1202 LAB MANUAL
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WARNING: Components and apparatus used in the labs sometimes have strong magnets present. Strong magnetic fields can affect pacemakers, ICDs and other implanted medical devices. Many of these devices are made with a feature that deactivates it with a magnetic field. Therefore, care must be taken to keep medical devices minimally 1' away from any strong magnetic field.

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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 because of 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.

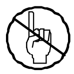
The amount you learn in lab will depend on the time you spend in preparation before coming to lab.

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 a 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 plunging 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

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. **Make sure to check with your TA to find out when your report is due.**

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.* Check with your course's syllabus for the specifics of the grading policy**.**

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.

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 by sending an email to the following address:

   labhelp@physics.umn.edu

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

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

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

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

Respect your colleagues (fellow students) and their ideas.

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

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

LABORATORY 1: GEOMETRIC OPTICS

In this lab, you will solve several problems related to the formation of optical images. Most of us have a great deal of experience with the formation of optical images: they can be formed by flat or curved mirrors, water surfaces, movie projectors, telescopes, and many other devices. We can see because the cornea and a flexible lens in each eyeball form images on our retinas (sometimes with the aid of "corrective lenses," in the form of contacts or eyeglasses). Solving the problems in this laboratory should help you explain many of your daily experiences with images with the concept of light rays that travel from sources or illuminated objects in straight lines.

OBJECTIVES:

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

- Describe features of real optical systems in terms of ray diagrams.
- Use the concepts of real and virtual images, as well as real and virtual objects, to explain features of optical systems.
- Explain the eye's function in human perception of images.

PREPARATION:

Before coming to lab, read Sections 1 & 4 of Chapter 23 and Sections 1-3, 9 and 13 of Chapter 24 in Sternheim & Kane.

Keep the objectives of the laboratory in mind as you read the text. It is likely that you will do these laboratory problems before your lecturer addresses this material; the purpose of this laboratory is to introduce you to the material.

Before coming to lab you should be able to:

- Create graphs of measured quantities, and determine mathematical relationships between the quantities based on the graphs.
- Draw a ray diagram to locate the image formed by an object and a convex lens.
- Use the geometrical properties of similar triangles to find unknown quantities.

LABORATORY 1: GEOMETRIC OPTICS

PROBLEM #1: IMAGES WITHOUT LENSES OR MIRRORS

Your group is developing an imaging device for use in diagnosing ulcers. Because it will be used inside the human stomach, the device must be small and durable. To meet these criteria, you would like to develop a camera that does not use a lens. While developing an initial presentation about lens-less image formation for your clients, you investigate a model of a lens-less camera: a light source (representing the object to be imaged), a mask with a small hole, and a screen. What are the properties of an image projected on a screen by a small hole?

Read Sternheim & Kane: sections 23.1, 23.4 & 24.10.

EQUIPMENT

You have a long filament bulb, a small flashlight, a table clamp, a three-finger clamp, hole punches, black paper for making masks with various hole sizes and shapes, an empty lens holders to hold the masks, an optics bench and a screen.

Read the section *Excel – MAKING GRAPHS* in the **Software** appendix. You will be using the software later in the semester, so please take the time now to become familiar using it.

Read the appendices titled a **Review of Graphs, Significant Figures** and **Accuracy, Precision & Uncertainty** to help you take data effectively.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Suppose you held a point-like light source close to a mask with a small circular hole in it. Draw a diagram, showing the light rays that would make it from the light source to the screen. Beside the diagram, sketch a picture of what you expect to see on the screen.

2. What would happen if the light were moved down? On your original diagram, add the light rays that would make it from the light source in its new position to the screen. How would the position of the light spot on the screen change?

3. Draw a new ray diagram for a similar situation with a new light source, in the shape of a vertical arrow that emits light from all parts. Sketch a picture of what you would expect to see on the screen.

4. How would the size of the image on the screen change if you move the screen away from the mask? What if you move the screen closer to the mask? Use your ray diagram to write a relationship among the length of the arrow, the distance from the

arrow to the mask, the length of the arrow's image on the screen, and the distance from the mask to the screen.

The ratio of the size of the arrow and the size of the arrow's image is the linear magnification of the system. (Note that the length of an inverted image is customarily negative, so that an optical system that results in an inverted image has a magnification < 0.)

5. What would you expect to see on the screen if the top half of the arrow were covered? What would you expect to see on the screen if the hole in the mask were made smaller? What would you expect to see on the screen if the mask were removed altogether, leaving just the arrow-shaped light source and the screen? Draw a sketch to support each of your predictions.

PREDICTION

Write an equation that relates the size of the image produced on the screen to the size of the light source, the distance between the light source and the mask, and the distance between the mask and the screen.

EXPLORATION

Remove the cover from the flashlight, so that it acts as a point-like light source. Describe what you see on the screen without the mask. Does this match your prediction from the warm-up questions?

Place a mask with the smallest hole possible between the flashlight and the screen. Describe what you see on the screen in this case. What happens when you move the flashlight up? Down? Left? Right? Toward the mask? Away from the mask? Does this match your predictions from the warm-up questions?

Place the same mask between the long filament bulb and the screen. Describe what you see on the screen in this case. What happens to the image on the screen when you cover the top part of the light bulb? When you cover the bottom part of the light bulb? Do your observations match your predictions from the warm-up questions?

Describe what you see on the screen when you slowly tip the light bulb to the left or the right. What happens when you move the light bulb toward the mask or away from the mask? What happens when you move the screen toward the mask or away from the mask?

How does the size or shape of the mask's hole affect what you see on the screen?

MEASUREMENT

Make measurements sufficient to quantitatively examine the relationship of the size of the image to the distance between the light source and the mask, and the distance between the mask and the screen. Be sure to measure the length of the bulb's filament.

ANALYSIS

Did your warm-up question responses match the observations you made in the explorations? If not, how can you change the sketches from the warm-up questions to account for your observations? When the image of the long filament bulb appeared on the screen, did it appear erect or inverted? How could you tell?

Compare your predicted values for the size of the image with those you measured. Also compare your predicted values for the magnification with those you measured. Were your predictions accurate? If not, can you adjust your prediction (if so, support with new diagrams) or otherwise account for any discrepancy?

CONCLUSION

In designing a camera with no lens, what factors might be important in your choice of pinhole size, and why would they be important? What factors might be important in determining the distance between the camera's pinhole and its imaging surface, and why?

PROBLEM #2: IMAGE FORMATION WITH A PARTIALLY COVERED LENS

Your group, consulting for a drug company that hopes to develop new antibiotics, needs to make a video recording of a bacteria specimen under special conditions. These conditions involve light levels too intense for your recording equipment. One of your colleagues suggests partially blocking the microscope lens with a shutter to reduce the light levels for the recording equipment. Others argue that this would block part of the image, so that some parts of the sample would not be recorded.

You decide to test your co-worker's idea with a simplified optical system. You arrange a long filament bulb, lens and screen on an optical bench, so a focused image of the bulbs filament appears on the screen.

Read Sternheim & Kane: sections 23.1, 23.4, 24.2 & 24.3

EQUIPMENT

You have an optical bench, a convex lens mounted in a lens holder, a screen, long filament lamp, table clamp, three-finger clamp (to hold the lamp) and a ruler.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a fairly large sketch, showing a convex lens and a source of light that has a defined top and bottom.
2. Sketch the paths of two light rays from the top of the light source to the lens, and continue the sketch for each ray on the other side of the lens. (For the rays you choose, simple rules should tell you the path they take after passing through the lens, if confused, refer to your text.) Do you expect an image to form in this situation? If so, indicate the position of the image in your sketch. Where should you position the screen in order to see the image?
3. Repeat steps 1 and 2, placing the light source at one of the lens's focal points. Do you expect an image to form in this situation?
4. Repeat steps 1 and 2, placing the light source closer to the lens than its focal point. Do you expect an image to form in this situation?
5. What will happen to the image if the top half of the lens is covered? Indicate on your diagram which rays could pass through the lens in this situation, and which would be blocked.

6. Side-by-side, sketch the light source, the image you expect to see when the lens IS NOT covered, and the image you expect to see when the top half of the lens IS covered. Qualitatively compare the sizes, shapes, orientations, and brightness of the source and the two images.

PREDICTION

Describe how covering part of a convex lens will change the shape and brightness of the image produced.

EXPLORATION

Experiment to find a way you can estimate the focal length of your converging lens. (Hint: Light from a distant object is parallel and focuses very close to the focal point of a converging lens.)

Position the light source, the convex lens, and screen on the optical bench so that a focused image appears on the screen. Does the image still exist if the screen is removed? How could you check?

Can you project an image on the screen when the distance from the light source to the lens is longer than the focal length? When the light source is closer to the lens than its focal length? What happens when the light source is *at* the lens's focal length?

Project a clear image of the light source on the screen. Sketch the shapes of the light source and its image. Is this sketch similar to the one you drew for the warm-up questions? If not, describe the differences.

Cover part of the lens. How does the image change? What changes if you cover different parts of the lens – top, bottom, right, left, middle? What changes if you cover more than half of the lens?

Draw sketches in your lab notebook of what you see on the screen. Indicate which part of the lens was covered for each sketch, as well as the alignment of the image relative to the source. Point out differences among the images formed when different parts of the lens are covered.

Gradually move the cover from the lens to the light source, in such a way that it always blocks about half of the light traveling toward the lens. Describe carefully how the image on the screen changes during this process.

ANALYSIS

Did your prediction and warm-up question responses match your observations? If not, how can you change the sketches from the Warm-up questions to account for your observations? Can you use the fact that light travels in straight lines, and sketches similar to your (amended) sketches from the warm-up questions, to explain how the image changed as you slowly moved the cover from the lens to the light source?

CONCLUSION

Do your results rule out use of the method proposed by your colleague for reducing light intensity? How is an image formed by a lens? Which rays "participate" in forming the image for a point on an object?

Do your results suggest any advantages that lenses with large diameters have over small lenses? Do your results suggest any advantages of using lenses instead of pinholes to form images, or advantages of using pinholes instead of lenses?

PROBLEM #3: IMAGE POSITION

Your group is working to develop and study new proteins. To analyze the composition of a protein mixture you have produced, the protein solution is placed in an electric field. Proteins with different total charges will drift at different speeds in the solution, and can be separated for further analysis.

Your group needs to focus an optical apparatus at known positions within the protein solution in order to record an image of a small part of the volume. For every point in an image, you must be able to specify the location of the corresponding point in the protein solution. For simplicity, you decide to model your optical apparatus with a single convex lens. Your group will investigate relationships between the positions of points on an object and points in its image in two parts.

For this part, you investigate the relationship between an object's distance from the lens and the distance of its image from the lens, along the principal axis.

Read Sternheim & Kane: sections 23.1, 23.4, 24.2 & 24.3

EQUIPMENT

You have an optical bench, a set of convex lenses in holders, a long filament lamp, table clamp, three-finger clamp, screen and ruler.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

It is useful to have an organized problem-solving strategy such as the one outlined in the following questions.

1. Draw a fairly large sketch, showing a convex lens and a source of light with an easily identified top and bottom. Label the lens's focal points, and position the source so that an image will be created, which could be projected on a screen.
2. Determine the position of the image, by sketching the paths of rays from the top of the light source and the bottom of the light source. Indicate the position of the image in your sketch. Where should you position the screen in order to see the image? How many rays are needed to determine the position of the image?
3. Repeat the steps above with a lens of the same focal length, but with the light source farther away from the lens. Has the image moved closer to or farther from the lens?

4. From your ray diagrams and geometry or trigonometry, write an equation that relates the distance between the lens and the image, the distance between the lens and the object, and the lens's focal length.
5. Solve the equation in step **4** for *distance of the object from the lens*. What do you predict as a shape for a graph of *the distance of the object from the lens vs. the distance of the image from the lens* for a lens of fixed focal length? Sketch the shape of the graph you expect. Does the graph cross each *axis*? If so, what are the values of the intercepts?
6. Solve the equation in step **4** for *the distance of the object from the lens*. What do you predict as a shape for a graph of the distance of the object from the lens vs. the distance of the image from the lens? What are the values of the intercepts where the graph crosses each axis? Draw a sketch of the graph shape you expect and indicate the expected values of the intercepts.

PREDICTION

Write out an expression that relates the distance of the image from the lens, the distance of the object from the lens, and the focal length of the lens. Use this expression to predict features of the graphs of *the distance of the object from the lens vs. the distance of the image from the lens* and (1/*the distance of the object from the lens*) vs. (1/*the distance of the image from the lens*).

EXPLORATION

Estimate the focal length of each convex lens by using a source of light that is far from the lens. Where should light from a very distant object be focused?

Position the light source, convex lens and screen on the optical bench. Align the light source with the principal axis of the lens. Adjust their positions so that a focused image appears on the screen.

Move the source slightly toward and away from the lens, each time adjusting the screen's position to show a crisp image. Does the direction in which you have to move the screen match your responses to the warm-up questions?

Try focusing an image of the vertical filament light bulb on the screen. Can you adjust the position of the screen, lens, or bulb to project an image of the front part of the bulb on the screen? Can you project the filament? Are you able to project other parts of the bulb?

MEASUREMENT

Record the positions of the image, lens and light source for several distances between the lens and the light source. In order to explore features of *the distance of the object from the lens vs. the distance of the image from the lens* and (1/*the distance of the object from the lens*) vs. (1/*the distance of the image from the lens*) graphs, record several measurements and plan your experiment so the data points are not "clumped together" on the graphs. Plot the points on each graph *as you go*. Take measurements for at least two different convex lenses.

ANALYSIS

In the warm-up questions you predicted the shape of two different graphs. Choose one of these graphs to use for your measurements and determine the focal length of each lens. Compare the focal length found on your graphs with the focal length calculated from your prediction equation.

CONCLUSION

How does the image position change as an object is moved along the optical axis? If you know the focal length of a lens and the position of the image, could you use your graphs *and* the relationship you predicted among *the distance of the object from the lens*, *the distance of the image from the lens*, and *the focal length* to determine the position of the object producing that image?

Are your results consistent with your predictions? Was it consistent with your estimate using a distant light source? Did your graphs have the shape you expected? Were the estimated and calculated values for the focal length of each lens in agreement? Explain any discrepancies between your predictions and your measurements.

PROBLEM #4: IMAGE SIZE

Your group is working to develop and study new proteins. To analyze the composition of a protein mixture you have produced, the protein solution is placed in an electric field. Proteins with different total charges will drift at different speeds in the solution, and can be separated for further analysis.

Your group needs to focus an optical apparatus at known positions within the protein solution in order to record an image of a small part of the volume. For every point in an image, you must be able to specify the location of the corresponding point in the protein solution. For simplicity, you decide to model your optical apparatus with a single convex lens. Your group is investigating the relationships between the positions of points on an object and points in its image in two parts.

For this part, you investigate the relationship between a point of the object a distance from the principal axis and the distance of its corresponding point of the image from the principal axis.

Read Sternheim & Kane: sections 23.1, 23.4, 24.2 & 24.3

EQUIPMENT

You have an optical bench, a set of convex lenses in holders, a long filament lamp, a table clamp, three-finger clamp, screen and ruler.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a fairly large sketch, showing a convex lens and a source of light (such as a vertical arrow). Label the lens's focal points, and position the source so that an image will be created, which could be projected on a screen.
2. Determine the position of the image, by sketching the paths of two light rays from the top of the light source. Indicate the position of the image in your sketch. Where should you position the screen in order to see the image?
3. To your initial diagram, add a second object at the same position, but approximately twice as long. Determine the position and size of the image, as you did for the first object. How do the position and size compare to those of the original object?
4. From your diagrams and geometrical knowledge of similar triangles, write an equation that relates the height of the object to the height of the image, in terms of the *distance of the object from the lens* and *the distance of the image from the lens*.

5. Write an equation for the linear magnification in terms of *distance of the object from the lens* and *the distance of the image from the lens* (*Linear Magnification* is the ratio of *image height* over *object height.* The magnification is traditionally negative if the image is inverted.)
6. What shape would you predict for a graph of *magnification* vs. *distance of object from lens/distance of image from lens*? What is the significance of the slope of this graph? Where do you expect the graph to intercept the horizontal and vertical axes? How could you use such a graph to determine the distance from a point in an object to the principal axis of the optical system, if you knew the distance from the principal axis to the corresponding point in its image?

PREDICTION

Write an expression relating the size of an object to the size of its image, in terms of the distance from the object to the lens and the distance from the lens to the image. Explain how this can be used to relate the position of a point on an object to the position of a corresponding point on the image.

EXPLORATION

Position the long filament lamp, the convex lens, and a screen on the optics bench. Align the light source with the principal axis of the lens. Adjust their positions so that a focused image of the filament appears on the screen.

Cover part of the light source. If half of the light source is covered, what fraction of the image disappears?

Shift the light source in a direction *perpendicular* to the principal axis. How does the position of the image change? How does the image change as it moves further from the principal axis? If you double the distance of a chosen point on the filament from the principal axis, what happens to the distance of the corresponding point on the image from the principal axis?

MEASUREMENT

Measure the spacing of a unique characteristic of the light source that can easily be seen in the corresponding image .

Arrange the light source so that a clear image of the selected characteristic is projected on the screen. Measure *the distance from the object to the lens* and *the distance from the image to the lens*. Make any other measurements necessary to determine the linear magnification for this arrangement. Repeat with the same lens for at least two more variations in the distance of the object from the lens.

Repeat the above series of measurements with a second convex lens.

ANALYSIS

Did the linear magnification for each series of measurements agree with your predicted relationship between linear *magnification*, *the distance of the object from the lens*, and *the distance of the image from the lens*?

CONCLUSION

Is the linear magnification of an optical system solely a property of the lens in the system, or are other factors important as well?

Are your results consistent with your predictions? If not, explain the sources of any discrepancies. How does the position of a point on an image change as the corresponding point on the object is moved perpendicular to the principal axis?

If you know the distances *of the object and the image from the lens*, and the position of a point on an image, can you determine the corresponding position on the object?

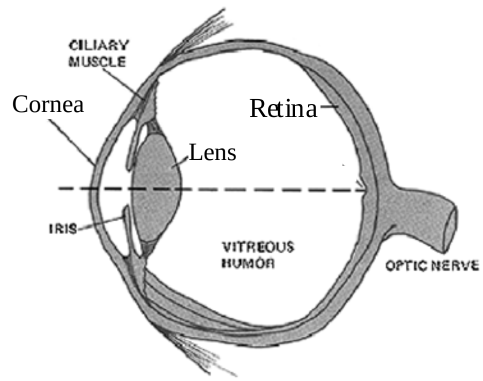
If an optical system has a linear magnification, and the image of an object moves upward a distance X perpendicular to the principal axis, how far did the object move, and in what direction?

You learnt about linear magnification. What is angular magnification? What is optical power of a lens? And what is the magnifying power of a lens? (note: they are NOT the same.)

PROBLEM #5: THE EYE – COMPENSATING FOR AN ARTIFICIAL LENS

A diagram of a human eye is shown. In an eye, the *cornea* and the *lens* can normally project a focused image of objects at a wide range of distances on the *retina*. To achieve such flexibility, the *ciliary muscle* in the eye can slightly change the shape of the *lens* to adjust its focal length.

Image of a Human Eye



Your friend's grandmother has just had cataract surgery. During the surgery, the flexible *lens* in one of her eyes was removed and was replaced with a plastic lens whose focal length cannot be adjusted. As a result, she can only see clear images of objects when they are held at one particular distance from her eye. Your friend's grandmother has asked you to recommend a corrective lens -- one that will help her see at close range. She already has a good corrective lens for seeing far away. Before making specific recommendations for a corrective lens, you and your group decide to work with a simplified model of her eye.

Your eye model will use a single convex lens to approximate the behavior of the inflexible lens and cornea, and a screen to take the place of the retina. You will use additional lenses to model the effects of corrective lenses for improving the vision of your eye model on close range objects. You will also be given one concave lens that allows your model to focus on a distant object - this will determine the dimensions of the eye model to be tested using the convex lenses.

Read Sternheim & Kane: sections 23.1, 23.4, 24.2, 24.3, 24.7 & 24.13.

EQUIPMENT

You have convex lenses and a single concave lens in lens-holders, a screen, a long-filament light bulb and clamps, masking tape, an optical bench and a ruler.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Sketch a model representing a surgically repaired eye, use an arrow as the object. Sketch a ray diagram to indicate the optimal position of the retina for "seeing" an object at this distance.
2. Sketch ray diagrams to show what happens to the image position if the object moves *closer* to the "eye," or *farther away* than in the first diagram. If a corrective lens were added in each situation, would it have to be convex or concave to project a clear image on the "retina"?
3. Calculations in this problem will be simpler if you can assume that the distance between the "eye" lens and the corrective lens is small relative to other distances, so that bending due to *both lenses occurs in a single plane*. Sketch a diagram of the eye model (without the "retina") with a corrective lens just in front of the "eye" lens. Indicate the focal points of both lenses.
4. To determine the position of an image produced by the system of two lenses, first draw a ray diagram to show the position of the image (real or virtual) that would be produced by *just the corrective lens*.
5. Then, treat the *image* (real or virtual) that would be produced by the corrective lens alone as the *object* (virtual or real) to be imaged by the "eye" lens. (The object is treated as virtual if it is on the same side of the "eye" lens as the final image will be, or real if it is on the opposite side.) Add rays to show the position of the final image, produced by the "eye" lens.
6. Label each important distance in your sketch. Use the diagram and, if you completed them, the results of your work on the earlier problems **Image Position** and **Image Size** to write down equations relating these distances. (Watch the sign conventions!) Write an equation for the focal length of the corrective lens, in terms of the focal length of the "eye" lens, the distance from the lenses to the object, and the distance from the lenses to the image.
7. What does it mean if your equation predicts a corrective lens with a negative focal length? A positive focal length? An infinite focal length? Is each result possible? Could each of the three cases describe an actual lens?

PREDICTION

Formulate an expression that gives the focal length of a corrective lens, to be used in conjunction with a fixed lens. You may assume that both lenses are on the same plane, i.e. that they are very close together. The corrective lens should allow an object at a specified distance from the lenses to produce an image at a specified distance from the lenses. You may assume that the corrective lens is "weaker" than the other lens, i.e. $|f_0| < |f_c|$.

EXPLORATION

Consider the constraints on an eye with an inflexible lens. Can the focal length of the lens change? Can the distance between the lens and the retina change? With these constraints in mind, construct a model on the optics bench. Experiment to determine the size your model should be. Using the simple eye model without any corrective lens you should be able to demonstrate that an object is out of focus at a large distance, clearly focused at a moderate distance, and out of focus at a short distance. See if you can focus on an image far away with the concave corrective lens. Can you focus an image outside the window?

Investigate the effect of increasing distance between the corrective lens and the eye lens. Why is it important for this distance to be minimized? With the equipment available, how can the distance be minimized? *Hint: Using tape to affix the eye lens to the back side of a corrective lens might be the best option.*

MEASUREMENT

Determine the focal lengths of the convex lenses you will use in this experiment as precisely as possible, using new measurements and/or your results from the previous problems **Image Position** and **Image Size.**

With the corrective concave lens, determine the size of your model eye (distance from lens to retina) by focusing an object that is far away. When you have successfully produced a clear image, record the positions and focal lengths of each lens, as well as the positions of the light source and screen.

Repeat with the convex lenses, focusing on close up objects.

ANALYSIS

Compare your measured results for the long distance with the predicted focal length f_c of the required corrective lens given by your prediction. For the short distance, calculate the focal length of the required corrective lens from your measurements, by using the relationship you predicted among *the distance of the object from the lens, the distance of the image from the lens*, the eye focal length and the focal length of a corrective lens.

