reasonable attempt by your group to determine the outcome of the problem.

Our group predicted that the distance between the deflection plates can be calculated based on the resultant x and y deflections on the screen at different voltages. The distances D_x and D_y can be easily calculated, which lead us to conclude that the distance that we were interested in for this lab is simply the difference in these two distances.

$$qV_{acc} = \frac{1}{2} m_e u_{II}^2 \longrightarrow u_{II} = \sqrt{\frac{2qV_{acc}}{m_e}} \quad (u_{II} \text{ is the horizontal velocity of the electrons})$$

Time in and vertical velocity due to the deflection plates:

$$t_{in} = \frac{L}{\mathbf{u}_{II}} \quad \mathbf{u}_{\perp} = a_{\perp} t_{in} = \frac{qE}{m_e} t_{in} = \frac{q\Delta V_{\perp}}{sm_e} t_{in}$$

(s is the separation distance between the 2 parallel deflection plates)

$$\begin{aligned} \text{Deflection} &= \frac{1}{2} a_{\perp} t_{in}^2 + \mathbf{u}_{\perp} t_{out} \\ &= \frac{1}{2} a_{\perp} t_{in}^2 + \mathbf{u}_{\perp} \frac{D}{v_{II}} \\ &= \frac{1}{2} \frac{q\Delta V_{\perp}}{sm_e} \left(\frac{L}{v_{II}} \right)^2 + \frac{q\Delta V_{\perp}}{sm_e} \frac{L}{v_{II}} \frac{D}{v_{II}} \\ &= \frac{q\Delta V_{\perp}}{sm_e} \frac{L}{(v_{II})^2} \left[\frac{1}{2} L + D \right] \end{aligned}$$

(L is the length of the length of the plates; DV is the potential difference; D is the distance between the deflection plates and the screen of the CRT)

Slopes of x and y deflections vs. potential differences:

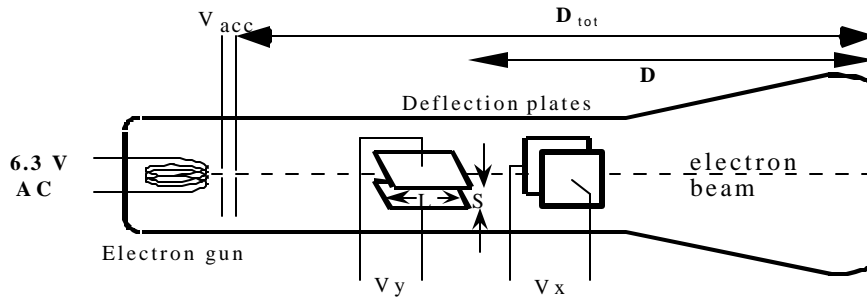
$$m_x = \frac{L}{2sV_{acc}} \left[\frac{1}{2} L + D_x \right] \longrightarrow D_x = \frac{2sV_{acc}}{L} \left[m_x - \frac{L^2}{4sV_{acc}} \right]$$

$$m_y = \frac{L}{2sV_{acc}} \left[\frac{1}{2} L + D_y \right] \longrightarrow D_y = \frac{2sV_{acc}}{L} \left[m_y - \frac{L^2}{4sV_{acc}} \right]$$

Distance between x and y deflection plates:

$$\begin{aligned} D_y - D_x &= \frac{2sV_{acc}}{L} \left[m_y - \frac{L^2}{4sV_{acc}} \right] - \frac{2sV_{acc}}{L} \left[m_x - \frac{L^2}{4sV_{acc}} \right] \\ &= \frac{2sV_{acc}}{L} (m_y - m_x) \end{aligned}$$

With some of the variables given in the laboratory manual, we can calculate this distance after taking our measurements and see whether the result is reasonable.



Experiment and Results

This section describes your experimental method, the data that you collected, any problems in gathering the data, and any crucial decisions you made. Your actual results should show you if your prediction was correct or not.

After hooking up the CRT, we turned it on and arranged the screen so that an x-deflecting voltage would move the beam along the horizontal axis and a y-deflecting voltage would move the beam along the vertical axis. With no deflecting voltage, the electron beam did not hit the screen directly in the center -- we took this point to be our reference point and measured our change in the x- and y-directions from it.

We measured the x-deflection for 6 voltages between 0 and 5 Volts. We then did the same for the y-deflection. (See table 1 from the lab journal)

A discussion of uncertainty should follow all measurements. No measurement is exact. Uncertainty must be included to indicate the reliability of your data.

The largest uncertainty in our measurements came from the deflection of the electron beam from the screen on the CRT. Since the marks on the screen were every 1.0 mm and the electron beam was somewhat distorted, we estimated the uncertainty of our deflection measurements to be 0.5 mm. We verified this uncertainty measurement by having each member of our group measure the x- and y-position of the electron beam at two test points. All measurements were within the stated uncertainty. The uncertainties in our measurement also lead to uncertainties in the slopes of the deflection vs. potential difference graph; the slopes were found to have uncertainties of 0.09 mm/V for x and 0.08 mm/V for y.

Using the values given in the manual, and those found from the experiment, we calculated the distance between the x and y deflection plates to be 36 mm with an uncertainty of 12mm.

Conclusions

This section summarizes your results. In the most concise manner possible, it answers the original question of the lab.

When we graphed the results from our data table, we saw that the y-deflection plates gave us a larger deflection at each deflection voltage used in the experiment. (See Graph A from the lab journal)

A good conclusion will always compare actual results with the predictions. If your prediction was incorrect, then you must discuss where your reasoning went wrong. If your prediction was correct, then you should review your reasoning and discuss how this lab served to confirm your knowledge of the basic physical concepts.

The result of our experiment is consistent with the dimensions of the CRT. The total length from the accelerating voltage plates to the screen is 96mm, and our result showed that the distance between the x and y deflecting plates is somewhere in the range of 24mm to 48mm. The upper bound value may be unlikely, since it won't leave much room for anything else to fit in the CRT. However, this doesn't mean that the range is unreasonable; any value in the range can still be made to fit inside the CRT. After

discussing this as a group we realized that we had over estimated the x- and y-position measurements, and the upper bound value is the result of this.

When we thought about the situation more carefully, we realized that we were correct in thinking that an electron is always traveling with the same velocity parallel to the CRT and that the time it is inside each deflection plate will be the same. Thus, at the far edge of each deflecting plate the electron beam has the same perpendicular velocity. Recalling our kinematics from last semester, we realized that this perpendicular velocity will be independent of the parallel velocity. Since the electron beam takes longer to travel from the far edge of the y-deflecting plates (the y-plates are further from the screen) than from the x-deflecting plates, the electron beam under y-deflection will have more time during which it has a y-velocity, and thus it will be deflected more. This allowed us to make the right assumptions and thus yielded a reasonable result.

|| After you have compared your predictions to your measured results, it is helpful to look at the data from an alternative perspective. This should be a short exercise demonstrating to yourself and to your TA that you understand the basic physics behind the problem.

The situation in this problem is similar to the situation in which a moving soccer ball is moving past two people (See diagram 1 from the lab journal). Either of these two people can kick it perpendicularly to its direction of motion. The diagram shows the resulting position when it reaches the edge of the field when person A kicks it (solid line) versus when person B kicks it (dashed line). Person A is further away from the edge of the field and, thus, her kick results in a greater deflection of the ball. This difference in deflection can be used to determine how far apart the two kickers are.