CONCLUSION

How do your results compare to your predictions? If you made assumptions in the warm-up questions, how well were they met by your physical model of the eye? What effect would the observed deviations from those assumptions have on the comparison between your predictions and the measurements you made? Can you account for differences between your measurements and your predictions?

People with *myopia* are nearsighted, so that they can clearly see objects close to their eyes, while objects far away appear blurry. Use your results to answer the following questions about myopia. Should corrective lenses for nearsighted people be concave or convex? Myopia results from slightly misshapen eyeballs: are the eyes of myopic people too short (placing the retina too close to the lens) or too long (placing the retina too far from the lens)? Support your reasoning with a sketch.

People with *hyperopia* are farsighted, so that they can clearly see objects far away; however, objects that are close appear blurry. Use your results to determine whether corrective lenses for farsighted people should be concave or convex, and whether those people have eyeballs that are too short or too long. Support your reasoning with a sketch.

PROBLEM #6: MICROSCOPE

While studying bacteria cultures for a medical research laboratory, you are exhausted at the end of each day, which invariably includes hours bent over a microscope. One of your co-workers proposes a solution: projecting magnified images onto a screen, where observations could be made more easily. Your boss claims that this is impossible but is unable to explain why. You and your colleagues decide to investigate the optics in a model microscope, in order to determine whether the suggestion might work.

You decide to model your microscopes with a "simple" compound microscope: the "objective lens" -- a strong (short focal length) convex lens placed near the object to be imaged -- and an "eyepiece lens" -- a weaker (longer focal length) convex lens placed near the eye. If the lenses and object are arranged properly, you should see an inverted and enlarged image of the object when you look through the eyepiece lens. Is it possible to project an image from a microscope onto a screen?

Read Sternheim & Kane: sections 23.1, 23.4, 24.2, 24.3 & 24.11

EQUIPMENT

You have an optical bench, a set of convex lenses in lens holders, a long filament lamp, table and three-finger clamps, a screen and rulers.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a sketch to represent the compound microscope and an object, which meets the following specifications. The two lenses should share the same optical axis. The distance from the object to the objective lens should be between the focal length and 2 times the focal length of the objective lens. The position and focal length of the "eyepiece" lens will be determined in step 3 below.
2. Draw a ray diagram to show the position and size of the image that produced by the objective lens.
3. In a compound microscope, the *image* produced by the objective lens is the *object* for the eyepiece lens. The eyepiece lens will be placed so that the *image* from the objective lens is between the two lenses, and is at a focal point of the eyepiece lens. Add an eyepiece lens to create this arrangement in your sketch.
4. Add rays to show how light will travel after passing through the eyepiece lens. Do the rays converge or diverge? Does the eyepiece lens form a real or virtual image? If so, what is its location?
5. Does the microscope form an image that could be projected on a screen? If so, where should the screen be placed? If not, should it be possible to adjust the microscope so that it could project an image on a screen?

PREDICTION

Given an objective lens and an eyepiece lens with known focal lengths, determine appropriate positions for the two lenses and for an object to be imaged by a model microscope. Determine the position of the image produced, and predict whether or not that image could be projected on a screen.

EXPLORATION

Arrange an approximate model of a compound microscope before taking careful measurements. First, estimate the focal lengths of each lens you will use to model the microscope.

Position the light source and a convex lens with short focal length (the "objective") on the bench. Verify that the principal axis of the lens is parallel to the bench and passes through the center of the source. Find the position of the image formed by the objective lens.

Place another convex lens (the "eyepiece") in position so that the image formed by the objective lens is approximately at a focal point of the eyepiece lens.

Look through the eyepiece lens. Can you see an image of the light source? Is it inverted or erect? Does it appear to be enlarged? Can you estimate how much the image is enlarged? Can an image be projected onto a screen? What do you observe if you move the eyepiece lens along the principal axis, or if you adjust the position of the light source or objective lens? How can you tell when you have achieved the conditions described in the warm-up questions for a compound microscope?

Try focusing the microscope on the vertical filament light bulb. (The filament is very bright, so you may wish to focus on some other part of the bulb.) Can you focus on different parts of the bulb?

MEASUREMENT

Carefully determine the focal length of each lens you will use in the model microscope.

Place the light source and the objective lens at a convenient distance apart. Following the methods you developed in the exploration, adjust the position of the eyepiece lens until you have achieved the conditions necessary for a compound microscope. Measure and record the relevant positions and focal lengths.

Will the microscope project an image on a screen, or can it be adjusted to do so? If so, measure image positions, magnification, lens positions and light source positions, and describe the image produced.

Repeat the process for a new distance between the light source and objective lens.

Repeat, if possible with the same two distances between light source and objective lens, for a second eyepiece lens.

ANALYSIS

For each distance between the lamp and objective lens, compare the observed separation of the two lenses with the expected value, from the warm-up questions. Can you account for any discrepancies?

Qualitatively, how did the second eyepiece lens change the magnification of the microscope? Why did you (or why didn't you) expect this change?

CONCLUSION

How does the position of the eyepiece depend on the distance between the object and the objective lens, and on the focal lengths of the lenses?

Is it possible to use a microscope to project an image on a screen for observation, without extra optical equipment? Do you support your boss's claim that it is not possible? If it is possible, explain why or why not you think it could be useful.

PROBLEM #7: MIRRORS

You've read in one of your biology classes that the perception of vision begins with the focusing of light on your retina, but what was really interesting was that not all creatures do this the same way. Your curiosity really gets piqued because you've witnessed at night your cat's "glowing" eyes across the room. Although you know a cat's eye contains a lens, you wonder if to enhance brightness the reflection that you see is also focusing the light. To test this idea you set up a mirror and shine a light source on it and record the location of the image of the light source. To accomplish this, you must know the relationship between an object's distance from the mirror and the distance of its image from the mirror, along the principal axis.

Read Sternheim & Kane: sections 23.1, 23.4, 24.1, 24.2, 24.3 & 24.9

EQUIPMENT

You have an optical bench, a concave mirror, a long filament lamp and clamps, a screen and rulers.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

It is useful to have an organized problem-solving strategy such as the one outlined in the following questions.

1. Draw a fairly large sketch, showing a concave mirror and a source of light (a vertical arrow). Label the lens's focal points, and position the source so that an image will be created, which could be projected on a screen.
2. Determine the position of the image, by sketching the paths of two light rays from the top of the light source. Indicate the position of the image in your sketch. Where should you position the screen in order to see the image?
3. Repeat the steps above with a mirror of the same focal length, but with the light source farther away from the mirror. Has the image moved closer to or farther from the mirror?
4. From your ray diagrams and geometrical knowledge of similar triangles, write an equation that relates the distance between the lens and the image, the distance between the mirror and the object, and the mirror's focal length.
5. Solve the equation in step **4** for (1/ *the distance of the object from the mirror*). What do you predict as a shape for a graph of (1/the distance of the object from the mirror) vs. (1/the distance of the image from the mirror) for a mirror of fixed focal length? What are the values of the intercepts where the graph crosses each axis? Draw a

sketch of the graph shape you expect and indicate the expected values of the intercepts.

6. Solve the equation in step **4** for *distance of the object from the mirror*. What do you predict as a shape for a graph of *the distance of the object from the mirror vs. the distance of the image from the mirror* for a mirror of fixed focal length? Sketch the shape of the graph you expect. Does the graph cross each axis? If so, what are the values of the intercepts?

PREDICTION

Write out an expression that relates the distance of the image from the mirror, the distance of the object from the mirror, and the focal length of the mirror. Use this expression to predict features of the graphs of *the distance of the object from the mirror vs. the distance of the image from the mirror* and (1/*the distance of the object from the mirror*) vs. (1/*the distance of the image from the mirror*).

EXPLORATION

Estimate the focal length of the concave mirror. To do so, take advantage of a convenient source of light that is much more distant than the focal length of each mirror. (Where should light from a very distant object be focused?)

Position the light source, the concave mirror, and a screen on the optical bench. Align the light source with the principal axis of the mirror. Adjust their positions so that a focused image appears on the screen.

Move the source slightly toward and away from the mirror, each time adjusting the screen's position to show a crisp image. Does the direction in which you have to move the screen match your responses to the warm-up questions?

Try focusing an image of the vertical filament light bulb on the screen. Can you adjust the position of the screen, mirror, or bulb to project an image of the front part of the bulb on the screen? The filament? Other parts of the bulb?

MEASUREMENT

Record the positions of the image, mirror and light source for several distances between the mirror and the light source. In order to explore features of *the distance of the object from the mirror vs. the distance of the image from the mirror* and (1/*the distance of the object from the mirror*) vs. (1/*the distance of the image from the mirror*) graphs, record several measurements and plan your experiment so the data points are not "clumped together" on the graphs. Plot the points on each graph *as you go*. Take measurements for at least two different mirrors.

ANALYSIS

In the warm-up questions you predicted the shape of two different graphs. Choose one of these graphs to use for your measurements and determine the focal length of each mirror. Compare the focal length found on your graphs with the focal length calculated from your prediction equation.

CONCLUSION

You should know by now that this mechanism of the reflection focusing the light doesn't really work for the cat. Why? Where would the image be focused? The eye of a scallop does use a reflecting surface to focus light. What can you predict about where the "retina" for the scallop should be?

What is the fundamental difference between the quantities involved in determining the focal length of a *spherical* mirror versus that of a lens. [Don't merely write formulas. Think about the variables they depend on. Do you see why (not how) these variables should exist in determining the focal length of a lens and/or mirror?]

PROBLEM #8: TOTAL INTERNAL REFLECTION

On a clear sunny summer day after a full day of work you take a swim in a pristine Minnesota lake. As you sink to the bottom you look up to the water surface. Straight above you see the clear blue sky, but as you look down the surface the blue sky disappears. All you see is what looks like a dirty mirror rippling with the waves. You are puzzled and wonder if this has something to do with your sense of perception… or could it be the clarity of the lake water? (Maybe you shouldn't have opened your eyes!) You remember this whole mysterious episode during a physics lecture about refraction, total internal reflection, and a critical angle. Fast-forward to now… where you'll have a chance to investigate this puzzling experience in the lake in your next lab. To do this will use a container half filled with water and a laser to project a beam in the container. You will project the laser into the container at an angle so that the beam never leaves the water. Watch for the projection of the beam outside of the container. Your goal is to calculate and measure this critical angle.

Read Sternheim & Kane sections 21.1-21.4 & 23.5.

EQUIPMENT

You have a diode laser, a plastic half petri container partially filled with water, a ruler and a protractor.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

Read Sternheim & Kane sections 21.1-21.4 & 23.5.

1. Draw a sketch of the arrangement you will use to project the beam through the container. Include laser, laser beam, container, and label all angles and indices of refraction.
2. Draw another diagram with an enlarged view of the beam going through the plastic layer. Apply Snell's law to this thin layer. Does angle of refraction leaving the plastic layer ultimately depend on the index of refraction of the plastic layer
3. Since the beam doesn't start in the liquid you will have to account for the refraction at two locations. What are those two locations? You can assume that the water surface is perpendicular to the side of the container.
4. Write down the expressions for Snell's law at these two locations. Remember the one location is the critical situation where the beam ceases to leave the water. How is this critical situations expressed with Snell's Law? Also write down a

trigonometric relationship that relates angles at these two locations. You should have 3 relationships.

5. One relationship should be solvable for the critical angle of the first part of the prediction. The other two relationships can be manipulated to solve for the angle of the trajectory of the incident laser beam in terms of the critical angle.

PREDICTION

First, calculate the angle at which the beam ceases to exit the surface of the water. The angle is measured from the normal to the surface to the trajectory of the beam.

EXPLORATION

Warning: ***Laser beams may cause permanent vision impairment or blindness.*** **Do NOT allow the laser beam (or its reflection) to point into anybody's eye. To avoid stray beams in the laboratory, make sure beams from your laser terminate on a screen at all times. Laser beams are extremely intense compared to light from any common light source (even compared to sunlight, as viewed from earth). Permanent blindness may result from prolonged exposure to any laser beam, even those from small laser pointers.**

Arrange the container and shine the laser through the container. Adjust the trajectory of the laser and observe where the beam ends up so that you can determine if it exits the water surface.

As you adjust the laser trajectory, does the resultant beam move in a continuous or gradual manner or does it abruptly change? What would you expect?

MEASUREMENT

Once you have a solid understanding of the limitations of your measurements proceed to measure the angles.

ANALYSIS

Compare your angle measurements to your predicted values. Are they within your uncertainty? If not, reevaluate your uncertainty and/or take your measurements again. What is the minimum percent error you can attain?

CONCLUSION

Do your predicted angles match your measured angles? Is your uncertainty reasonable? (i.e. an uncertainty of +/- 1 m is unreasonable, or +/- 45 °). So back to the pristine Minnesota lake… what are you seeing when you aren't seeing the sky? Explain.

☑ CHECK YOUR UNDERSTANDING
LAB 1: GEOMETRIC OPTICS

1. Use a ray diagram to determine the size and position of the image when a 5 cm tall object is located 18 cm from a converging lens with focal length 9 cm.

2. What would happen if the same object were located 9 cm from a converging lens with focal length 18 cm?

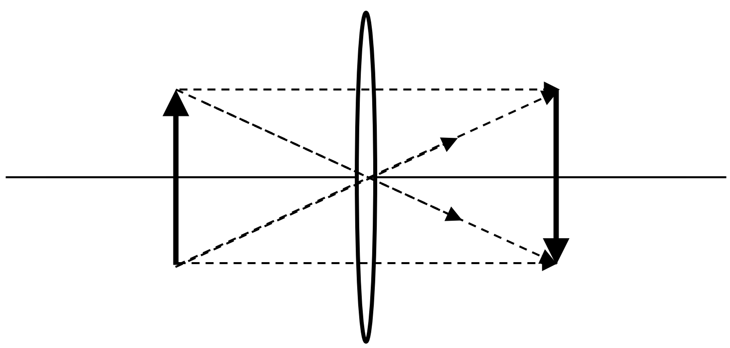
3. What would happen if the same object were located 18 cm from a converging lens with focal length 18 cm?

4. What would happen if the same object were located 18 cm from a diverging lens with focal length -18 cm?

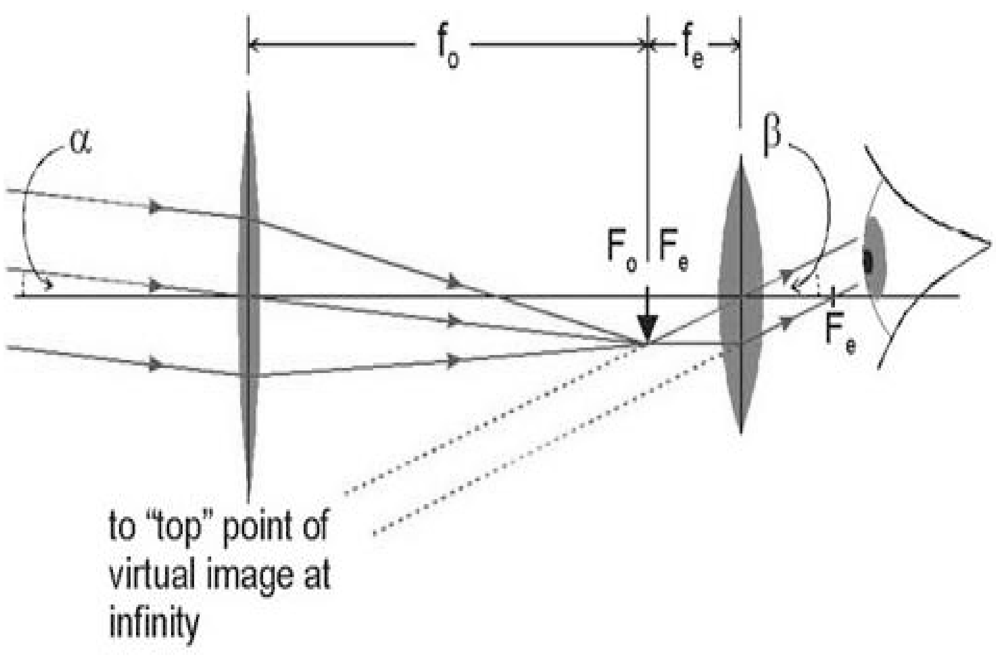
5. In any of the situations above, what would happen if the middle 2/3 of the lens were blocked?

6. In which of the situations above could an image be projected on a screen? In which of the situations above could an image be seen without a screen?

7. Describe the problems with the ray diagram below:



8. Describe the features of the optical instrument illustrated by the ray diagram below. Is this a diagram for a microscope or a telescope? Is the final image inverted or erect? Is the final image magnified?



PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: ______________

Course, Lab, Problem: ______________________________

Date Performed: ______________________________

Lab Partners' Names: ______________________________

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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

LAB 2: ENERGY AND ELECTRIC CIRCUITS

It is often useful to study physical systems to gain insight into biological ones because both obey the same fundamental principles. In addition, physical systems are easier to study because they are less complex than biological systems and can be more easily modified to test a hypothesis. Furthermore, using physical systems bypasses some moral and ethical questions inherent in experimenting with living organisms. Determining the relationships between simple physical systems and complex biological ones requires continually drawing on your knowledge, insight, and imagination to make the connections.

In this first laboratory, you will explore a system that has many features in common with biological systems. An electric circuit illustrates how energy can be transformed within a system, transferred to different parts of the system, and transferred out of the system. As with all biological systems, the source of energy within the system is a complex chemical interaction. In this case that source of energy is a battery. An electric circuit is similar to many biological processes that proceed through a cycle such as the Krebs cycle at the molecular level or the water cycle at the ecosystem level. In this case it is the electric charge that transports the energy from one place in the system to another. The key to understanding any cycle is to identify what is conserved in the process. In the case of an electric circuit, two conservation principles are important, conservation of energy and conservation of charge. These same two conservation principles also play crucial roles in all biological processes.

OBJECTIVES:

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

- Identify what is an electrical circuit and what is not.
- Use the concept of conservation of energy together with the concept of conservation of charge to describe the behavior of an electric circuit.
- Measure the current through an electric circuit element.
- Measure the voltage or potential difference between two points in an electric circuit.
- Use a digital multimeter (DMM) to measure various properties of an electric circuit.

LAB 2: ENERGY AND ELECTRIC CIRCUITS

PREPARATION:

Read Sternheim & Kane Chapter 17 sections 1-6 and 12.

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 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 difference between electrical current and voltage.
- Describe what is meant by a conservation principle.
- Describe the relationship between voltage and energy.
- Be able to write down Ohm's Law and identify all of the terms in the equation with physical quantities in an electric circuit.
- **Identify what physical quantity characterizes 'brightness'.**

PROBLEM #1: ELECTRICAL CONNECTIONS

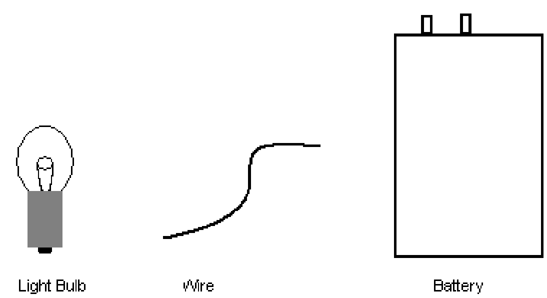
You are working for a research group that is studying the nerves in the retina of eyes. It is known that the neurons exchange signals via the flow of ions through junctions called synapses. You are interested in electrical synapses, abundant in the retina but rare everywhere else in the body.

Your research group decides to begin by using a battery, a wire, and a light bulb to make the simplest possible model of a single electrical synapse. In this model, chemical reactions in the battery provide the difference in voltage across the synapse that causes ions to flow from one neuron to the next. The flow of ions across the synapse is manifested in the bulb as light and heat. You are interested in modeling the flow of energy and charge, and your first step is to determine the simplest possible conditions under which energy can be transferred using a single battery, a single wire, and a single bulb. To do this you determine all of the possible configurations to light a bulb with a single wire and a single battery. How many different configurations will cause the bulb to light?

Read Sternheim & Kane Chapter 17 sections 1-6 and 12.

EQUIPMENT

You have a light bulb, battery and banana cable.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Make a drawing of a single light bulb connected to the battery with a single wire so that the bulb will light. What parts of each object must be touching for the light bulb to light? Is this the only configuration possible? If not, make drawings of other possible configurations.
2. What object in the circuit is the source of energy? Using your drawing(s), describe how the energy gets to the light bulb. What happens to the energy after it gets to the light bulb?

3. Along which path is the energy carried? Draw arrows to indicate the path of the energy carriers. Are the energy carriers conserved or do they just disappear at the light bulb? If they are conserved, where do they go after delivering energy to the light bulb?
4. What does the battery voltage have to do with this energy? How are the energy carriers related to the electric charge?
5. Using your drawing, describe how conservation of energy applies to the system defined as the light bulb while the bulb is lit. Identify the initial energy of the system, the final energy of the system, any energy entering the system, and any energy leaving the system.
6. Using your drawing, describe how conservation of charge applies to the system defined as the light bulb while the bulb is lit. Identify the initial charge of the system, the final charge of the system, any charge entering the system, and any charge leaving the system
7. Check the drawing(s) you made in question 1. Does it obey conservation of energy? Does it obey conservation of charge? If the answer to any of these questions is no, change your drawing so that the answers are yes.
8. Write down the general properties of an electric circuit that always obeys conservation of energy and conservation of charge and lights the bulb.

PREDICTION

How many ways can you connect the bulb, battery, and wire to make the bulb light?

EXPLORATION

Look closely at the inside and the outside of a bulb. Draw what you see. How are parts inside of the bulb connected to the outside of the bulb? If you can't see the connection, make a reasonable guess based on what you do see. What part of the bulb do you think actually lights? What parts of the bulb do you think conduct electricity and what parts do not?

Connect the bulb, battery, and wire as drawn in the warm-up questions. Does the bulb light? If not, try another configuration until you find one that does light. Draw all of the configurations that do not work as well as the ones that do.

Check which part of the bulb lights. Does it agree with what you thought initially?

Can the positive and negative ends of the battery be switched without affecting the operation of the circuit? Can the two ends of the bulb be switched? Are there any parts that cannot be switched? Write down a plan to systematically check all configurations you think might light the bulb.

MEASUREMENT

Connect the battery, bulb, and wire according to the plan that you wrote down in your Exploration section. Carefully make a drawing of each way you connect the items and the result of whether or not the bulb lights. Also write down the comparative bulb brightness for each configuration.

ANALYSIS

Examine your pictures of situations where the bulb lights and compare them with pictures of situations where the bulb did not light. Also compare the brightness of the bulb in each situation. Write down a general rule for connecting the objects together so that the bulb will always light. What is important and what makes no difference? Estimate how well you can determine relative bulb brightness. Can you tell the difference between a bulb lighting and not lighting?

CONCLUSION

What are the necessary conditions for energy transfer in an electric circuit? How many ways were you able to connect the bulb, wire, and battery to make energy transfer possible? What do these connections have in common? What is different among them? What are the general requirements for a simple working circuit? Compare your results to your predictions.

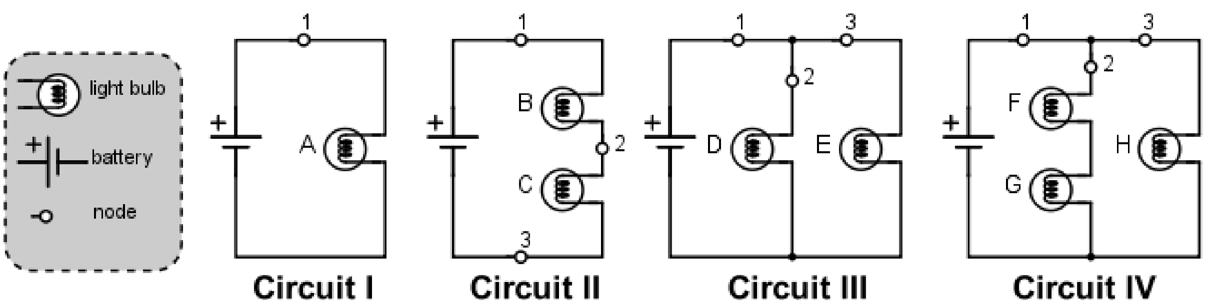
PROBLEM #2: QUALITATIVE CIRCUIT ANALYSIS

You are working at the Minnesota Arboretum testing the effects of light intensities on apple color. You have one area that you wish to expand so you decide to add another light fixture. 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.

Read Sternheim & Kane Chapter 17 sections 2 & 5.

EQUIPMENT

You will build four simple circuits shown below out of wires, bulbs, and batteries. Use the accompanying legend to build the circuits.



Note: Check to make sure the light bulbs are all of the same type. To find identical bulbs look for markings on the base and check to see that the color of the bead separating the filament wires is the same.

Read the section *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

First, qualitatively identify what physical quantity identifies 'brightness'. Don't throw random guesses. Ask yourself qualitatively: when you say a bulb is bright/dim what physical output from the bulb helps you distinguish this? Next, quantify this physical quantity through a physical variable. How does this variable (quantifying brightness) relate to the other electrical quantities you have learnt so far?

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. Use the expression for the physical quantity that identifies brightness to make your predictions.

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. If the bulbs are identical, they should have the same brightness in the same circuit.

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.

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?

Circuit IV

Connect Circuit IV. Compare the brightness of bulbs F and G with that of H. 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 B and C compare to the brightness of bulbs G and H? What can you infer about the current at point 1 in each of the two circuits?

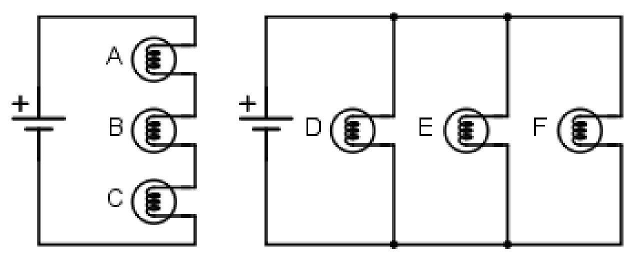
Comparing the four circuits, does the amount of current at point 1 appear to remain constant or to depend on the number of bulbs and how they are connected?

CONCLUSION

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

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

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



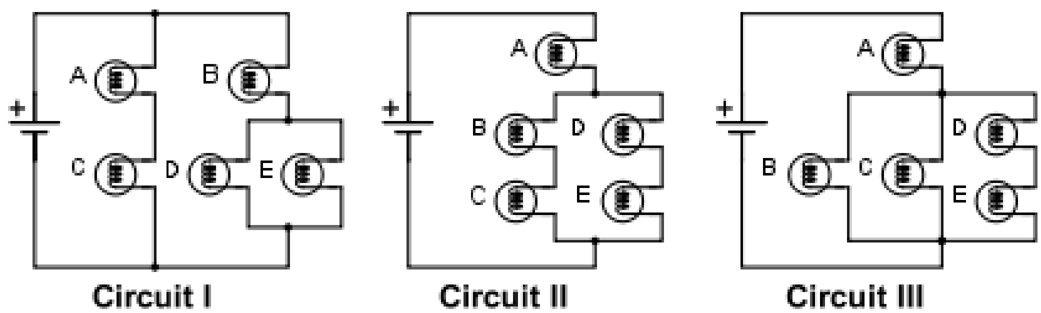
PROBLEM #3: QUALITATIVE CIRCUIT ANALYSIS B

You have a summer job in a Medical Equipment company. To ensure that the company's products meet safety requirements, you often have to judge current flows through different parts of complex circuits. You have been checking your work by tediously re-calculating each current. A fellow worker suggests that a qualitative analysis of the circuit could allow you to catch some kinds of mistakes very quickly. You decide to try this technique on several circuits for practice, modeling circuit elements with light bulbs. You reason that the relative brightness of bulbs in a circuit indicates the relative sizes currents passing through them. Compare the brightness of the bulbs in each of the circuits shown below.

Read Sternheim & Kane Chapter 17 sections 2 & 5.

EQUIPMENT

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



Note: Check to make sure the light bulbs are all of the same type. To find identical bulbs look for markings on the base and check to see that the color of the bead separating the filament wires is the same.

Read the section *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

First, qualitatively identify what physical quantity identifies 'brightness'. Don't throw random guesses. Ask yourself qualitatively: when you say a bulb is bright/dim what physical output from the bulb helps you distinguish this? Next, quantify this physical quantity through a physical variable. How does this variable (quantifying brightness) relate to the other electrical quantities you have learnt so far?

PREDICTIONS

1. Complete the following predictions. For each prediction, state your reasoning. Use the expression for the physical quantity that identifies brightness to make your predictions.

Circuit I:

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 II:

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 III:

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?

2. Using equations in your text for finding equivalent resistances and your conceptual understanding of circuits, predict the relative brightness of bulb A in the three circuits.

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 the "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 to measure the current through bulb A in each of the three circuits.

You should read the section in the appendix on using the DMM. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

CONCLUSION

Quantitative circuit analysis results from applying conservation of energy (Kirchhoff's loop rule) and conservation of charge (Kirchhoff's junction rule) to series and/or parallel configurations. For each circuit, write the corresponding equation(s).

PROBLEM #4: RESISTORS AND LIGHT BULBS

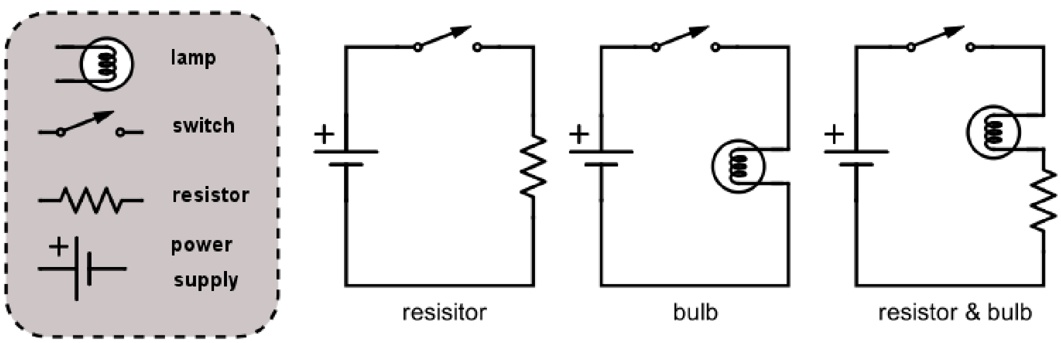
Talking with a friend about the role of electric circuits in biological systems, you realize that a light bulb may not be a good model for biological electrical energy transfer. The light bulb is a useful laboratory tool because it is easy to observe differences in the rate of energy transfer by observing its brightness. However, to give off light, the bulb filament must be raised to a temperature well above that of any biological system. There is a common electrical device called a resistor that transfers energy out of the electric circuit without the extreme behavior of a bulb. For this reason, the resistor might be a better object to model biological processes such as those in which an electric current results from the motion of ions through a cellular membrane.

As a first step in determining the similarities and differences of the electrical properties of light bulbs and resistors, you draw a graph of the relationship between the voltage across a light bulb to the current through the light bulb and compare it to a resistor. You decide to check your graphs by making the relevant measurements in the laboratory. Determine how the current through a light bulb depends on the voltage across it. How does that relationship compare to that for a resistor?

Read Sternheim & Kane Chapter 17 sections 2 & 5.

EQUIPMENT

You have banana wires, an 18V/5A power supply, digital multimeter (DMM), light bulb, and resistor. The power supply has the same function as a battery, to supply energy to the circuit by maintaining a constant voltage or potential difference. Because this voltage is not the result of chemical reactions, it is easy to change the voltage across the power supply within some range.



Read the section *The Digital Multimeter (DMM)* and *Resistor Codes* in the **Equipment** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

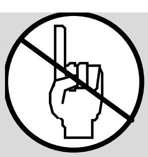
WARM UP

1. Draw a picture of a circuit containing one battery, one resistor, and two wires. On the picture show how you would insert a device to measure the voltage across the resistor. Now redraw the picture of the battery, resistor, and wires showing how you would insert a device to measure the current through the resistor.
2. Draw a graph of voltage across an object vs. the current through the object as given by Ohm's Law. How does one determine the resistance of the object from this graph?
3. As more current goes through a light bulb, it gets brighter because it gets hotter. Do you expect the increasing temperature to change the bulb's resistance? If so, how? Draw a graph of voltage across a light bulb versus current through a light bulb that shows your expectation of its resistance.

PREDICTION

Sketch a graph describing your expectations of the relationship between the voltage across a resistor and the current through the resistor. On your graph also sketch your expectation for the behavior of a light bulb.

EXPLORATION



WARNING: You will be working with a power supply that can generate 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. Never grasp a wire by its metal end.**

Connect your light bulb to the power supply in a circuit. Go through the range of voltages and observe the brightness change of the bulb. Decide on a range of voltages to use for your measurements. Looking at your prediction graph, determine how many measurements you should take and at what voltages. How many points are necessary to check your prediction when the bulb is dim? When the bulb is bright?

See the section on using the DMM in the appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Make sure that your DMM is set to measure a current or is set to measure a voltage depending on how it is connected in your circuit. Using a DMM to measure a current in a voltage-measuring configuration may damage the meter.

MEASUREMENT

Follow the measurement plan that you decided upon in the Exploration section for the light bulb and the same plan for your resistor. Make sure that your DMM is connected so that it measures either the voltage across the light bulb (or resistor) or the current through it. To make sure you are making reasonable measurements, check the resistance of your resistor by the following independent techniques. Compare these determinations with each other and with the results of your graph.

1. Use the color code on the resistor. What is the uncertainty in this value?
2. Use the DMM set to ohms to directly measure the resistance of the resistor. To do this the resistor must be disconnected form the circuit. What is the uncertainty in this value?

ANALYSIS

Make a graph of voltage versus current for your resistor and light bulb. Use the graph to determine the resistance of the resistor as a function of voltage (or current). Use the graph to determine the resistance of the light bulb as a function of voltage (or current).

CONCLUSION

Do the resistor and light bulb have the same electrical behavior? If so, what are their resistances? If not, is there a range of voltages where they have approximately the same behavior? Did your prediction match your results? Explain why or why not.

What are possible sources of systematic uncertainty? (If you need help determining uncertainty see the appendices) Does the equipment contribute any? Do you? Be specific in explaining how and why.

PROBLEM #5: SHORT CIRCUITS

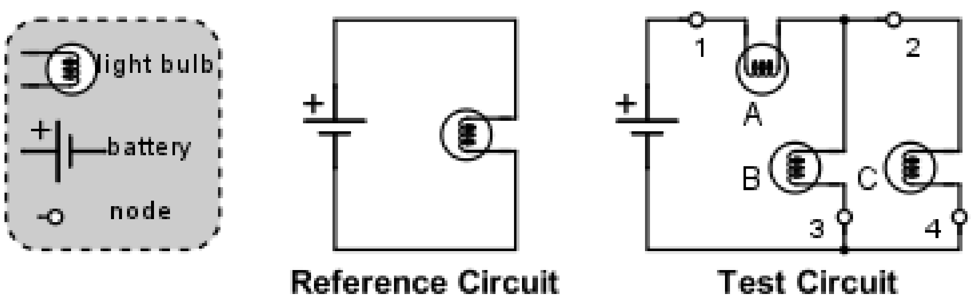
You have a part time job with a company that tests pacemakers. Pacemakers deliver electrical energy to the heart using a number of transducers. One possible failure mode of a pacemaker circuit is developing a low resistive current path, or short circuit, through surrounding tissue after implantation in the body. Your assignment is to see how this failure mode affects the functioning of the pacemaker transducers. You first want to determine how a low resistance path around a transducer affects the current through that transducer and thus its ability to deliver signals to the heart. You also need to determine how that low resistance path affects the current from the battery and thus the battery operational lifetime. Since you cannot induce these faults in a living person, you have been asked to make an electric circuit as a model of the process.

To make the effects visual, you decide to use light bulbs to model the transducers. The test circuit consists of a light bulb with one side connected to a battery and the other connected to two light bulbs in parallel. The other end of the parallel combination is connected back to the battery such that all of the bulbs light. For identical light bulbs you calculate the current through the battery and each bulb for the case of no short circuit and for all other cases where a short circuit develops as specified below. To make your calculations easier, you assume that each light bulb has a constant resistance and that the short circuit path has zero resistance. You will then check your calculations by measuring the relevant voltage differences and currents in your circuit.

For the test circuit, determine how a short circuit between two points in the circuit affects the brightness of each bulb. Calculate the current through each bulb, the voltage across each bulb, and the current output from the battery for each case.

Read Sternheim & Kane Chapter 17 sections 2- 5.

EQUIPMENT



Note: Make sure that you are using identical light bulbs. Look for markings on the base of the bulb and check to see that the color of the bead separating the filament wires is the same.

Read the section *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a diagram of the test circuit. Compare the potential differences across pairs of points (taken from the four points labeled) with each other and with the voltage across the battery. Label the voltage across each bulb. Compare the voltage across each bulb with the voltage between the labeled points. Explain why you think it is smaller, equal, or larger than the voltage across the battery.
2. Draw and label the current through each wire on the circuit diagram. Use conservation of charge to determine how these currents are related.
3. Using your circuit diagram follow an energy carrier (say a positive charge) from the battery around a complete circuit back to the battery. Use conservation of energy to write down an equation (or equations) relating the voltage differences across each bulb. You may need to consider more than one path for the charge to take.
4. Write down equations relating the voltage difference across each bulb to the current through that bulb using Ohm's law as an approximation
5. Using the equations from questions 2, 3 & 4; can you solve for the current through the battery? If not, find a different path around a complete circuit and write down the voltage equation for that path. Continue this process of choosing paths and writing down voltage equations until you have enough equations to solve for the current through the battery.
6. How is the brightness of a bulb related to the rate of energy transferred to the bulb? Write down an equation showing how the current through the bulb determines its brightness. Write down an equation showing how the voltage across the bulb determines its brightness.
7. Draw a wire between point 1 and point 2. How does the voltage across each bulb change? How does this voltage change affect the brightness of each bulb?
8. Now repeat questions 2 and 3 with this new circuit.
9. Repeat the above steps for the other short circuit configurations described in the Prediction section.

PREDICTION

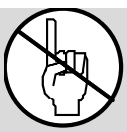
Determine the brightness of each of the bulbs when a wire is attached from point 1 to point 2 by calculating the current through each bulb in terms of the battery voltage and bulb resistance. Calculate the current output by the battery as a function of the battery voltage and bulb resistance.

Determine the brightness of each of the bulbs when a wire is attached from point 2 to point 3 by calculating the current through each bulb in terms of the battery voltage and bulb resistance. Calculate the current output by the battery as a function of the battery voltage and bulb resistance.

Determine the brightness of each of the bulbs when a wire is attached from point 1 to point 3 by calculating the current through each bulb in terms of the battery voltage and bulb resistance. Calculate the current output by the battery as a function of the battery voltage and bulb resistance.

Determine the brightness of each of the bulbs when a wire is attached from point 2 to point 4 by calculating the current through each bulb in terms of the battery voltage and bulb resistance. Calculate the current output by the battery as a function of the battery voltage and bulb resistance.

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. **Only apply the short circuit for a small amount of time**.

Build the test circuit and make sure all of the bulbs light. Try touching a wire to make a short circuit for a very small amount of time. Determine the shortest time necessary to make a reliable observation of the bulb brightness. Use this technique to make your measurements.

Read the section on using the DMM in the appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Decide how you will insert a DMM in your circuit to measure the current from your battery. Make sure the DMM has the correct setting before you put it in the circuit to prevent damage to the meter. Does the DMM significantly affect your circuit? Look at the brightness of the bulbs before and after you insert the DMM. Determine how long you will need to keep a short circuit connected to make an accurate measurement with your DMM.

Decide on the best way to make the set of measurements that you need.

MEASUREMENT

Follow the measurement plan that you decided upon in the Exploration section using the reference circuit for brightness comparisons and the DMM for current measurements.

ANALYSIS

Examine your circuit diagrams for the three bulbs with each short circuit and compare the brightness of the bulb in each situation. Estimate how well you can determine relative bulb brightness. Does this qualitative brightness determination agree with your quantitative current measurements?

Does the resistance of your DMM affect the current measurements in each case? Does introducing the DMM to measure the current through a bulb have a noticeable effect on the brightness of that bulb? Estimate the size of this effect.

CONCLUSION

Did your predictions match your observed results? Explain your answers. What effects might such malfunctions have on human patients?

PROBLEM #6: QUANTITATIVE CIRCUIT ANALYSIS

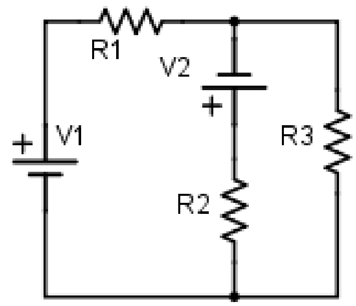
You work with a team building networks of circuits designed to imitate the behavior of networks of neurons in the brain. You are assigned the job of tuning the parameters of a circuit that represents a feedback loop within a single neuron. You run into trouble in your calculations, and decide to test some of your assumptions about variations in the current supplied to your feedback circuit, using the model circuit shown below. Determine the current through each resistor in the circuit shown.

Read Sternheim & Kane Chapter 17 sections 2 & 5.

EQUIPMENT

Build the circuit shown to the right with wires, resistors, and a voltage source (batteries or a power supply).

You have a digital multimeter (DMM) for measuring resistance, current and voltage.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw and label a circuit diagram, showing all voltage differences and resistors.
2. Label the current through each circuit element. Give the same label to currents that are equal.
3. Choose the circuit paths you will use and label them on the diagram.
4. Write down an equation that represents conservation of current to each independent point in the circuit where wires come together.
5. Use conservation of energy to get the sum of the potential differences across all 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 wrote above matches the number of unknowns.
6. 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.

PREDICTION

Write an expression for the current through each resistor in the circuit, in terms of the resistances and voltages labeled in the circuit diagram.

EXPLORATION

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Build the circuit. 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, the current flowing through each resistor and the potential difference provided by each battery in the circuit. So that you can check your measurements, measure the potential difference across each resistor.

ANALYSIS

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

CONCLUSION

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

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

PROBLEM #7: QUANTITATIVE CIRCUIT ANALYSIS B

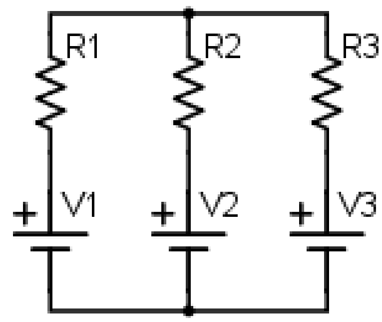
You again work with a team building networks of circuits designed to imitate the behavior of networks of neurons in the brain. You are assigned the job of tuning the parameters of a circuit that represents a feedback loop within a single neuron. You run into trouble in your calculations, and decide to test some of your assumptions about variations in the current supplied to your feedback circuit, using the model circuit shown below. Determine the current through each resistor in the circuit shown.

Read Sternheim & Kane Chapter 17 sections 2- 5 & 12.

EQUIPMENT

You will have wires, resistors, batteries and a power supply to build a circuit shown to the right. *A power supply must be used for one battery to vary the current.*

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



Circuit I

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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. Label the current going through each circuit element (in this case resistors and batteries.)
3. Choose the circuit paths you will use and label them on the diagram. Make sure they are independent.
4. Write down Ohm's law for every resistor.
5. Write down an equation that represents conservation of current to each independent point in the circuit at which wires come together (a junction).
6. Use conservation of energy to get an equation for the sum of the potential differences around each loop you have chosen.

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

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

PREDICTION

Calculate the current through each of resistors in Circuit I as a function of voltages of the batteries and resistances involved in the circuit.

EXPLORATION

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

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

Complete your measurement plan.

MEASUREMENT

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

ANALYSIS

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

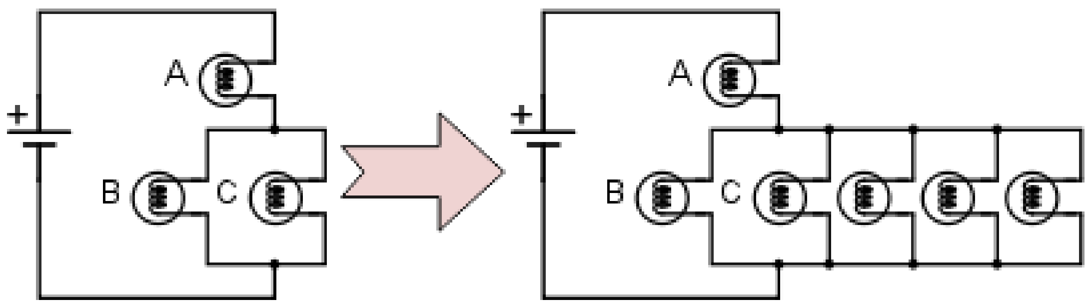
CONCLUSION

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

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

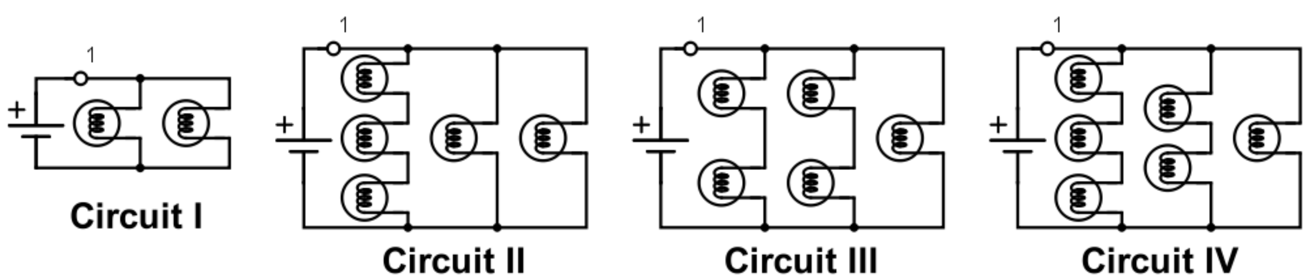
☑ CHECK YOUR UNDERSTANDING
LAB 2: ENERGY AND ELECTRIC CIRCUITS

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

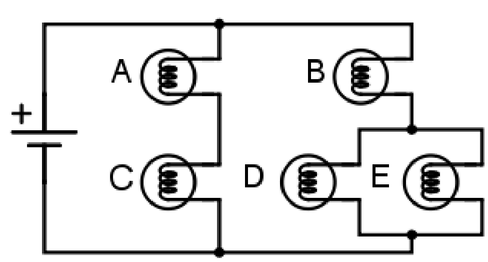


In household circuits, a fuse or circuit breaker is in the position occupied by bulb A, why?

2. Rank Circuits I through IV from the largest current at point 1 to the smallest current at point 1. Explain your reasoning.

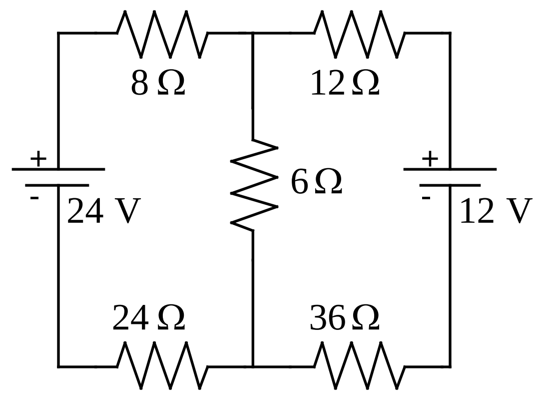


3. Predict what will happen to the brightness of bulbs A, B, C and D if bulb E were removed from its socket. Explain your reasoning.

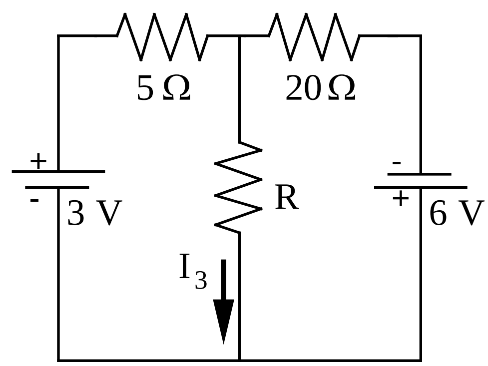


☑ CHECK YOUR UNDERSTANDING
LAB 2: ENERGY AND ELECTRIC CIRCUITS

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?

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: __________
Course, Lab, Problem: ______________________________
Date Performed: ______________________________
Lab Partners' Names: ______________________________
____
____

	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

LAB 3: ENERGY AND CAPACITORS

All biological systems rely on the ability to store and transfer electrical energy. One feature that many of these systems have in common is a structure that behaves like a capacitor, the simplest device that stores electrical energy. By studying the way capacitors store and transfer energy, you can gain insight into the way many biological systems store and transfer energy. In this laboratory you will investigate the storage and transfer of energy in capacitors.

The problems in this lab involve transferring stored electrical energy as work or as light.

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.
- Describe the rate at which a capacitor loses or gains energy based upon the system in which it is involved.

PREPARATION:

Read Sternheim & Kane Chapter 6 section 4, Chapter 16 sections 9 & 11, Chapter 17 section 7 and Chapter 18 section 4.

Before coming to lab you should be able to:

- Calculate the energy stored in a capacitor as a function of its capacitance and its voltage.
- Calculate the energy of an object given its speed and mass.
- Solve the rate equation, $\frac{dN(t)}{dt} = A \cdot N(t)$, and understand all quantities involved.

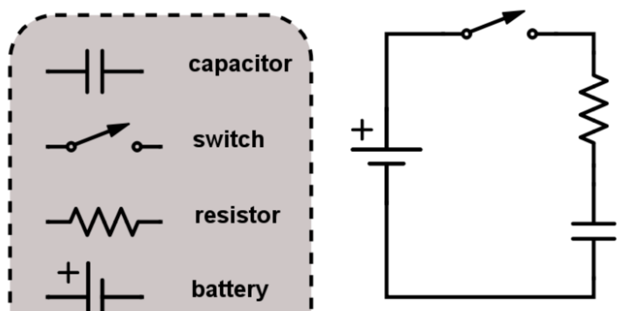
PROBLEM #1: CHARGING A CAPACITOR

One summer you volunteer at a summer biology camp for high school students. You plan to demonstrate the effect of lightning on the creation of organic substances. To imitate the lightning, you plan to discharge a capacitor into the atmosphere. Each time the capacitor is discharged, it must be recharged for the next demonstration. To save time, you want to charge the capacitor as fast as possible. However, you are not sure whether the resistance in series with the capacitor should be small or large to achieve quick recharging of the capacitor. To find the answer, you model the circuit with a capacitor, a resistor, and a battery in series. In 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 1/8 of its initial value depend upon the resistance of the resistor?

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

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



Circuit I

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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. Write an equation for the sum of all potential differences in a closed loop.
3. Write down the relationship between the potential difference across the capacitor and the charge separated on its plates? Write down the relationship between the current through the resistor and the voltage across it? Are these equations always true, or only for specific times?

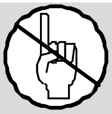
4. Use these relationships to rewrite your potential difference equation for the closed loop in terms of the voltage of the battery, the capacitance of the capacitor, the resistance of the resistor, the current through the circuit, and the charge separated on the capacitor.
5. Explain how each of the 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 in the circuit at these two times? What is the charge on the capacitor at these two times?
6. Write an equation relating the rate that charge accumulates on the capacitor to the current through the circuit. To do this, determine how the rate at which the charge on the capacitor is changing relates to the rate at which charge comes from the battery. Then, determine how the rate at which charge comes from the battery relates to the current in the circuit.
7. The unknown quantity in your loop equation is the current in the circuit and the charge on the capacitor. You need to eliminate the charge on the capacitor from your equations to obtain an equation for the current in the circuit in terms of the known quantities. You may find it helpful to differentiate both sides of the equation with respect to time and use the relationship from step 6 to eliminate the charge.
8. Solve the equation from the previous step for current 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.
9. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current obtained above (what is the current when t=0?)
10. Using your equation for the current, write an expression for the time taken for the current to fall to half its initial value. Now find an expression for the time taken for the current in the circuit to halve again, and so on. How does the time for the current to halve change as the time since the circuit was closed increases?
11. How does the time it takes for the current to drop to 1/8 of its original value compare to the time it takes for the current to drop to 1/2 of its original value? How does that time depend on the resistance in the circuit? Sketch a graph of that time vs. the resistance.

PREDICTION

How does the time taken for the current in the circuit to fall to 1/8 of its initial value depend upon the resistance of the resistor?

Sketch a graph of the time taken for the current to fall to 1/8 of its initial value 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.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

If you have not done so, read about using the DMM in the appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit before you build it. 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?

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, build the circuit **with a light bulb in place of the resistor**, but leave the circuit open.

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?

Build the circuit, including a DMM in the circuit to measure the current. 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 value and a range of resistances that allow you to most effectively construct a graph to test your prediction.

Complete your measurement plan.

MEASUREMENT

Measure the time taken for the current in the circuit to drop to 1/8 of its initial value for different resistance of the resistor. Do this at least twice for each resistor for averaging.

ANALYSIS

Using the measured values of the capacitance of the capacitor, the resistances of the resistors, and the voltage of the battery, construct a graph of your prediction of the time it takes the current to drop to 1/8 of its initial value vs. resistance. Using your data, construct a graph of the measured times versus resistance.

CONCLUSION

How does the time for the current in the circuit to drop to 1/8 of its initial value depend upon the value of the resistor? Compare your prediction result with your measurement result. Explain any differences.

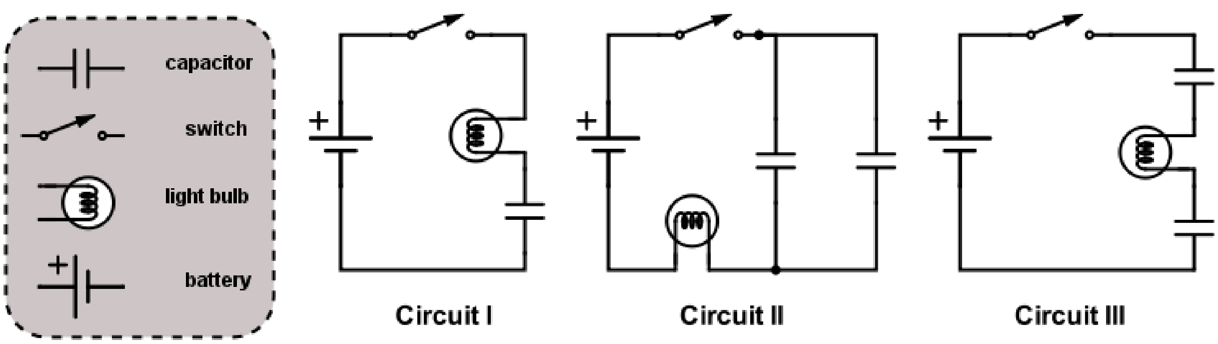
PROBLEM #2: CONNECTION OF TWO CAPACITORS

You are working in a research group that is studying the effect of sudden currents on protein suspensions. The method used in the research is to charge a capacitor and discharge it to provide a large current. One day, you need to increase the capacitance of the capacitor to get larger discharging current. However, no larger capacitor is available. Fortunately, you have another capacitor with the same capacitance as the original. You wish to use both capacitors at the same time, but you are not sure how to connect the two capacitors together to achieve maximum capacitance. To model the situation, you set up three kinds of circuits with the capacitors. For each, you will investigate how long it takes for the bulb to dim after the circuit is closed. You think that the longer the time the bulb is lit, the larger the capacitance. How does the capacitance of two capacitors in parallel compare to that of two capacitors in series?

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

Build the circuits shown below out of wires, resistors and light bulbs, capacitors with equal capacitance, and batteries. You will also have a stopwatch and a digital multimeter (DMM).



Note: Check to make sure the light bulbs are all of the same type. To find identical bulbs look for markings on the base and check to see that the color of the bead separating the filament wires is the same.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. For each of the circuits, draw a circuit diagram. 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 II? What about the two capacitors of Circuit III? When will the bulb go out?

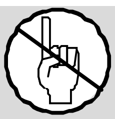
2. Recall from Kirchhoff's loop rule that the sum of potential differences across each element around any closed circuit loop is zero. Write an equation relating the potential difference across each of the elements of Circuit II. Do the same for two closed circuit loops in Circuit III. What is the relationship between the charges on the two capacitors in Circuit II? What is the relationship between the charges on the two capacitors in Circuit III?
3. 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 the bulb and the voltage across it? Are these equations always true, or only for specific times?
4. Use these relationships to rewrite your Kirchhoff loop equations in terms of the voltage of the battery, the capacitance of each of the capacitors, the resistance of the bulb, the current through the circuit, and the charge stored on each of the capacitors.
5. 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 in the circuit between these two times? What is the charge on each of the capacitors between these two times?
6. Write an equation relating the rate that charge accumulates on each of the capacitors to the current through the circuit. To do this, determine how the rate at which the charge on each of the capacitors is changing relates to the rate at which charge comes from the battery. Then, determine how the rate at which charge comes from the battery relates to the current in the circuit.
7. The unknown quantities in your loop equations are the current in the circuit and the charge on each of the capacitors. You need to eliminate the charge on each of the capacitors from your equations to obtain an equation for the current in the circuit in terms of the known quantities. You may find it helpful to differentiate both sides of each equation with respect to time and use the relationship from step 6 to eliminate the charge.
8. Solve the equation from the previous step for current 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.
9. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current obtained above (what is the current when t=0?).
10. Complete the above steps for the all of the circuits. How does the equation for current as a function of time compare for Circuits I, II, and III? Sketch a graph of

current versus time for all three circuits (plot them on the same graph). In which circuit do you expect the bulb to go out first?

PREDICTION

Graph the current in each of Circuits I, II, and III as functions of time, assuming each capacitor has the same capacitance. Rank the total time it takes for the bulbs in Circuits I, II, and III to turn off from shortest to longest.

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

Pay attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build 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 your two capacitors have the same capacitance. Begin your observations by using bulbs instead of resistors.

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

Build Circuit III, but do not close the circuit. 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 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.

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

Draw graphs of the measured values of the current as a function of time for each of the circuits I, II, and III.

CONCLUSION

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

PROBLEM #3: QUALITATIVE CAPACITORS

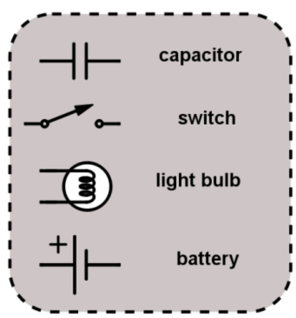
You and a friend are discussing how ion concentrations on either side of a cell membrane change with time. In particular you want to investigate how ions (say Na+) migrate and how voltage across the membrane builds up over time. To clarify this, you model the cell membrane very crudely as a capacitor in series with a light bulb and battery. A capacitor can be thought of as a device used to hold separated charges (similar to the cell membrane). Your friend claims 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? In a circuit consisting of a battery, bulb, and capacitor; determine how the brightness of the bulb changes with time.

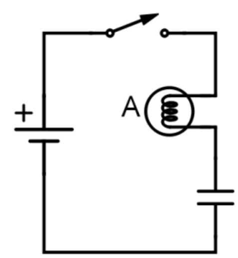
Note: This problem, and the problems **Quantitative Capacitors** and **Rates of Energy Transfer in RC Circuits** are fundamentally similar. This problem involves a qualitative analysis of an RC circuit, **Quantitative Capacitors** involves a quantitative analysis, and **Rates of Energy Transfer in RC Circuits** analyzes RC circuit behavior from the point of view of energy transfer to or from the capacitor.

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

You have wires, bulbs, capacitors and batteries. Use the accompanying legend to help you build the circuit. You also have a stopwatch and a digital multimeter (DMM).





Circuit I

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

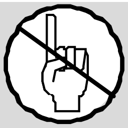
PREDICTION

How do you think the brightness of the light bulb changes over time?

What is it that makes the light bulb glow? Explain.

Sketch a graph of the brightness of the bulb, as a function of time, assuming the capacitor to be initially uncharged. Is there a limit as to how much charge the capacitor can hold?

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

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? How do you check if the capacitor is charged? How can you tell if the capacitor is completely charged? How can you be sure the capacitor is not charged?

After you are convinced that all of the circuit elements are working and that the capacitor is not charged, build the circuit but do not make the final connection yet.

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

From your observation of the bulb's brightness, how does the current going through the bulb change over time? You can check this using the DMM set for current. How does the charge on the capacitor change over the same time? Can you measure this with the DMM? Use conservation of energy to explain what you observe.

From what you know about a battery, how does the voltage across the battery change over time? Check this using the DMM set for Volts. From your observations of the brightness of the bulb, how does the voltage 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 energy to explain what you observe.

After a few moments, open the circuit. Is the capacitor charged or not? 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, will the bulb light if you close the circuit and the capacitor is charged? Uncharged? Try it. Was the capacitor charged before you closed the circuit? Was the capacitor still charged long after the circuit was closed? Use conservation of energy to explain your results.

CONCLUSION

Was your friend right about how the brightness of the bulb changed over time?

Sketch a qualitative graph of the brightness of the bulb as a function of time after you complete the circuit. How does this compare to your prediction?

PROBLEM #4: QUANTITATIVE CAPACITORS

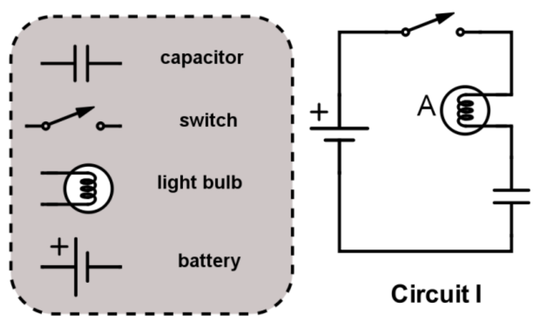
You and a friend are discussing how ion concentrations on either side of a cell membrane change with time. In particular you want to investigate how ions (say Na+) migrate and how voltage across the membrane builds up over time. Now you are wondering how the properties of the membrane affect the migration process. You decide to model the cell membrane, very crudely, as a capacitor in series with a light bulb and a battery. A capacitor can be thought of as a device used to hold separated charges (similar to the cell membrane). You decide to get a quantitative understanding of the rate at which a capacitor charges by using a capacitor in series with a light bulb and battery. How does the time that the light bulb is lit depend on the capacitance of the capacitor connected in series with it?

NOTE: This problem, and the problems **Qualitative Capacitors** and **Rates of Energy Transfer in RC Circuits** are fundamentally similar. This problem involves a quantitative analysis of an RC circuit, **Qualitative Capacitors** involves a qualitative analysis, and **Rates of Energy Transfer in RC Circuits** analyzes RC circuit behavior from the point of view of energy transfer to or from the capacitor.

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

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



Circuit I

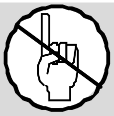
If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

PREDICTION

From your experience, make an educated guess about how the time that the light bulb is lit depends on the capacitance of the capacitor.

Sketch a graph of the time it takes for the light bulb to turn completely off as a function of the capacitor's capacitance. Assume the capacitor is initially uncharged. Write down what you mean when you say the light bulb is completely off.

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

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Be sure the capacitors are not charged.

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

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 voltage across the battery change over time? Check this using the DMM set for volts. From your observations of the brightness of the bulb, how does the voltage 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 this with a DMM? Use the concepts of voltage and energy 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, and what you mean by the light bulb being ‘off’.

MEASUREMENT

Use your measurement plan to record how long it takes for the light bulb to turn off for each capacitor in the circuit.

ANALYSIS

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

CONCLUSION

How did your measurement compare with your prediction? Using conservation of charge and conservation of energy, explain how the capacitance affects the time it takes for the bulb to turn off.

PROBLEM #5: RATES OF ENERGY TRANSFER IN RC CIRCUITS

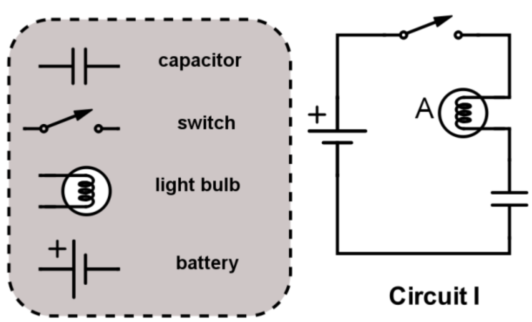
For a class project in biomedical electronics, you thought of developing a simple 'stun gun' for use in self-defense. The 'stun gun' has a capacitor charged to a high voltage. When a pair of electrodes at the tip of the 'gun' touch the skin of an attacker the capacitor discharges (ouch!). Being cautious, you also imagine a scenario in which the gun misses the attacker the first time, so you are concerned about how fast the gun can 'reload'. To shed light on this issue, you assembled a circuit containing a capacitor in series with a battery and light bulb. You are interested in determining the rate and therefore the time it takes for the capacitor to charge. Can you characterize the rate at which energy enters the capacitor? What determines the time it takes for a capacitor to charge (or discharge)? In this problem you are interested in not just the total charge time but also in how energy enters the capacitor during the charging process. Determine how the energy stored in the capacitor changes as a function of time while charging.

Note: This problem, **Quantitative Capacitors** and **Qualitative Capacitors** are fundamentally similar. This problem analyzes RC circuit behavior from the point of view of energy transfer to or from the capacitor, **Qualitative Capacitors** involves a qualitative analysis of an RC circuit, and **Quantitative Capacitors** involves a quantitative analysis.

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

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



Circuit I

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

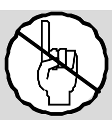
1. In this experiment, you are looking at rates of change. Make a list of the things that are changing in the circuit while a capacitor is charging.

2. Write down appropriate rate equation(s) for properties of the circuit that change with time. Write down the meaning of each letter in the rate equation(s).
3. List the terms (letters) in the rate equation you can measure with tools in the lab. Which terms in the rate equation will you need to calculate as a result of your experiment? How many of these terms are there?
4. Explain the role of the capacitor in the rate equation.
5. Explain the role of the battery in the rate equation
6. Solve the rate equation. Are there any unknown quantities in this equation? Write them down. How about initial conditions?
7. How are the time-varying quantities, which you can measure directly and which you have written rate equation(s) for, related to the capacitor's energy? To the rate of energy input to the capacitor?
8. How is the stored energy in a capacitor related to the voltage across the capacitor terminals?

PREDICTION

Which equation(s) will you use to determine the rate at which energy enters the capacitor?

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

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

You are interested in rates of change, so you will need to time things. Begin with the smallest capacitor available. You will need to take measurements at several times as the capacitor charges. What do you need to measure? What is the best way to coordinate data taking? Does this capacitor charge too quickly for you to measure?

You might want to connect a resistor in series with the light bulb (or use a resistor in place of the bulb) to reduce the charging rate to something measurable. How can you measure the resistance of this combination? How much resistance does the light bulb contribute? What role does the bulb play? How are the light bulb and resistor similar? How are they different?

Try using different capacitors and resistor sizes until you find a few combinations that will allow you to get some good sets of data.

MEASUREMENT

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Measure the voltage across the capacitor as a function of time. Take several measurements as the capacitor charges - you will find it easier to fit your prediction equation to a larger number of data points.

For each circuit, remove the resistor/light bulb combination and measure its resistance using the digital multimeter. Take data for a few capacitor/resistor sizes.

ANALYSIS

Using a graphing program or a spreadsheet, plot your data for voltage (and perhaps also for current) as a function of time. Plot the solution to your rate equation for the voltage. You may adjust the 'fit' parameters (e.g. the capacitance) until your measured and calculated graphs match.

From the time-evolution of the voltage across the capacitor, construct a plot of the rate at which energy is transferred to the capacitor.

CONCLUSION

Knowing the rate at which energy enters the capacitor, what determines the time for the capacitor to charge?

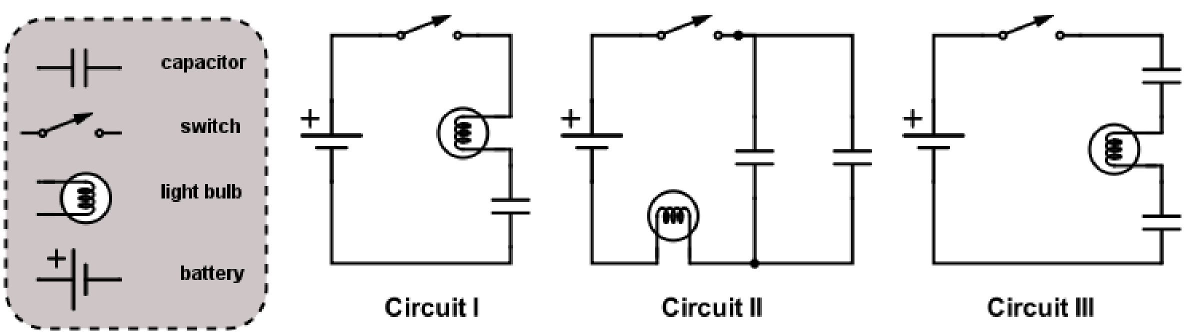
PROBLEM #6: CIRCUITS WITH TWO CAPACITORS

You have a job in a research group studying nocturnal fish. Your task is to photograph the creatures at certain intervals using a 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 slowly charging a capacitor with a battery and then quickly releasing the stored 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, of 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. First you calculate which of the two ways of connecting the two capacitors results in the most stored energy. Next you decide to test your calculation by seeing which circuit takes longest to charge through a bulb. You reason that more energy stored will result in a longer charge time. Which circuit consisting of a bulb, a battery, and two capacitors takes the longest time for the bulb to dim?

Read Sternheim & Kane sections 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

Build the circuits shown below out of wires, *identical* bulbs, two *different* capacitors, and batteries. Use the accompanying legend to help you build the circuit. You will also have a stopwatch.



Note: Check to make sure the light bulbs are all of the same type. To find identical bulbs look for markings on the base and check to see that the color of the bead separating the filament wires is the same.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a picture of each arrangement of the capacitors, light bulb, and battery. On each picture, label the capacitance of each capacitor, remembering that you only have two capacitors, with different capacitances. Also, label the electric potential difference across each circuit element and the charge stored on each capacitor.

2. Decide on the physics principles you will use. In the case of 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 the energy stored on its plates, the charge stored in it, and its capacitance.

4. For each capacitor, write an equation that relates the charge on each capacitor, the potential difference across the capacitor, and the capacitance of the capacitor.

5. When the current stops flowing through the circuit, is the charge on the two capacitors in Circuit II the same? 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 is larger, you must find the energy stored in terms of common quantities such as the potential difference across the battery and the capacitance of each capacitor.

7. From step 6, you have 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 this make sense?

PREDICTION

Rank the total time it takes for each of the bulbs in Circuits I, II, and III to turn off (use the symbol **'='** for "same time as"; the symbol **'>'** for "more time than"; and the symbol 'Ø' if the bulb never lights). Explain your reasoning.

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

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

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. 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.

After the brightness of the bulb no longer changes, what is the relationship between the potential differences across the elements of the circuit? Check this using the DMM set for potential difference (Volts). Use the concept of potential difference 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 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 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 and the concept of potential difference to explain your results.

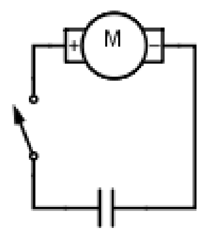
PROBLEM #7: EFFICIENCY OF AN ELECTRIC MOTOR

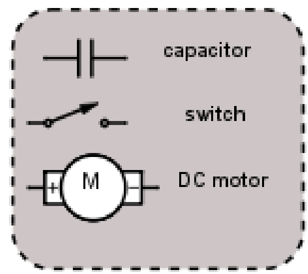
You have a job in a University research group investigating locomotion of prokaryotes such as the bacteria *Escherichia Coli*. These organisms 'swim' by rotation of rigid helical flagellum[1] like a propeller. A tiny molecular motor situated at its base drives the flagellum. The energy to drive this motor comes from hydrolysis of ATP molecules. You would like to measure the efficiency of this energy conversion process, but since the equipment for this experiment is expensive and the measurements time consuming, you would like to understand a simpler physical model first. You decide to model the energy source using a (charged) capacitor and the tiny molecular motor with a DC electric motor. A mass is lifted when the motor runs. What fraction of the energy that can be stored in a capacitor is converted into usable energy?

Sternheim & Kane sections 6.3, 16.4, 16.9, 17.7 and 18.4.

EQUIPMENT

You have a mass that can be lifted using an electric motor. The motor is supported using rods and clamps. You will also have two different capacitors, a battery or power supply, several banana cables, a meter stick and a DMM.





If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a picture of the situation. Label all relevant distances, masses, speeds, and energies.
2. Decide on your system and the initial and final times at which you will consider your system. Write down the initial energy of your system. Write down the final energy of your system.
3. Make a list of items in the equipment that are not part of the system defined in step 2. Identify any energy transferred into or out of your system in the time interval you are using.
4. Efficiency is defined as the ratio of useful energy output divided by the energy input. Write down the energy input to the electric motor. Write down the energy output of the electric motor.

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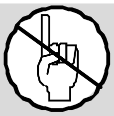
[1] R. Cotterill, *Biophysics: An Introduction*, Wiley, 2002, pp. 215-216.

PREDICTION

Calculate the efficiency of the electric motor by determining the energy transferred from the capacitor and the final energy of the lifted mass.

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

Pay attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

Note: Make sure you connect the + terminal of the battery to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Charge the capacitor by connecting it to a battery. How can you use the DMM to tell if the capacitor is fully charged? What do you mean by fully charged? Try charging it for different amounts of time. How long does it take the capacitor to fully charge?

Connect the mass 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 connected the terminals to the motor?

How far is the mass lifted? When the mass stops lifting is the capacitor out of energy? What implications does this have for your measurements? How long will the capacitor support the mass before it begins to fall? How can you tell when energy is still being transferred to the mass? What happens when energy is no longer being transferred to the mass?

Write down your measurement plan.

MEASUREMENT

What is the initial position of the mass? What is the energy stored in the capacitor at this time? Measure the distance the mass is lifted when the capacitor is connected to the motor. What was the energy of the capacitor at the final position?

Was it necessary for the capacitor to be completely discharged at the final position? If it was not, what implications does this have for your experiment? What is more important, the total energy the capacitor is able to store, or the amount of energy the capacitor transfers?

Is there a way you can visually determine that the capacitor is no longer transferring energy to the mass? What are the obvious changes to your system when energy is no longer being supplied to the mass from the capacitor?

What are the uncertainties associated with your measurement? Try to think of any possible sources of uncertainty and quantify them.

ANALYSIS

Calculate the initial energy of the mass. Calculate the final energy of the mass.

Calculate the initial energy of the capacitor. Calculate the final energy of the capacitor.

Combine the quantities you decided to be energy input and output to determine the efficiency of the electric motor. What are the implications if this number is equal to one? What if it is less than one? Greater than one?

CONCLUSION

Did your results match your predictions? Explain any differences.

How efficient is the electric motor?

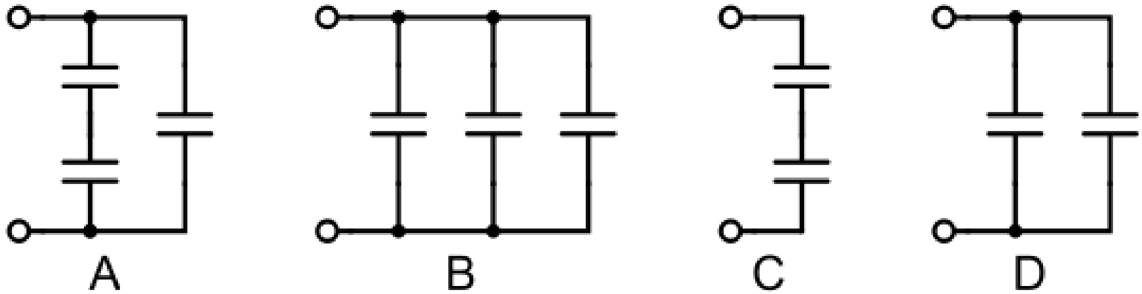
☑ CHECK YOUR UNDERSTANDING
LAB 3: ENERGY AND CAPACITORS

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 μF.

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 μF.



PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: ____________

Course, Lab, Problem: ______________________________

Date Performed: ______________________________

Lab Partners' Names: ______________________________

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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

Physics Lab Report Rubric

LAB 4: ELECTRIC FIELD AND POTENTIAL

Many forces in nature cannot be modeled as contact forces, such as those you have used to describe collisions or friction interactions. Forces sometimes characterized as "action-at-a-distance" involve objects exerting forces on each other although not in physical contact. The gravitational force, in fact, fits this characterization. You are just now learning about another action-at-a-distance force: the electric force. Action-at-a-distance can be difficult to fit into our physics framework for two reasons. First, it is hard to conceive of objects interacting when they are not touching. Second, objects that interact by these action-at-a-distance forces form systems that can have potential energy. The concept of action-at-a-distance does not satisfactorily describe where this potential energy resides.

The notion of a "field" solves these problems. In 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 creates a field and the other object interacts directly with that field. The magnitude of the force on an object is the magnitude of the field at the space the object occupies (caused by other objects) 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. In the case of the electrical force, it is the electric charge. The direction of the electrical or gravitational force on an object is *along* the direction (towards or opposite) of the field (at the object's position). The potential energy of the system can be envisioned as residing in the field.

Thinking of interactions in terms of fields solves the intellectual problem of action-at-a-distance. It is, however, a very abstract way of thinking about the world. We use it only because it leads us to a deeper understanding of natural phenomena and inspires the invention of new devices. The problems in this laboratory are primarily designed to give you practice visualizing fields and their associated potentials, and in using the field concept to solve problems.

In this laboratory, you will first explore electric fields by building different configurations of charged objects (physically and with a computer simulation) and mapping their electric fields and potentials. In the last two problems of this lab, you will measure the behavior of electrons moving through an electric field and compare this behavior to your calculations.

As you progress through the problems in this laboratory, pay particular attention to learning about relationships among (and differences between) the oft-confused concepts of *field*, *force*, *potential*, and *potential energy*.

LAB 4: ELECTRIC FIELD AND POTENTIAL

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 Sternheim & Kane Chapter 16 section 1-5, 7 & 8

You may find the supplementary text, “There Are No Electrons” by K. Amdahl, (ISBN 096 278 1592), a useful resource for conceptual understanding of electricity.

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.
- Add vectors in two dimensions.
- Calculate the electric field due to a point charge.
- Calculate the electric potential due to a point charge.

PROBLEM #1: ELECTRIC FIELD VECTORS

As part of your internship with a local power company, you have been assigned to a team reviewing published research about the effects of electric fields on human health. To evaluate the merits of apparently conflicting research, you need a computer program to simulate the electric field due to complicated charge configurations. Your team leader has assigned you the task of evaluating such a program. To test the program, you will compare its predictions to your own understanding of the electric field created by a few simple charge configurations. You start with the very simple configuration of a single positive charge. You then try a single negative charge. Finally, you consider a positive charge near a negative charge of equal magnitude (a dipole configuration). Qualitatively, determine the electric field distributions of a single positive charge, a single negative charge and a dipole.

Read Sternheim & Kane sections 16.1-5.

EQUIPMENT

You will use the computer application Electrostatics 3D. This program will allow you to evaluate the electric field vector at any point near any given charge distribution. You will also have a ruler and protractor.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

To solve this problem it is useful to have an organized problem-solving procedure such as the one outlined in the following questions.

1. Draw a positively charged point object. What does the electric field look like surrounding a positive charge? How is this different from the field surrounding a negative charge?

2. At a point in space some distance from the positively charged point object, imagine you have another positively charged point object. The force on such a "test charge" (1 Coulomb) is the electric field at that point due to the charge configuration. Draw a vector representing the magnitude and direction of the force on the test charge due to the other charge.

3. Now move your test charge to another point and draw the vector representing the force on it. (How does the magnitude of the force on the test charge depend on its distance from the positively charged point object? Make sure the length of your vector represents this dependence.) Continue this process until you have a satisfactory map of the electric field in the space surrounding the positively charged point object.

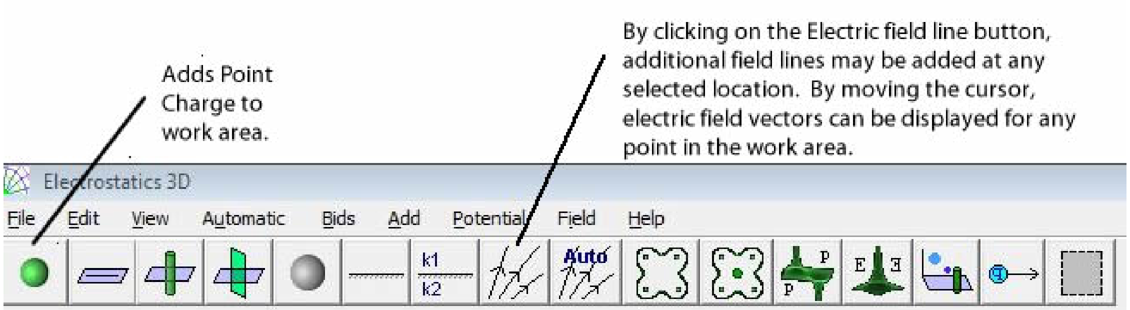
4. Repeat the above steps for a negatively charged point object and for a dipole. (Should your test charge have a positive or negative charge in these cases?) For the dipole, remember that if two objects exert a force on a third object, the force on that third object is the **vector sum** of the forces exerted by each of the other objects.

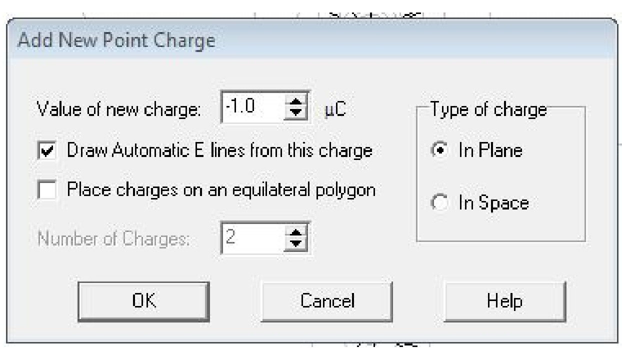
PREDICTION

Using your knowledge of the forces exerted by charged objects, draw vectors representing the electric field around the following charge distributions: (i) A positively charged point object; (ii) A negatively charged point object; (iii) A dipole (two equal but oppositely charged point objects separated by a small distance). As usual, the length of the vector should represent the magnitude of the field. In each case, draw enough vectors to give a qualitative idea of the behavior of the field. Where do you think the electric field will be the strongest? The weakest?

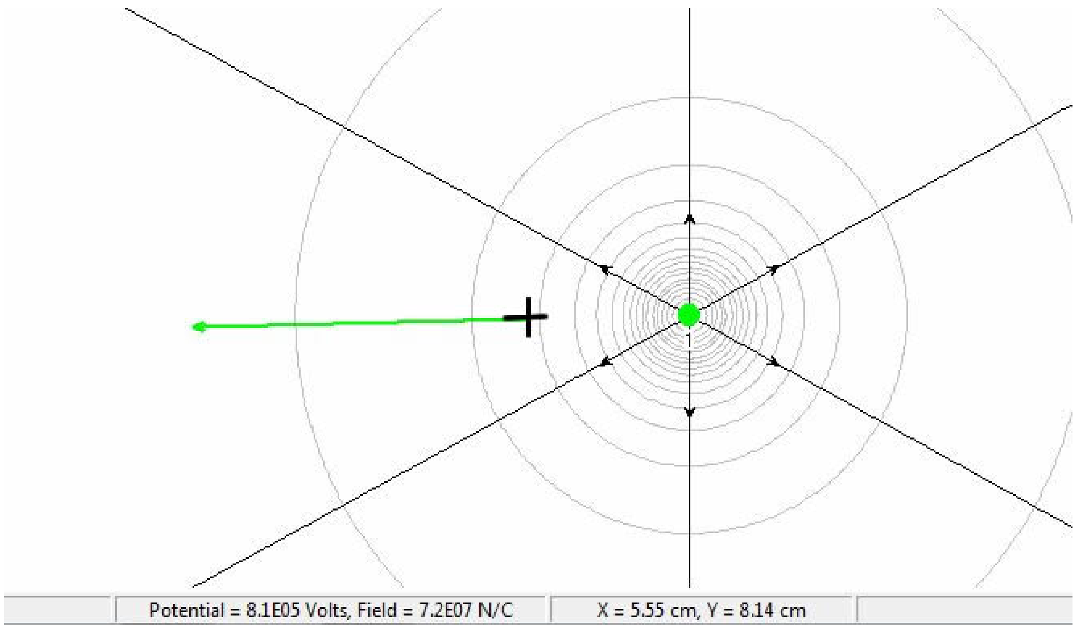
EXPLORATION AND MEASUREMENT

In the folder Physics on the desktop, open Electrostatics 3D and click on the *Point Charge* button found on the far left side of the toolbar. A dialog box opens allowing you to enter the magnitude of the point charge, and whether it is positive or negative. To start out, you should de-select *Draw Automatic E-lines from this charge*. Once you select *OK*, you can place the point charge within the workspace by clicking the mouse button. You should take note of the position of the point charge, the x and y coordinates within the workspace are given at the bottom of the screen.





Click the Electric Field line button on the toolbar and move the cursor within the workspace to where you would like to evaluate a field vector. An electric field vector will appear with direction given by the arrowhead and the relative magnitude given by the length. Position and values for potential and field will be displayed on the bottom of the workspace. Clicking the mouse replaces the vector with an infinite field line, and moving the cursor will display new position, potential and field values for the new location. Repeat this procedure over consistent intervals (i.e. a grid) in the horizontal and vertical directions until you have created a reasonable table of data for the electric field.



Discuss in your group and note in your notebook:

- What are the differences and similarities between the "field lines" and "field vectors" representations of the electric field?
- Are they equally useful? Why or why not?

Repeat the above exercise for the electric field of a negatively charged point object. Save your result to a table. Discuss in your group and note in your notebook:

- How does the vector field compare to that for the positive point charge?
- What effect does increasing the change value have on the vector field map?

Finally, create a dipole by dragging two equal but opposite point charges into the workspace. Make sure to take the position data for both point charges. Try a different spacing between the two charged objects in 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 due to a single charged point object? How about when you are *very* close to one of the charged objects in the dipole?

Make a table of the electric field caused by a dipole. *It is especially important that you take your vector data moving equal increments in the horizontal and vertical directions.* Save your results to a table.

You should experiment with other electric field representations. Specifically, try to understand what role symmetry plays in the creation of electric fields.

ANALYSIS

Consider your dipole electric vector data.

- Sketch the electric field as a function of position along the parallel axis of symmetry. Repeat for the perpendicular axis. How do these graphs compare with your prediction?
- If you are very far away from the dipole, how does the field compare to that of a single point charge? How does it compare if you are very close to one of the point charges?
- In general, where are the maxima and minima of the electric field? Does your answer depend on whether you are considering one or the other axes of symmetry? Why or why not?
- 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 does the magnitude of the force compare to that of the force at a different point in space where the electric field vector is shorter or longer?

CONCLUSION

How does each of the field vector data compare with your prediction? Investigate both direction and magnitude of the electric field vectors. How does the magnitude of the electric field change with position in each case? Where is the field strongest in each case? How is this shown in your map? Where is the field weakest in each case?

For the dipole, how does the magnitude of the electric field change with the position change along (a) the line passing through both charged objects of the dipole, and (b) the line passing through the dipole's center and perpendicular to the first line. Can you generalize this observation?

Suppose the objects making up your dipole were fixed in space, and that you placed a positively charged mobile object nearby. If the mobile object started at rest, how would it move? (Be careful not to confuse the object's acceleration with its velocity!) Does the way the mobile object moves depend on where you start it?

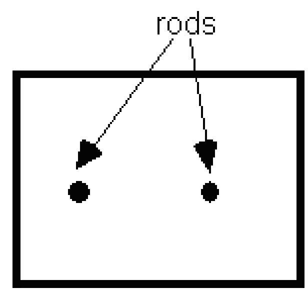
PROBLEM #2: ELECTRIC FIELD OF A DIPOLE

In your summer job with a bioengineering company you have been studying the electric potential generated by different organisms. Your specific assignment is to test a portable instrument designed to measure electric field potential. To find out if it works correctly, you decide to use it to determine the electric potential 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 touching conductive paper. You then measure the electric potential on the paper. From the electric potential pattern, determine what electric field pattern is created by the tips of two metal rods with opposite charge.

Read Sternheim & Kane sections 16.1-5.

EQUIPMENT

You have electrostatic paper, two brass rods (to serve as electrodes), banana cables, alligator clips, a battery and a wood block to increase contact pressure between the electrodes and the paper. Measurements will be made using a Digital Multimeter (DMM) set to read volts connected to a pin tip probe. You will also have the Electrostatics 3D 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 setup.

Read the sections *Electrostatic Paper and Accessories* and *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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 one charged object, imagine you have another positively charged point object. Draw a vector representing the force on that "imaginary" object. How does the magnitude of the force on the "imaginary" object depend on its distance from the positively and negatively charged objects that you drew originally? Make sure the length of your vector represents this dependence. Remember that if two objects exert a force on a third object, the force on that third object is the vector sum of the force exerted by each of the other objects.

3. Now move your "imaginary" object to another point in space and draw the vector representing the force on it. Continue this process until you have a satisfactory map of the electric field in the space surrounding the dipole.

PREDICTION

Based on your knowledge of the strength and direction of the electric force, sketch a map of the electric field created in a plane perpendicular to two point charges with opposite charges. Where do you think the electric field will be the strongest? The weakest? Do you anticipate any symmetry in the strength and/or direction of the field vectors? Use your electric field pattern to predict the pattern of the electric potential.

When you get to lab, check your sketch by making a field map of two oppositely charged point charges using *Electrostatics 3D*.

EXPLORATION

You may compare your prediction with a field map of a dipole produced by the Electrostatics 3D simulation program. For instructions on how to use this program see the Exploration section of the problem '**Electric Field Vectors'**.

Set up the conductive paper and DMM as instructed in the appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

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. Does the probe measure the electric field? What does the probe measure? 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 prediction?

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. The electric field direction will be the direction of probe orientation that reads the largest voltage difference. The electric field value is approximately equal to the voltage divided by the distance between probe tips. 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.

CONCLUSION

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

PROBLEM #3: ELECTRIC POTENTIAL DUE TO MULTIPLE CHARGED OBJECTS

You are a member of a team designing a compact particle accelerator in which ions of low-Z atoms will be directed at radio resistant malignant tumors. Charged atomic nuclei will be accelerated when they pass through a charged electrode structure. The team must determine the effect of several electrode configurations on the final speed of various nuclei. The charged electrode configuration will be extremely complicated, so your team has decided to use a computer simulation. The first step is to calculate the electric potential that will affect the nuclei.

Your immediate task is to determine if the simulation can be trusted. You decide to calculate the electric potential caused by a set of charged objects complex enough to test the simulation, but simple enough for direct calculation. 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 $\frac{1}{3}$ 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's simulation of the same configuration. What is the electric potential at the corner of a square made of charged point objects?

Read Sternheim & Kane sections 16.1-5.

EQUIPMENT

The computer program Electrostatics 3D, a protractor and a ruler.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

The following questions should help with your prediction.

1. Make a picture of the situation. Label the objects and their charges. Draw and label all relevant distances and angles. Draw appropriate right triangles so that you can use the Pythagorean Theorem to find needed distances.

2. What variables affect the potential at the unoccupied corner of the square? For each charged object, write down a formula expressing the electric potential from that object at the point of interest.

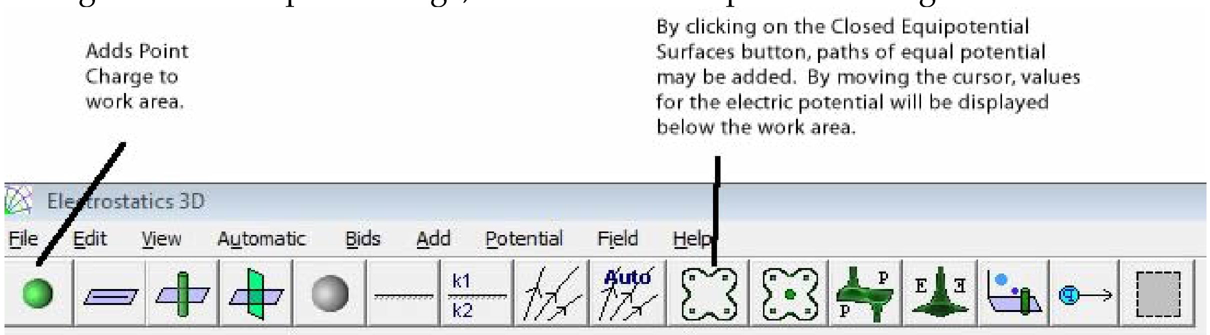
3. Add the electric potentials due to each of the charged objects to find the potential at the unoccupied corner due to all three of them. This "adding" up of different charges is possible by the principle of "Linear Superposition."

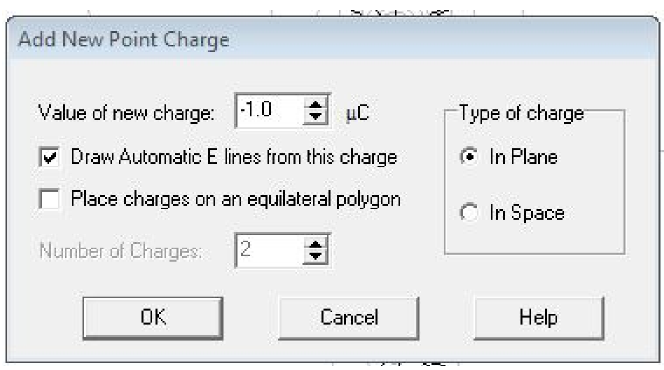
PREDICTION

Two equal negatively charged point objects are in opposite corners of a square. A positively charged point object, with a charge of $\frac{1}{3}$ the magnitude of the negative objects, is located in a third corner of the square. Calculate the electric potential at the fourth corner of the square.

EXPLORATION

In the folder Physics on the desktop, open Electrostatics 3D and click on the Point Charge button found on the far left side of the toolbar. You can now place a point charge within the workspace. Once placed, a dialog box opens allowing you to enter the magnitude of the point charge, and whether it is positive or negative.





Click the Closed Equipotential Surfaces button and move the cursor within the workspace to where you would like to evaluate the electric potential. Position and values for potential and field will be displayed on the bottom of the workspace as you move the cursor around the work area. Clicking the mouse will cause an equipotential surface to be displayed, and moving the cursor will display new position and potential values for the new location.

You can reveal simulated electric potential values anywhere in the workspace by moving the cursor where you would like to evaluate the electric field.

To place objects at precise points on the screen you will need to keep track of the position data displayed at the bottom of the workspace. You might find it helpful to map out the (x) and (y) positions required in the workspace to simulate the assigned configurations.

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? 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?

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? For more on this topic, see the section '**Using Linear Relationships to Make Graphs Clear**' in the appendix **A Review of Graphs.**

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?

Now, explore the distribution of three charges. Drag two equal negative charges and one positive charge of 1/3 the value of one negative charge onto the screen in the configuration specified in the problem statement above. Make sure the charges are accurately placed using the position data. Note the value of the electric potential in the fourth corner of the square. What parameter can you easily vary to change the value of the potential in that corner while preserving the other conditions of the problem? In your notebook, note whether or not such manipulations change the direction of the electric field at that corner, and record the direction. Determine a measurement plan.

MEASUREMENT

Place charges on the screen to simulate the situation described in the problem. Measure the electric potential of an object 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.

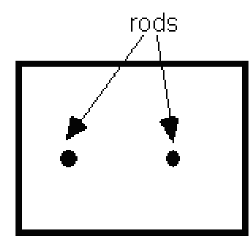
PROBLEM #4: ELECTRIC FIELD AND POTENTIAL

You work for a team consulting with a company that produces technology for medical education. A school has asked the company to produce cheap, durable equipment that can measure and depict the electric field and the electric potential distribution inside a human body. The equipment will be used in the education of EKG technicians. Because the electric field and electric potential are related, you know that it is not necessary to measure both the field and potential directly. To convince yourself and the company that it is appropriate to measure only the potential distribution, you decide to investigate a method of determining the electric field from the electric potential. You decide to investigate a single dipole first, since many electric fields and electric potentials can be modeled in terms of dipole combinations. Determine the electric field and electric potential near a dipole and how the field and potential are related.

Read Sternheim & Kane sections 16.1-5.

EQUIPMENT

You have electrostatic paper, two brass rods (to serve as electrodes), banana cables, alligator clips, a battery and a wood block to increase contact pressure between the electrodes and the paper. Measurements will be made using a Digital Multimeter (DMM) set to read volts connected to a pin tip probe. A white sheet of paper with a grid similar to the grid on the conducting paper is useful for recording the field. For this problem you only use one terminal of the dual tip probe used earlier. The GND socket of the DMM is connected to the ground of the power supply or the cathode of the battery. You will also have the Electrostatics 3D program.



Overhead view of conductive paper for this problem.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. On a piece of paper, draw a horizontal axis and a vertical axis. Place two charged objects on the horizontal axis so that they create a dipole centered around the vertical axis. (Leave enough space between the objects so that at least five equipotential lines will fit between them.)
2. How is the electric potential due to the two point-like charged objects of a dipole related to the potential due to each of the objects? Write an equation describing the dipole electric potential on your paper. Clearly identify all variables.

3. Calculate the electric potential at the point where the axes intersect, and label the point with its potential. What other points have the same potential? Draw the line connecting those points (an equipotential line). Select another point on the horizontal axis between the two charges, label it with its electric potential, find other points with the same electrical potential, and sketch the equipotential line associated with that point. Repeat for at least three more equipotential lines. (Be sure to keep a constant potential difference between adjacent lines.) You may be able to intuitively see where the equipotentials lie, but better results can be obtained with the equation formed in **(2)**.
4. What symmetry would you expect to see in the equipotential lines? Do your equipotential lines exhibit that symmetry? Since pairs of adjacent lines have equal potential differences, would you expect them to be equally spaced on the paper? Why or why not?
5. What is the relationship between electric potential differences between two points and the electric field? How would you find the direction of the electric field vector at a point on an equipotential line? How would you find the magnitude of the electric field vector at a point on an equipotential line? Qualitatively sketch the electric field vectors at several points on each equipotential line. (The relative lengths of the lines should indicate the relative magnitudes of the electric field at the points.)

PREDICTION

Qualitatively sketch equipotential lines for the dipole. Potential differences between adjacent pairs of equipotential lines in the sketch should be approximately equal. Based on the equipotential lines, sketch electric field vectors at several points. Explain your method.

EXPLORATION

Set up the conductive paper as instructed in the appendix.

Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

If you use the power supply, set it to provide no more than 15 Volts DC.

Connect the two rods representing a dipole to the battery or power supply. Connect the single-tip probe to the DC voltage socket of the digital multimeter (DMM). Use a wire to connect the GND socket of the DMM to the cathode of the battery or the GND of the power supply.

Turn on the power supply. Be careful to avoid a short circuit. Place the tip of the probe against the paper. The DMM displays a value of voltage. What does it mean? Move the tip to other places. Observe whether the value displayed in DMM changes. What does the change mean?

Try to stabilize the tip on the paper. Can you get a stable value from the DMM? Is there a fluctuation due to the small shaking of your hand? If there is large fluctuation, how will you make your measurement consistently? Estimate the uncertainty in your measurements of electric potential.

Select a point between the two rods of the dipole. Put the tip at this point and read the value from DMM. On your copy of the grid, record the voltage reading for that point. Find more points that produce the same voltage reading, and mark your copy of the grid to indicate their positions. Connect your marks with a smooth curve. What does the curve mean?

Practice the above process and find more similar curves.

MEASUREMENT

Record the voltage reading given by the DMM at the point midway between the two rod-points that form the dipole. As in the exploration, find other points that produce the same reading and connect them with a smooth curve.

Make a voltage reading at a second point, and repeat the process of producing a curve of constant voltage readings. Calculate the difference in voltages between points on this curve and points on the first one.

Repeat the process for at least three more points (curves). Be sure that the voltage difference between adjacent curves is constant.

ANALYSIS

What is the significance of the curves of constant voltage readings you have created? How are they related to the warm-up questions?

Write down the equation that expresses the electric field in terms of spatial variation in the electric potential. Based on the equation, develop a technique to estimate the direction and magnitude of the electric field for a point on a curve of constant voltage readings. (Hint: What are the units of electric field and potential?) What assumptions must you make to estimate electric fields based on the limited amount of data you have collected about voltage on the conductive paper?

Use your technique to estimate the magnitude of the electric field at several points along curves of equal voltage readings. Create a map of the electric field on your copy of the grid, by drawing arrows to represent the direction and magnitude of the field at each of those points.

CONCLUSION

What parts of your measured map correspond to parts of your predicted map of electric potential and field for a dipole? Can you account for any differences? How do these maps of electric field compare to your dipole results in the problems on '*Electric Field Vectors*' and '*Electric field of a dipole*'? Can you account for any differences?

Symmetries should be apparent in your map of potential. Can you explain these symmetries with your prediction equation?

Use the Electrostatics 3D program to simulate a dipole, and use the software to draw equipotential lines (with constant potential difference between adjacent lines). To draw equipotential lines, select *Equipotential Surfaces - closed* from the **Potential menu**. Select several points on the equipotential lines, and show electric field vectors for those points. Compare the simulation result with your measured result.

Is the method used here, deriving the electric field from electric potential, reasonable? How could you improve its accuracy? Is it possible to determine the electric potential from the electric field? Do you think it would be better or worse (for the team's medical education project) to measure the electric field directly and derive the electric potential, or to measure the electric potential directly and derive the electric field?

PROBLEM #5: DEFLECTION OF AN ELECTRON BEAM BY AN ELECTRIC FIELD

You are a member of a team designing a compact particle accelerator in which ions of low-Z atoms will be directed at radio resistant malignant tumors. Charged atomic nuclei will be accelerated when they pass through a charged electrode structure. The team has moved on to the problem of aiming the atoms that emerge from the accelerator. You plan to add controls to the accelerator that will aim the beam by passing it through a region with an adjustable electric field. You decide to use a cathode ray tube (CRT) to model the particle accelerator and study the plan. 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. Inside the tube, the electrons pass between two sets of oppositely charged parallel plates: one set oriented horizontally, and another oriented vertically. **You decide to calculate how the deflection of the beam depends on the strength of the electric field.**

Read Sternheim & Kane sections 16.1-5, 16.7 & 16.8. Review Kinematics if necessary.

EQUIPMENT

You have a Cathode Ray Tube. You also have a Cenco power supply, banana cables, DMM and an 18v/5amp power supply. The applied electric field is created by connecting the internal parallel plates to the power supply.

Note: The CENCO power supplies can have transient AC voltage in the DC output, **making it less than ideal for creating an electric field –** use the 18volt/5amp supplies**.**

Read the section *Cathode Ray Tube and Accessories* in the **Equipment** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

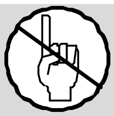
1. Draw a picture of the important components of the CRT. Only include one set of the deflection plates as shown in the appendix. Draw the trajectory the electron would take if there were no electric field between the plates. If there is an electric field between the deflection plates, will there be *regions* where different forces act on the electron? Label these regions. Draw the trajectory the electron would take when there is electric field between the plates. On the trajectory, draw and label arrows representing the electron's velocity and acceleration for each region. The distance between where the non-deflected beam hits the CRT screen and where the deflected beam hits is the *deflection*.

2. What forces cause electrons to accelerate in each region? On your picture, draw an arrow representing each force. (Are there any forces you can assume to be negligible?) For each region, label the electron's trajectory and the electron's velocity and acceleration as it enters the region, while it is in the region, and when it leaves the region. Qualitatively describe the shape of the electron's trajectory in each region.
3. The magnitude of the electric field (in Newtons per Coulomb) between two equally charged parallel plates is equal to the voltage between the two plates (in Volts) divided by the distance between the plates (in meters). What is the direction of the electric field between the two accelerating plates? See the appendix for the position of the accelerating plates. How much energy is transferred to the electron by this field? Using conservation of energy, write an equation for the electron's velocity as it leaves the electron gun in the CRT. What is the direction of the electron as it leaves the accelerating field? What assumptions have you made?
4. What is the net force exerted on an electron as it travels through the region between the deflecting plates? Use Newton's second law to write an equation for the acceleration of an electron as it travels through this region. You will need to define a coordinate system if you have not already done so. Does the electric field vary in the region between the deflecting plates? What does that tell you about the acceleration of the electron in that region?
5. Use your drawing from step 1 and kinematics to determine the position and direction of the electron as it enters the region between the deflection plates and when it leaves that region. Write down an equation giving the electron's change in position as it emerges from the deflecting plates (how much it was deflected while traveling between the plates). Write another equation giving the electron's direction.
6. Use your drawing from step 1, the position and direction of the electron as it leaves the deflection plates, and geometry to write down an equation giving the position of the electron when it hits the screen. Use the deflection distance from each region to write an expression for the total deflection during the electron's motion through all regions of the CRT.
7. Examine your equations giving the electron's position at the screen. You know the total deflection in terms of the accelerating voltage, length of the deflecting plate region, distance from the plates to the screen, separation distance of the plates, and potential difference across the plates. Are there any other unknowns in your equation? Do you have enough equations to solve for the unknowns? If so, solve your equations algebraically for the deflection of an electron. If not, write down additional equations that relate some of the unknown quantities in your equations to quantities that you know.
8. Complete your solution by using the actual numbers that describe your situation. Refer to the distances shown on the diagram of the CRT in the appendix. Does your solution make sense? If not, check your work for logic problems or algebra mistakes.

PREDICTIONS

Calculate how the electric field between the horizontal parallel plates affects the position of the electron beam spot. Use this equation to make a graph of the position as a function of the strength of the electric field between the plates.

EXPLORATION



WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. One unfortunate student in a past year had a hole burned through his finger from improper use of the lab equipment. **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.**

Follow the directions in the appendix 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 switch on the power supply. The electric potential difference between the cathode and anode should be in the range of 250V-500V. 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, determine the CRT beam when non-deflected. In this position the effect of all of the outside forces on the electron is negligible.

Now apply a voltage across one set of deflection plates, noting how the electron beam moves across the screen as the voltage is increased. How will you adjust the voltage level and how will you 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.

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?

Write down your measurement plan.

MEASUREMENT

Measure the position of the beam spot as you change the electric field applied to the deflection plates. Make sure you take enough measurements at each point for averaging.

Note: Always be sure to record your measurements with the appropriate number of significant figures and with your estimated uncertainty. Otherwise, all your data will be useless. See the appendices for a review if necessary.

ANALYSIS

Draw a graph of your prediction equation of the deflection of the electron beam as a function of the voltage applied to the deflecting plates. Put your measurements on this graph.

CONCLUSION

How does the graph based on your data compare to the graph based on your prediction? If they are different, explain why.

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

PROBLEM #6: DEFLECTION OF AN ELECTRON BEAM AND VELOCITY

You are attempting to control the direction of charged particles emerging from a particle accelerator, and using a cathode ray tube (CRT) as a model. 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. While inside the tube, the electrons pass between pairs of charged deflecting plates that create an electric field, which changes the path of the electron beam. To refine your model for aiming charged particles with electric fields, you wish to determine how the velocity of the electrons leaving the electron gun region of the CRT affects the position of the beam spot.

Read Sternheim & Kane sections 16.1-5, 16.7 & 16.8. Review Kinematics if necessary.

EQUIPMENT

You have a Cathode Ray Tube. You also have a Cenco power supply, banana cables, DMM and an 18v/5amp power supply. The applied electric field is created by connecting the internal parallel plates to the power supply.

Note: The CENCO power supplies can have transient AC voltage in the DC output, **making it less than ideal for creating an electric field –** use the 18volt/5amp supplies**.**

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

If you have done the problem **Deflection of an Electron Beam by an Electric Field**, you can refer to back to the Warm-up questions and Prediction for that problem. Numbers 1-8 below are identical for that problem

1. Draw a picture of the important components of the CRT. Only include one set of the deflection plates as shown in the appendix. Draw the trajectory the electron would take if there were no electric field between the plates. If there is an electric field between the deflection plates, will there be *regions* where different forces act on the electron? Label these regions. Draw the trajectory the electron would take when there is electric field between the plates. On the trajectory, draw and label arrows representing the electron's velocity and acceleration for each region. The distance between where the non-deflected beam hits the CRT screen and where the deflected beam hits is the *deflection*.
2. What forces cause electrons to accelerate in each region? On your picture, draw an arrow representing each force. (Are there any forces you can assume to be negligible?) For each region, label the electron's trajectory and the electron's velocity

and acceleration as it enters the region, while it is in the region, and when it leaves the region. Qualitatively describe the shape of the electron's trajectory in each region.

3. The magnitude of the electric field (in Newtons per Coulomb) between two equally charged parallel plates is equal to the voltage between the two plates (in Volts) divided by the distance between the plates (in meters). What is the direction of the electric field between the two accelerating plates? See the appendix for the position of the accelerating plates. How much energy is transferred to the electron by this field? Using conservation of energy, write an equation for the electron's velocity as it leaves the electron gun in the CRT. What is the direction of the electron as it leaves the accelerating field? What assumptions have you made?
4. What is the net force exerted on an electron as it travels through the region between the deflecting plates? Use Newton's second law to write an equation for the acceleration of an electron as it travels through this region. You will need to define a coordinate system if you have not already done so. Does the electric field vary in the region between the deflecting plates? What does that tell you about the acceleration of the electron in that region?
5. Use your drawing from step 1 and kinematics to determine the position and direction of the electron as it enters the region between the deflection plates and when it leaves that region. Write down an equation giving the electron's change in position as it emerges from the deflecting plates (how much it was deflected while traveling between the plates). Write another equation giving the electron's direction.
6. Use your drawing from step 1, the position and direction of the electron as it leaves the deflection plates, and geometry to write down an equation giving the position of the electron when it hits the screen. Use the deflection distance from each region to write an expression for the total deflection during the electron's motion through all regions of the CRT.
7. Examine your equations giving the electron's position at the screen. You know the total deflection in terms of the accelerating voltage, length of the deflecting plate region, distance from the plates to the screen, separation distance of the plates, and potential difference across the plates. Are there any other unknowns in your equation? Do you have enough equations to solve for the unknowns? If so, solve your equations algebraically for the deflection of an electron. If not, write down additional equations that relate some of the unknown quantities in your equations to quantities that you know.
8. Complete your solution by using the actual numbers that describe your situation. Refer to the distances shown on the diagram of the CRT in the appendix. Does your solution make sense? If not, check your work for logic problems or algebra mistakes.

Use conservation of energy to write an equation for the velocity of the electrons as they leave the electron gun in the CRT as a function of the voltage across the accelerating plates in the CRT. The relationship between the initial electron velocity and the accelerating voltage can be used to rewrite your deflection equation in terms of the electron velocity.

Sketch a graph of your prediction equation's dependence on initial electron velocity for a fixed field between the deflection plates.

Sketch a graph of your prediction equation's dependence on accelerating voltage for a fixed, non-zero transverse electric field.

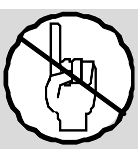
Does your solution make sense? If not, check your work for logic problems or algebra mistakes.

PREDICTION

Calculate how the deflection of the electron beam spot changes as the initial velocity of the electrons changes.

Use this equation to make a graph of the deflection of the beam spot as a function of the initial velocity of the electrons.

EXPLORATION



WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. One unfortunate student in a past year had a hole burned through his finger from improper use of the lab equipment. **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.**

Follow the directions in the appendix 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, determine the CRT beam when non-deflected. In this position the effect of all of the outside forces on the electron is negligible.

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 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.

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?

Write down your measurement plan.

MEASUREMENT

Measure the deflection of the beam spot as you change the initial velocity of the electrons in the beam but keeping the electric field between the deflection plates constant. Be sure to make enough measurements of each condition to determine the reliability of the measurement. Average these measurements if appropriate.

Note: Always be sure to record your measurements with the appropriate number of significant figures and with your estimated uncertainty. Otherwise, all your data will be useless. See the appendices for a review if necessary.

ANALYSIS

Calculate the initial electron velocity for each accelerating voltage you used. Use a spreadsheet program (such as Excel on your lab workstation computer) to make 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?

Use your prediction equation to calculate the deflection of the electron beam as a function of the accelerating voltage. Plot this on the same graph as your measurements and compare.

.

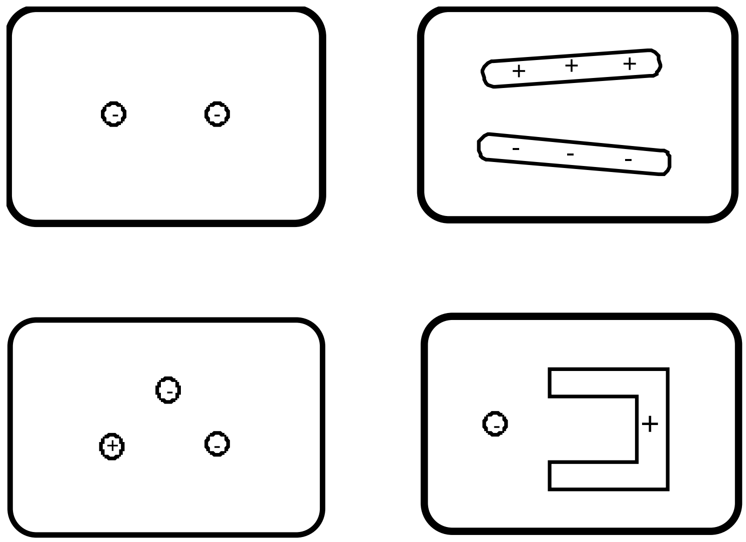
CONCLUSION

Did your data agree with your prediction of how the electron beam would deflect due to the initial electron velocity? If not, why not?

How does the deflection of the electron beam vary with initial electron velocity? How does it vary with accelerating voltage? State your results in the most general terms supported by your data.

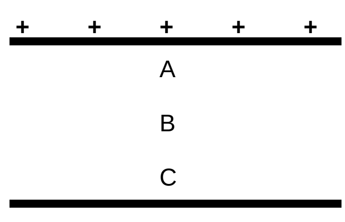
☑ CHECK YOUR UNDERSTANDING
LAB 4: ELECTRIC FIELDS AND POTENTIAL

1. For each of the charge configurations below, map the electric field. Assume that each object is made of metal and that the trays are filled with water.



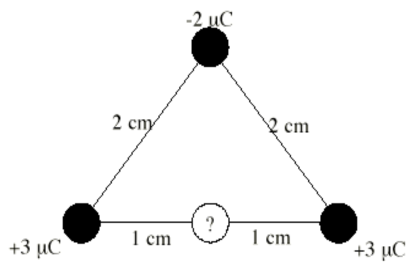
2. For a CRT with the same plates and electron gun as you used in lab, assume that the distance from the center of the Vx plate to the fluorescent screen is 10 cm and the distance from the center of the Vy plate to the screen is 8 cm. If V_{acc} is 300V, Vx = -8V and Vy = 3V, what is the displacement of the electron beam?

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

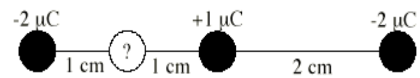


☑ CHECK YOUR UNDERSTANDING
LAB 4: ELECTRIC FIELDS AND POTENTIAL

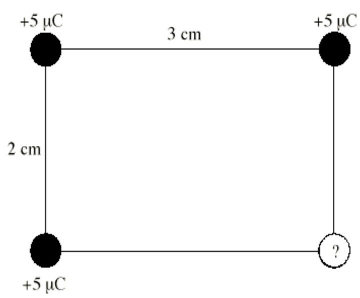
4. For each of the charge configurations below, find the electric field and the electric potential at the point marked with the "?".



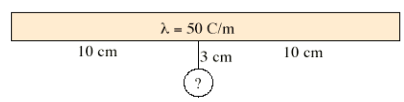
Configuration 1



Configuration 2



Configuration 3



Configuration 4

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: __________
Course, Lab, Problem: ______________________________
Date Performed: ______________________________
Lab Partners' Names: ______________________________

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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

LAB 5: 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 data for computers. Magnetism also allows us to explore the structure of the Universe, the atomic structure of materials, and the quark structure of elementary particles.

The magnetic interaction can best be described using the concept of a field. For this reason, your experiences exploring the electric field concept 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.

In this set of laboratory problems, you will map magnetic fields from different sources and use the magnetic force to deflect electrons. The activities are very similar to the first lab of this semester dealing with electric fields and forces.

OBJECTIVES:

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

- Explain the differences and similarities between magnetic fields and electric fields.
- Describe the pattern of magnetic fields near various 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 Sternheim & Kane Chapter 19 section 1, 2 & 9-12. Review your notes from Lab IV (Electric Field and Potential).

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.

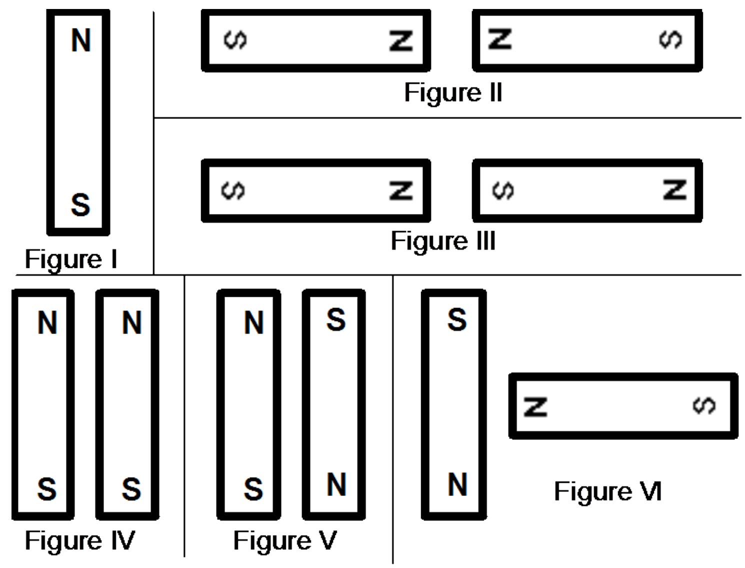
PROBLEM #1: PERMANENT MAGNETS

You have a job working with a company that designs magnetic resonance imaging (MRI) machines. The ability to get a clear image of the inside of the body depends on having 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 must determine the map of the magnetic field created by each of the distributions of permanent magnets shown below.

Read Sternheim & Kane section 19.1

EQUIPMENT

You will have two permanent magnets, a magnetizer (if needed) and a clear plate filled with a viscous liquid and particles of taconite. When a magnet is placed on top of one of these plates, the Taconite pieces align themselves with the magnetic field. You will also have a compass. The magnet configurations you need to consider are as follows:



Read the section *Magnetizing a Bar Magnet* in the **Equipment** appendix if you need to re-magnetize your magnets.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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. 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.

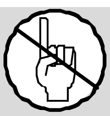
- The direction of the magnetic field points away from a North pole, and towards a South pole.
- The field at a point is the vector sum of the fields from all sources.

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 for all parts of the configuration.

PREDICTION

Sketch a map of the magnetic field for each magnet configuration in the figures in the equipment section. Assume that the different magnet configurations in each figure do not interact with the magnets in the other figures.

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 (the transparent bar inside the plate will help redistribute the flecks when moved).

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 behave as you would expect, a magnetizer can be used to correct the polarity and intensity if necessary.

Place a permanent magnet on the Taconite plate. If the flecks are difficult to see, put a piece of white paper behind the plate. How long must you wait to see the 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 run an organic dairy farm, have high-voltage power lines across their property. They are concerned about the effect that the magnetic field from the power lines might have on the health of their dairy cows. 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 a current carrying wire to determine the map of the magnetic field caused by the current carrying wire.

Read Sternheim & Kane sections 19.1&2.

EQUIPMENT

You will have a Hall probe and interface, a magnetic compass, banana cables, a meter stick, an 18volt/5amp power supply and the Magnetism 3D application. Make sure to use the correct power supply – *do not use the Cenco CRT power supplies, they are not designed to be used in this manner!*

Read the section *The Magnetic Field Sensor (Hall Probe)* in the **Equipment** appendix.

Read the section *Measuring Constant Magnetic Field* in the **Software** appendix.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

PREDICTIONS

Sketch your best guess of the map of the magnetic field near a current carrying wire when the wire is (a) stretched straight, and (b) formed into a loop.

EXPLORATION

Start the Magnetism 3D simulation.

To study magnetic fields of current carrying wires, you will want to choose Add Unlimited Vertical Wire or Add Vertical Wire Loop from the **Add menu**. Once you have added an element to the workspace, you should select Draw Magnetic Field (B) Lines from the **Field menu**. Now you can scroll the cursor around the workspace and the simulation will display a vector and show the position and magnitude of the field along the bottom of the workspace. You can click the mouse with the cursor in a specific location and an infinite field line will appear. Once you have a clear picture of what the direction of the field is, you can create a pdf file using the *Print* command under *File*. You might also find it useful to play around with 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 Cenco CRT power source**).

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 the Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in in the *Magnetlab Guide Box* in the upper right corner of the application. Does the Hall probe ever read a zero field?

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

MEASUREMENT

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

ANALYSIS

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

CONCLUSION

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

PROBLEM #3: MEASURING THE MAGNETIC FIELD OF PERMANENT MAGENTS

Still working on retainer for your friend's parents, the organic dairy farmers, you are now ready to measure the magnetic field near high-voltage power lines. Before making this measurement, you decide to practice by using your Hall probe on a bar magnet. Since you already know the map of the magnetic field of a bar magnet, you decide to use the Hall probe to determine how the magnitude of the magnetic field varies as you move away from the magnet along each of its axes. While thinking about this measurement you wonder if a bar magnet's magnetic field might be the result of the sum of the magnetic field of each pole. Although, to date, no isolated magnetic monopoles have ever been discovered, you wonder if you can model the situation as two magnetic monopoles, one at each end of the magnet. Is it possible that the magnetic field from a single magnetic pole, a monopole, if they exist, has the same behavior as the electric field from a point charge? You decide to check it out by studying how the magnitude of the magnetic field from a bar magnet along each of its axes depends on the distance from the magnet. Is the behavior of the magnetic fields with respect to the distance from a magnetic pole similar to the behavior of an electric field with respect to the distance from a point charge?

Read Sternheim & Kane sections 19.1&2
Review your notes from the earlier problem: **Electric Field from a Dipole**

EQUIPMENT

You will have a bar magnet, a meter stick, a Hall probe and a computer data acquisition system. You will also have a taconite plate and a compass.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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. 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, using your coordinate system.

3. Assume that the magnetic field from a magnetic monopole is analogous to the electric field from a point charge, i.e. the magnetic field is proportional to g/r^2 where g is a measure of the strength of the monopole. 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 the magnetic field strength along that axis as a function of position along the axis.

6. Repeat the above steps for the other axis.

PREDICTION

Calculate the magnetic field strength as a function of distance along each axis of a bar magnet. Make a graph of this function for each axis. How do you expect these graphs to compare to similar graphs of the electric field along each axis of an electric dipole?

EXPLORATION

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

Start the MagnetLab program and follow the Hall probe calibration procedure outlined in the Software appendix. Instructions are also displayed in the *Magnetlab Guide Box* in the upper right corner of the application.

Take one of the bar magnets and use the probe to check 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 each 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 would the shape of the graph of magnetic field strength versus distance for the magnetic dipole compare to the shape of the graph of electric field strength versus distance for an electric dipole? 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: MEASURING THE MAGNETIC FIELD OF ONE COIL

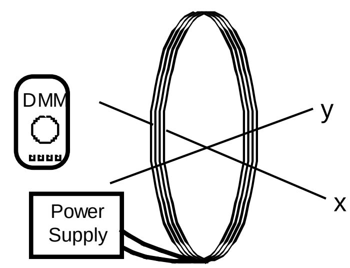
You read in your text that a coil of wire carrying a current gives a similar magnetic field as a bar magnet - a magnetic dipole field. This seems strange, so you decide to check it using a large coil of wire and a Hall probe, as well as a simulation. You decide to measure the strength of the magnetic 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.

Read Sternheim & Kane sections 19.2, 19.7
Review **Measuring the Magnetic Field of Permanent Magnets**

EQUIPMENT

You have a coil of 200 turns of wire, an 18volt/5amp power supply, a compass, meterstick, digital multimeter (DMM), Hall probe and a computer data acquisition system. You will also have the Magnetism 3D application.

Do not use the Cenco CRT power supply for this problem.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

If you have done the problem **Measuring the Magnetic Field of Permanent Magnets**, you already have the equation that describes the magnetic field strength of a magnetic dipole along an axis of symmetry. If not, answer the warm-up questions below to determine this.

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. 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, using your coordinate system.

3. Assume that the magnetic field from a magnetic monopole is analogous to the electric field from a point charge, i.e. the magnetic field is proportional to g/r^2 where g is a measure of the strength of the monopole. 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 the magnetic field strength along that axis as a function of position along the axis.

6. Repeat the above steps for the other axis.

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?

PREDICTION

Compare the magnitude of the magnetic field as a function of distance along central axis of a coil of known radius and carrying a known electric current to that of a bar magnet.

Also compare the field map of the current carrying coil with that of a bar magnet.

EXPLORATION

First, see what the Magnetism 3D simulation gives you. Start the application, and then select Add Solenoid, Vertical Wire Loop or Rectangular Magnet from the **Add menu**. To study magnetic fields of current carrying coil, you will likely want to select Add Solenoid, and then specify the properties of the coil desired. *Don't select over 25 loops per centimeter and de-select the option for an Iron Core* when specifying the properties of the coil. Once an element has been added to the workspace, you should select Draw Magnetic Field (B) Lines from the **Field menu**. Now you can scroll the cursor around the workspace and the simulation will display a vector and show the position and magnitude of the field along the bottom of the workspace. You should pick points both inside and outside the coil for a complete map of the magnetic field. You can click the mouse with the cursor in a specific location and an infinite field line will appear. Once you have a clear picture of what the direction of the field is, you can create a pdf file using the *Print* command under *File*. You might also find it useful to play around with different sizes of current to note any changes. ***Note: that you will use this for qualitative comparisons only!***

Once finished simulating a coil, you might spend time simulating a bar magnet using Magnetism 3D.

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 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 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 as explained in the Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the *Magnetlab Guide Box* in the upper right corner of the application. Does the Hall probe ever read a zero field?

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 in 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.

If you are not familiar with a DMM, see the Equipment appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

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 are a member of a research team studying magnetotactic bacteria. Magnetotactic bacteria from the southern hemisphere preferentially swim to the south along magnetic field lines, while similar bacteria from the northern hemisphere preferentially swim to the north along magnetic field lines. Your team wishes to quantify the behavior of magnetotactic bacteria in closely controlled magnetic fields.

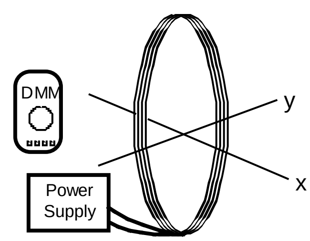
You know from your physics class that a coil of wire can be used to produce a magnetic field, which can be varied by changing the current through it. You set yourself the task of calculating the magnetic field along the axis of the coil as a function of its current, number of turns, radius, and the distance along the axis from the center of the coil. To make sure you are correct, you decide to compare your calculation to measurements.

Note: This problem is fundamentally the same as the problem **Measuring the Magnetic Field of One Coil**, but requires that you derive the expression for the magnetic field produced by a current carrying coil. If you have already acquired data for that problem, no new data is required.

Read Sternheim & Kane sections 19.2, 19.7

EQUIPMENT

You have a coil of 200 turns of wire, an 18volt/5amp power supply, a compass, meterstick, digital multimeter (DMM), Hall probe and a computer data acquisition system.



<u>Do not</u> use the Cenco CRT power supply for this problem.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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, (phonetically, "Bee-Oh Saw-Varr"), 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?

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

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

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

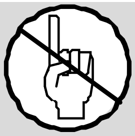
PREDICTION

Calculate the magnitude of the magnetic field as a function of the position along the central axis of a coil of known radius, the number of turns of wire, and the electric current in the coil.

Use this expression to graph the magnetic field strength as a function of position along the central axis of the coil.

EXPLORATION

If you have the data from **Measuring The Magnetic Field of One Coil** you do not necessarily need to make any additional measurements. Go directly to the analysis section. If you have not done this, 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 as explained in the Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the *Magnetlab Guide Box* in the upper right corner of the application. Does the Hall probe ever read a zero field?

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.

If you are not familiar with a DMM see the Equipment appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

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?

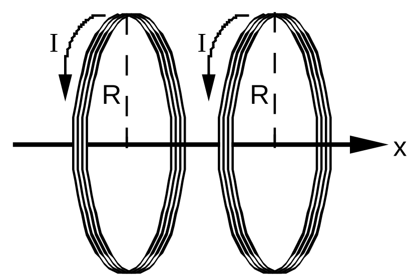
PROBLEM #6: MEASURING THE MAGNETIC FIELD OF TWO PARALLEL COILS

As in the previous problem of *"Determining the magnetic field of a coil"*, you are a member of a research team studying magnetotactic bacteria, which preferentially swim along magnetic field lines. Your team now wishes to quantify the behavior of magnetotactic bacteria in magnetic fields which are uniform. However, the magnetic field from one coil varies strongly with position; that configuration is not suitable for the test, and the group needs something that can produce a more uniform field. 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.

Read Sternheim & Kane sections 19.2, 19.7

EQUIPMENT

You have two 200 turn coils, a base, banana wires, and an 18volt/5amp power supply. The coil base has markings showing correct spacing for a uniform field.



You also have a digital Multimeter (DMM), a compass, a meter stick, and a Hall probe. A computer is used for data acquisition with the **MagnetLab** program.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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, **Determining the Magnetic Field of a Coil**, you measured the magnetic field due to 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?

PREDICTION

Calculate the magnitude of the magnetic field for two coils as a function of the position along their central axis, for the special case where the distance between the coils is the same as the radius of the coils. Use this expression to graph the magnetic field strength versus position along the axis.

EXPLORATION

Connect the large coils to the power supply with *the current flowing in the opposite direction in both coils*. Using your 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 both coils*. Using your 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 as explained in Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the appendix, or in the *Magnetlab Guide Box* in the upper right corner of the application. Be sure the sensor amplification switch on the Hall probe is set to 6.4mT range. **The MagnetLab application requires the probe to be set to the 6.4mT range to work correctly.** Does the Hall probe ever read a zero field?

For the 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?

Explore 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?

When using the MagnetLab program, consider where you want your zero position to be, so that you can compare to 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.

Use the Hall probe to measure the magnitude of the magnetic field along the axis of the coils of wire. Be sure to measure the field on both sides of the coils.

What are the units of your measured magnetic fields? How do these compare to the units of 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.

If you are not familiar with a DMM, see the Equipment appendix. Pay special attention to the connections and settings that are used to measure voltages and currents, and why the DMM should be connected in the circuit differently for voltage and current measurements. Do you know why we should connect them in these ways?

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 as a function of distance along the axis? Did your measured values agree with your predicted values? If not, why not? What are the limitations on the accuracy of your measurements and analysis?

Does this two-coil configuration satisfy the requirement of giving a fairly uniform field? Over how large a region is the field constant to within 20%? This very useful geometric configuration of two coils (distance between them equals their 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 electron linear accelerators used in cancer therapy. Your team is developing a steering mechanism that uses magnetic fields to precisely guide the electrons to their target, where they suddenly slow down and emit high-energy photons that can control tumors. To introduce this project to a group of stockholders, you wish to demonstrate how a magnetic field can guide an electron beam across a CRT screen. 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 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.

Read Sternheim & Kane sections 19.2, 19.7 & 19.9.
Review **Deflection of an Electron Beam by an Electric Field**

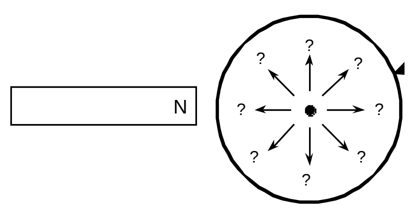
EQUIPMENT

You have a cathode ray tube (CRT), bar magnet, meterstick, and compass.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

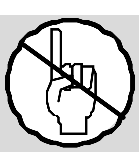
PREDICTION

If you bring the north end of a magnet near the side of the CRT, which arrow represents the deflection of the electron beam on the screen?



Does the size of the deflection increase or decrease as the magnet gets closer to the CRT? As you increase the size of the magnetic field? Does the size of the deflection depend on the speed of the electrons? Explain your reasoning.

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.**

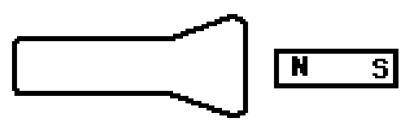
Connect the CRT according to the directions in the Equipment appendix and review the problem **Deflection of an Electron Beam by an Electric Field** in your lab journal. If known, select the accelerating voltage that gave the largest deflection for the smallest electric field. Record the location of the non-deflected beam spot using the selected accelerating voltage.

NOTE: In this experiment we are interested in understanding the effects of ONLY a magnetic field and NOT an electric field. Do not use the deflection plates.

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, you should re-magnetize it following the instructions in the Equipment appendix. 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 if 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 a second magnet. 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?

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.

ANALYSIS

Draw a picture relating the three vectors representing the velocity of the electron, the magnetic field, and the force on the electron 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 attempting to design a better electron microscope; in particular, you wish to improve the mechanism that guides the electron beam across a sample. 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 earlier, 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.

Read Sternheim & Kane sections 19.2, 19.7 & 19.9 and review Kinematics.
Review **Deflection of an Electron Beam by an Electric Field**

EQUIPMENT

You have a cathode ray tube (CRT), digital multimeter (DMM), compass, meterstick, Helmholtz coils, banana cables, Hall probe and computer data acquisition system. The magnetic field is provided by connecting the Helmholtz coils to a power supply and placing the CRT between the coils.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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 the earlier problem **Deflection of an Electron Beam by an Electric Field**)

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?

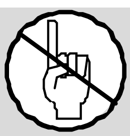
5. Determine the path of the electron as it travels after it leaves the magnetic field region until it strikes the screen. Use geometry to determine how far from the center the electron strikes the screen.

PREDICTION

Write an equation for the deflection of an electron as a function of the strength of a constant magnetic field and the velocity of the electron when the direction of the magnetic field is such as to give maximum deflection. Use this equation to graph the deflection as a function of magnetic field strength for a typical electron velocity in the CRT.

EXPLORATION

Review your notes from your exploration in the problem **Magnets and Moving Charge**.



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.**

Connect the CRT according to the directions in the Equipment appendix and review the problem **Deflection of an electron beam by an Electric Field** in your lab journal. If known, select the accelerating voltage that gave the largest deflection for the smallest electric field. Record the location of the non-deflected beam spot using the selected accelerating voltage.

NOTE: In this experiment we are interested in understanding the effects of ONLY a magnetic field and NOT an electric field. Do not use the deflection plates.

You should have between 250 and 500 volts between the cathode and anode *(Note: cathode is negative and anode is positive)*. 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.

The voltages listed on the CRT power supplies are approximate, you should check and measure ALL voltages AND currents with a DMM. Read the Equipment appendix if you need to review using a DMM.

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. Does it matter what direction the currents flows in the two Helmholtz coils? Should it be in the same direction or opposite directions? Ensure to send currents in the coils accordingly.

Set up your Hall probe as explained in the Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the appendix, or in the *Magnetlab Guide Box* in the upper right corner of the application. Be sure the sensor amplification switch on the Hall probe is set to 6.4mT range. **The MagnetLab application requires the probe to be set to the 6.4mT range to work correctly.** Does the Hall probe ever read a zero field?

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

Use the Hall Probe to Measure the magnetic field between the Helmholtz coils.

Use the Hall probe to measure the magnitude and direction of the magnetic field between the coils. Measure the field near the coils. Be sure your Hall Probe is calibrated and has the correct orientation to accurately measure the magnetic field.

Measure the position of the beam spot for each selected magnetic field. Make at least two measurements for averaging.

The voltages listed on the CRT power supplies are approximate, you should check and measure ALL voltages AND currents with a DMM. Read the Equipment appendix if you need to review using a DMM.

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

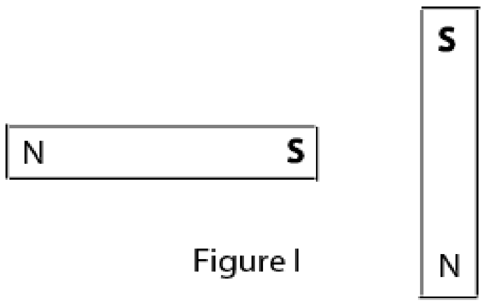
How does the deflection of the electron beam depend on the magnetic field? Did your data agree with your prediction? If not, why? What are the limitations on the accuracy of your measurements and analysis?

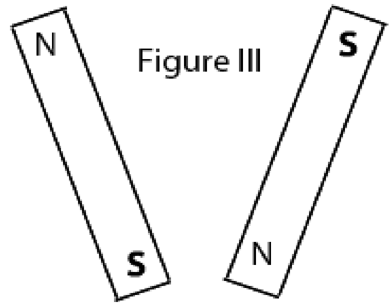
How does the deflection of the electron beam depend on the electron speed? Did your data agree with your prediction? If not, why? What are the limitations on the accuracy of your measurements and analysis?

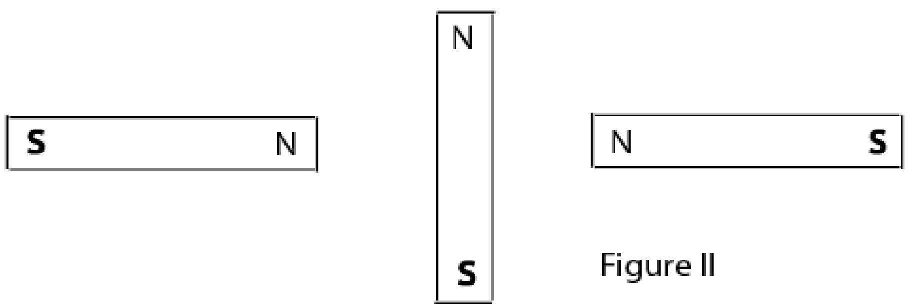
Compare the control of the deflection of an electron beam with a magnetic field to the control of the deflection by an electric field.

☑ CHECK YOUR UNDERSTANDING
LAB 5: MAGNETIC FIELDS AND FORCES

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







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

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

☑ CHECK YOUR UNDERSTANDING
LAB 5: MAGNETIC FIELDS AND FORCES

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: ____________

Course, Lab, Problem: ______________________________

Date Performed: ______________________________

Lab Partners' Names: ______________________________

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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

LAB 6: ELECTRICITY FROM MAGNETISM

In the previous problems you explored the magnetic field and its effect on moving charges. You also saw how magnetic fields could be created by electric currents. 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 much of the world's activities.

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 Sternheim & Kane Chapter 20.1 & 20.3.

Before coming to lab you should be able to:

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

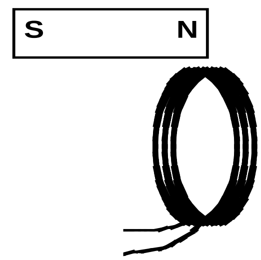
PROBLEM #1: MAGNETIC INDUCTION

One of the great technical problems in modern society is how to generate enough electricity for our growing demand. You have been assigned to a team that is 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 using a bar magnet and a coil of wire, and how you can influence the size of that potential difference.

Read Sternheim & Kane Chapter 20. 1.

EQUIPMENT

You have a small coil of wire and a bar magnet. You will use a voltage probe with software called VoltageTimeLAB.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

PREDICTION

How can you use the magnetic field of the bar magnet to induce a potential difference across the ends of a coil of wire? How many different ways can you think of? What influences the size of the potential difference? For each method, draw a picture of your procedure(s) to induce the current in the coils.

EXPLORATION

Plug the voltage probe into the SensorDAQ interface using the required Ch. 1. Attach the clips to the two ends of the coil and start the VoltageTimeLab program. Make sure you read the software appendix if necessary.

Using the magnet and the coil, 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.

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 (the sign of your measured induced potential difference will depend on how your voltage probe is hooked up to the coil). How do you get the largest potential difference?

PROBLEM #2: MAGNETIC FLUX

You have produced a potential difference in a coil of wire by changing the amount of magnetic field passing through it. However, a literature search on the web shows that most existing generators use mechanical means such as steam, water, or airflow to rotate coils of wire in a constant magnetic field. To continue your design of a generator, you need to calculate how the potential difference depends on the change of orientation of the coil with respect to the magnetic field. A colleague suggests you use the concept of magnetic flux that combines both the magnetic field strength and the orientation of the coil with respect to the magnetic field direction. 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.

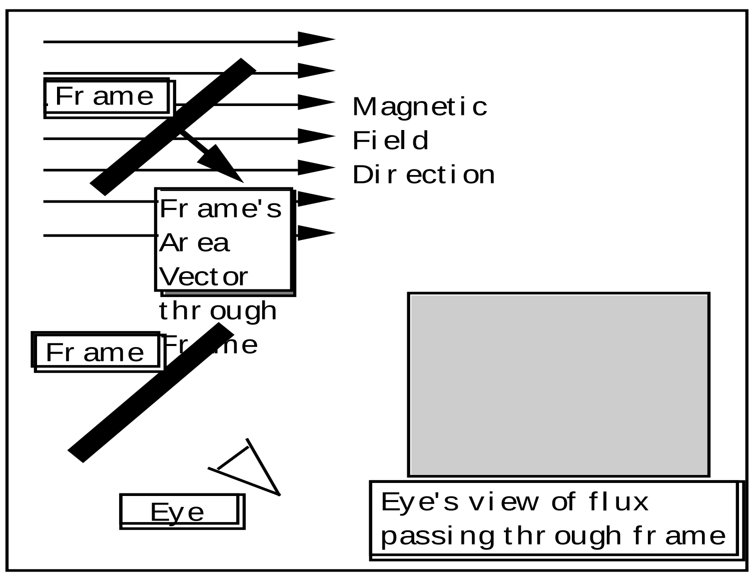
Read Sternheim & Kane Chapter 20, sections 1.

EQUIPMENT

Diagram of <u>Flux Simulation</u> screen to right.

Read the sections *Flux Simulator* and *Measuring Constant Magnetic Field* in the **Software** appendix.

To make the measurement, a magnetic field sensor (Hall probe) is placed midway between two Helmholtz coils. The sensor can be rotated and the angle measured. The sensor measures the amount of magnetic field perpendicular to the area of the Hall effect chip (white dot).



WARM UP

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?

PREDICTION

Calculate the magnetic flux through an area (the frame of the simulation or the Hall probe 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?

EXPLORATION

Open the Flux Simulator 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 this what you expected the eye to see? Why or why not?

Now examine the apparatus with which you will make your measurement.

To measure the amount of magnetic field (not flux) present, you will need to use the Hall Probe. Connect the Hall probe as explained in the Equipment and Software appendices**.** 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the appendix, or in the *Magnetlab Guide Box* in the upper right corner of the application. Be sure the sensor amplification switch on the Hall probe is set to 6.4mT range. **The MagnetLab**

application requires the probe to be set to the 6.4mT range to work correctly. Does the Hall probe ever read a zero field?

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 over 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 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 **the magnitude** of the magnetic field between the Helmholtz coils. Rotate the probe through 360 degrees, making measurements at whatever angle intervals you think are appropriate. Include uncertainties with your 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 upon 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?

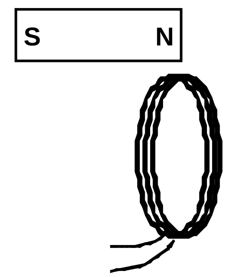
PROBLEM #3: THE SIGN OF THE INDUCED POTENTIAL DIFFERENCE

To continue your investigation of how to improve the efficiency of electric generators, you decide to determine 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 your materials. You decide to start your investigation with the simplest situation possible – a coil of wire and a bar magnet.

Read Sternheim & Kane Chapter 20, sections 1.

EQUIPMENT

You have a small coil of wire and a bar magnet. You will use the voltage probe with the VoltageTimeLAB software.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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 induced potential difference across the ends of the coil relate to the induced current in the coil?

PREDICTION

Draw a coil of wire wrapped either clockwise or counterclockwise with the two ends of the wire protruding as shown in the above diagram. Add a bar magnet being pushed through the center of the coil in one direction.

Given the orientation of coil and magnet you have chosen, which of the protruding wires you would expect to be at a higher potential when:

i) The north pole of a bar magnet is pushed through the coil in the direction you've chosen.

ii) The south pole of a bar magnet is pushed through the coil in the direction you've chosen.

EXPLORATION

Plug the voltage probe into the SensorDAQ interface using the required Ch. 1. Attach the clips to the two ends of the coil and start the VoltageTimeLab program. Make sure you read the software appendix if necessary.

Using the magnet and the coil, make sure that the apparatus is working properly and that you are getting appropriate potential difference graphs 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 given the way the coil is wrapped and the way you hooked up your voltage probe? Explain any differences.

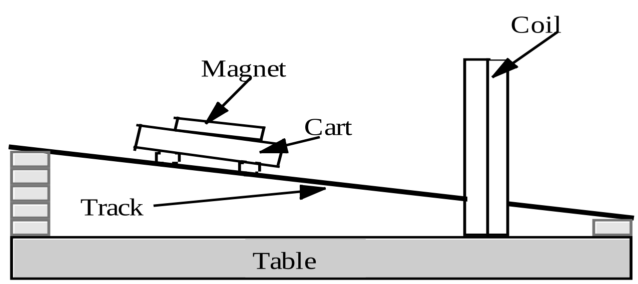
PROBLEM #4: THE MAGNITUDE OF THE INDUCED POTENTIAL DIFFERENCE

To continue investigating how to improve the efficiency of electric generators, you decide to calculate 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. You mount a magnet on a cart and roll the cart down a ramp. At the end of the ramp, the cart passes through the center of a coil of wire. You can calculate the speed of the magnet as it goes through the coil from where it is released on the ramp. You will use this to calculate the induced potential difference around the coil.

Read Sternheim & Kane Chapter 20, sections 1.

EQUIPMENT

You have a coil of 200 turns of wire, a magnet, meterstick, cart, and track. The track is raised at an incline using wooden blocks. You also have voltage probe with software called VoltageTimeLAB.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a picture of the situation. Label important distances and kinematic quantities. Decide on an appropriate coordinate system and add it to your picture.
2. Use Faraday's Law to relate change of magnetic flux to the magnitude of the induced potential difference in the coil.
3. Draw a magnetic field map of a bar magnet. Draw the coil of wire on the magnetic field map. As the bar magnet passes through the coil, when is the flux change the strongest? What is the relationship between the velocity of the bar magnet and the change of the magnetic flux through the coil? This tells you, qualitatively how the flux changes with time.
4. Look at the time rate 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.

PREDICTION

Calculate the induced potential difference in the coil as a function of the distance from the coil at which the cart is released and other quantities that are not changed. Make a graph of this function.

EXPLORATION

Before you begin exploring, consider what the signal displayed by the VoltageTimeLab program will look like. Will you be able to tell by the signal when the cart has passed through the ring? 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 the earlier problems **Magnetic Induction** and **The Sign of the Induced Potential Difference**.

Plug the voltage probe into the SensorDAQ interface using the required Ch. 1. Attach the clips to the two ends of the coil and start the VoltageTimeLab program. Make sure you read the software appendix if necessary.

Push the bar magnet through the coil to make sure that the apparatus is working properly and that you are getting appropriate signal on the screen. How does the graph compare to your expectations? Make sure you can freeze the screen while showing your desired data.

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 bar 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?

Does the orientation of the magnet matter? Try different orientations. Do the magnetic bumpers in the cart matter? Try a cart without a bar magnet.

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 that you see displayed. You might want to move the magnet by hand to see if your understanding is correct.

Try adding another bar magnet to the cart to increase the magnitude of the induced potential difference. Does it matter how the second magnet is oriented?

Develop a measurement plan to take the data you need to answer the question.

MEASUREMENT

Follow your measurement plan and record the maximum potential difference across the ends of the coil of wire as a function of 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

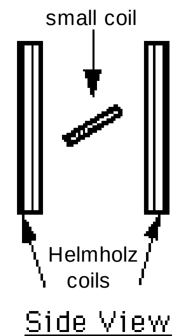
To begin investigating how to improve the efficiency of electric generators, your supervisor assigns you the task of building a working model of a generator from which it is easy to take measurements. Your model consists of Helmholtz coils to generate a well-defined magnetic field and a smaller coil of wire, 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 you expect and then take some measurements to make sure that the results correspond to your understanding of the situation. You will need to determine how the expected potential difference may depend on time, the rate of small coil rotation, and other parameters in your setup.

Read Sternheim & Kane Chapter 20, sections 1 & 3.

EQUIPMENT

The small coil mounts to the base between the Helmholtz coils, as shown to the right. The Helmholtz coils are connected to a power supply. The small coil is labeled with the # turns of wire, and can be rotated by a motor. **DO NOT connect a power supply to the small coil or you will damage it.**



You will have a Hall probe, a DMM, and a meterstick. You will also have a voltage probe with the VoltageTimeLAB software.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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.

PREDICTION

Calculate the potential difference produced by a coil of wire spinning in a uniform magnetic field as a function of its angular speed.

EXPLORATION

DO NOT connect a power supply to the small coil or you will likely damage it!

You will want the largest magnetic field possible that you can safely produce with the equipment available.

Connect the large Helmholtz coils to the power supply with *the current flowing in the opposite direction in both coils*. Using your 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 both coils*, using the adjustable voltage. Using your 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?

Develop a plan for measuring the magnetic field using the Hall probe.

Set up your Hall probe as explained in the Equipment and Software appendices. 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? If you notice an ambient field, can you determine its cause?

Go through the Hall probe calibration procedure outlined in the appendix, or in the *Magnetlab Guide Box* in the upper right corner of the application. Be sure the sensor amplification switch on the Hall probe is set to 6.4mT range. **The MagnetLab application requires the probe to be set to the 6.4mT range to work correctly.** Does the Hall probe ever read a zero field?

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, disconnect the Hall probe from the interface. Plug the voltage probe into the interface and attach the clips to the two ends of the small coil. The ends of the small coil are attached to threaded posts located on opposite ends of the axle about which the coil spins. Use the VoltageTimeLAB to get an on-screen display of the small coil's potential difference versus time. Review the appropriate section of the Software appendix if necessary.

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 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. Be sure to record in your journal how you found the effective area; think carefully about how you do this.

Decide where you place the Hall probe to measure the magnetic field produced by the Helmholtz coils. Calibrate the probe at the point of interest with the power supply off.

Measure the strength of the magnetic field, produced in the region of interest by the Helmholtz coils, using the Hall Probe.

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. If you have not done so, read the Software appendix that details how to use the VoltageTimeLAB application.

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?

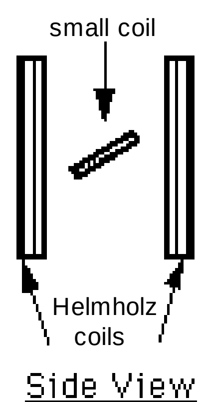
PROBLEM #6: TIME-VARYING MAGNETIC FIELDS

You are working for a research team 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 works its way through the intestine gathering data. Naturally you can't have the probe connected to external wires and you don't want to use a battery inside the person. Instead you plan to power the probe by using an external time-varying magnetic field and a small pick-up coil of wire inside the probe. Your boss is concerned that it won't work because you have no control over the orientation of the probe within the patient's intestine. Specifically, you can't control the angle dependence between the coil and the magnetic field. You have been asked to investigate the magnitude of this problem. You decide to study how the induced potential difference depends on the angle the coil makes with the external magnetic field. To do this you will also need to understand how the induced potential difference depends on the time variation of the magnetic field.

Read Sternheim & Kane Chapter 20, sections 1, 3 & 5.

EQUIPMENT

The small coil mounts to the base between the Helmholtz coils, as shown to the right. The Helmholtz coil is connected to a function generator. The small coil can be rotated by hand. **DO NOT connect a power supply to the small coil or you will damage it.**



A function generator outputs an electrical current, which changes with time as a sine function. When the Helmholtz coil is connected to a function generator, an alternating current goes through the coils. *Only use frequencies of less than 100 Hz.*

You will have a DMM, a compass, meterstick and a protractor is affixed to the induction coil. You will also have a voltage probe with the VoltageTimeLAB software.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a picture of the equipment, labeling the direction of the magnetic field and the orientation of the small coil. Choose a coordinate system on the small coil.
2. Use Faraday's Law to relate the changing magnetic flux (by the Helmholtz coils) through the induction coil to the potential difference across the ends of the coil of wire.

3. Draw a diagram showing only the small coil, a vector giving the direction of the magnetic field, and the area vector for the coil. Write an equation relating the magnetic flux through the small coil, when it is stationary and at some angle to the magnetic field, to the strength of the magnetic field.
4. Write an equation for the magnetic field produced by the current in the Helmholtz coils, assuming the current through the Helmholtz coils varies with time as a sine function.
5. Write an expression for the change in magnetic flux through the small coil.
6. Combine the expressions you have written to write an expression for the time-varying potential difference across the ends of the small coil at some angle to the magnetic field. Use that result to write an expression for the maximum potential difference across the ends of the coil at any particular angle and graph the maximum potential difference vs. the angle.

PREDICTION

Calculate the potential difference across the pick-up coil, for a magnetic field changing with a known period, as a function of the angle the coil makes with the magnetic field. From this expression, make a graph of the maximum potential difference as a function of the angle.

EXPLORATION

DO NOT connect a power supply to the small coil or you will damage it.

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 LOΩ 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 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 and decrease 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 voltage probe to the small coil to read the potential difference across it using the

VoltageTimeLAB application. Or, if you are applying a frequency near 60hz, you might try using a DMM, setting it to read AC voltage.

Slowly change the orientation of the small coil to get the maximum and minimum potential difference.

Adjust the amplitude of the signal generator to give the maximum reading possible. Now set the function generator to 1Hz and compare the AC voltage reading to the DC voltage reading while using a DMM to measure the potential difference across the small coil. Slowly increase the frequency and observe the results for both AC and DC settings. Decide on the best frequency to use for your chosen method of measuring the induced potential differences in the small induction coil.

Connect the Hall probe as explained in the appendices. Decide where you will place the Hall probe to measure the magnetic field.

Go through the Hall probe calibration procedure outlined in the appendix, or in the *Magnetlab Guide Box* in the upper right corner of the application. Be sure the sensor amplification switch on the Hall probe is set to 6.4mT range. **The MagnetLab application requires the probe to be set to the 6.4mT range to work correctly.** Does the Hall probe ever read a zero field?

Use a Hall probe and MagnetLAB to investigate how the magnetic field between the Helmholtz coils varies as a function of time at the frequency you have selected. Make sure to try a number of different frequencies and orientations of the Hall probe between the coils. How does this relate to your earlier measurements using the compass?

Adjust the amplitude of the function generator to give a magnetic field reading with the Hall probe. How does the magnetic field reading 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 function generator frequency and amplitude you have chosen to use.

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 enough data 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.

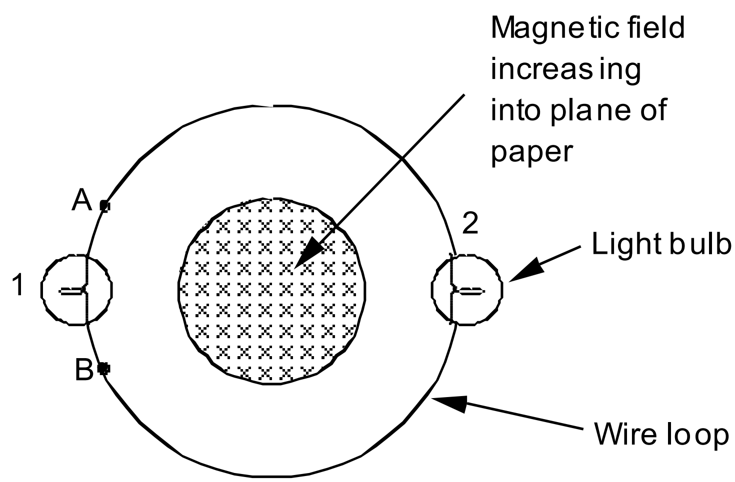
CONCLUSION

Does the time variation of the potential difference across the pick-up coil agree with your prediction? If not, why?

Highlight the similarity and differences with the previous problem, **The Generator.**

☑ CHECK YOUR UNDERSTANDING
LAB 6: ELECTRICITY FROM MAGNETISM

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 9 Ω is placed perpendicular to a uniform magnetic field of 2.0 T. The magnetic field suddenly reverses direction. What is the total charge that passes through the coil?

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: ____________
Course, Lab, Problem: ______________________________
Date Performed: ______________________________
Lab Partners' Names: ______________________________
____
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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

LAB 7: WAVE OPTICS

In this lab, you will solve problems in ways that take advantage of light interference, a phenomenon most easily understood in terms of the wave nature of light. Like waves, light can interfere constructively and destructively with itself. Under some conditions, this causes distinctive patterns of light and dark fringes that would not be seen if light had no wave-like behavior. These conditions may be less familiar to you than the conditions for which geometrical optics is useful. The results of interference can, however, be seen in common situations such as the colored fringes that form in parking lot puddles where a thin layer of oil floats on the water, or the colored light patterns that reflect from a compact disc.

OBJECTIVES:

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

- Describe interference patterns in terms of constructive and destructive interference.
- Predict how changes in the size of an object or slit, or the wavelength of the light, will affect interference patterns.

PREPARATION:

Read Sternheim & Kane chapter 21 section 1-4 and chapter 23 sections 6, 7 & 9.

Keep the objectives of the laboratory in mind as you read the text. It is likely that you will do these laboratory problems before your lecturer addresses this material; the purpose of this laboratory is to introduce you to the material.

Before coming to lab you should be able to:

- Find unknown quantities using trigonometric relationships.
- Relate constructive and destructive interference of two waves to phase/path differences between the two waves.
- Describe why laser light is described as coherent.
- Create graphs of measured quantities and determine the equation describing linear relationships between graphed quantities.

PROBLEM #1: INTERFERENCE DUE TO A DOUBLE SLIT

Your group is involved in a project investigating some properties of viruses. You need to categorize viruses by size, but have found that they are too small to view with any microscope that uses visible light. You know, however, that for a small object illuminated by coherent light, a diffraction pattern will be formed rather than an image. The size of an object can be determined from its diffraction pattern, and you would like to try a diffraction technique with viruses.

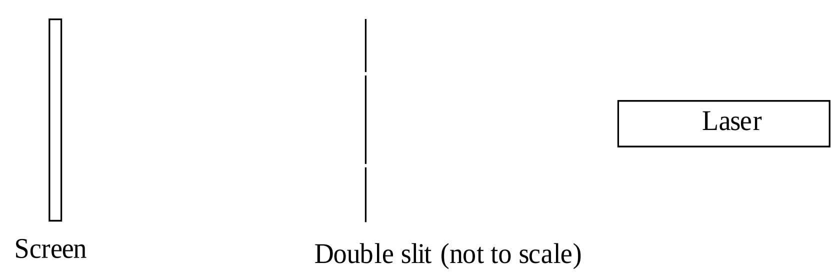
Two issues occur to you. The first issue is, of course, how to determine the size of an object from its diffraction pattern. The second issue has to do with the form in which the viruses will be studied. Your group can isolate a single *type* of virus, but cannot isolate a single *example* of the virus. As a result, you will be forced to study the pattern produced by several viruses in very close proximity to one another. You hope that some information about the size of a single virus can be extracted from the pattern formed by many viruses. If the technique is to be useful, you must be able to distinguish the diffraction pattern due to a *single virus* from the pattern that results from *several copies* of the same type of virus.

In this problem and the next, **Interference Due To A Single Slit,** you will study light interference in a simplified system to explore how these two issues can be dealt with. In this lab problem, you will investigate the interference pattern due to more than one object. In the single slit problem you will develop a technique for determining the size of an object from its diffraction pattern. In this lab problem, a diode laser will be the light source, and pairs of closely spaced slits will represent the viruses. You are interested in what pattern is formed on a screen by coherent light that passes through a pair of narrow slits and how that pattern depends on the separation of the slits.

Read Sternheim & Kane sections 21.1-21.4 & 23.6-23.9.

EQUIPMENT

You have a diode laser, a slide with four sets of double slits, a magnetic slide holder, a screen, an optical bench, and a ruler.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a sketch of the arrangement you will use to project the interference pattern on the screen. Include laser, laser beam, slits, and screen.
2. Draw another diagram with an enlarged view of the slits and the screen. Show a laser beam wave front reaching the slide. Are the parts of the wave front that reach the two slits in phase? If they are out of phase, determine the phase difference between them.
3. Indicate the point on the screen that is equidistant from the two slits. Label this as *O*. Are the parts of the wave front that reach *O* from the bottom slit and the top slit in phase? If they are out of phase, determine by how much. Choose another point *P* on the screen. Are the parts of the wave front that reach *P* from the two slits in phase? If they are out of phase, determine the relative phase difference. Is this determination simplified if you assume that the distance between the slide and the screen is much larger than the distance between the slits? If so, explain.
4. What condition must the phase difference meet to produce a bright spot in the interference pattern? Use your diagram to write an expression for the vertical distances (above or below *O*) to the points where interference maxima should be produced. What condition must the phase difference meet to produce a dark spot in the interference pattern? Write an expression for the distances to interference minima.
5. Should the minima (or maxima) be equally spaced from one another? Write an expression for the wavelength of the incident light, in terms of the spacing between minima (maxima).
6. Sketch a graph, showing light *intensity vs. position* on the screen. Identify positions of interference maxima and minima.
7. What should happen to the distances between bright spots if the spacing between the slits is doubled? What should happen if the distance from the slits to the screen is doubled?
8. What pattern would you expect to see on the screen if light from the two slits did not interfere? Could you distinguish between this pattern and the one shown in your graph?

PREDICTION

Write an expression describing the double-slit interference pattern that relates the vertical positions of interference maxima on the screen to: the distance between the slits, the distance between the slide and the screen, and the wavelength of the laser's radiation. (For this prediction, do not include the effects of single slit diffraction. You will deal with those effects in the next lab problem **Interference Due To a Single Slit**.)

EXPLORATION

Warning: ***Laser beams may cause permanent vision impairment or blindness.*** **Do NOT allow the laser beam (or its reflection) to point into anybody's eye. To avoid stray beams in the laboratory, make sure beams from your laser terminate on a screen at all times. Laser beams are extremely intense compared to light from any common light source (even compared to sunlight, as viewed from earth). Permanent blindness may result from prolonged exposure to any laser beam, even those from small laser pointers.**

Arrange the laser and the slide with double slits on the optics bench. The laser should be parallel to the optics bench and perpendicular to the slide, and its beam should be aimed at one of the pairs of slits. The screen should be vertical and perpendicular to the optics bench.

By inspection, make sure both slits are illuminated approximately equally. Adjust the positions so that you clearly observe an interference pattern on the screen.

How does the interference pattern compare with your predictions? Which features did you predict, and which ones did you not predict?

Some of the features you see may be the effect of light from one slit interfering with light from the other slit. Other features may be the effect of light from one part of a slit interfering with light from another part of the same slit. There are four pairs of slits on the slide, with different slit widths and different separations between the slits. Use these to make a judgment about which features of the interference pattern are due to each type of interference.

How does the interference pattern change for different slit separations? How does the pattern change when you adjust the distance from the slits to the screen? Do your observations match your predictions?

How important do you think is laser light for this problem? If possible, try illuminating the slits with an alternative light source. Do you still see the interference/diffraction picture? Record your results.

MEASUREMENT

Continuing your exploration, sketch the interference patterns for two pairs of slits with the same slit widths and different slit separations.

Place a sheet of paper on the screen as a recording device. On the paper, label positions of the maxima you can observe. Be sure to record the distance from the slits to the screen. Repeat this operation, for the two pairs of slits, for at least two different distances between the screen and the slits. (Be sure to record the distance from the slits to the screen each time, and the widths and separations of the slits reported on the slide.)

Measure the positions of the interference maxima for each trial.

ANALYSIS

Compare the sketches you prepared during measurement to the graphs from your warm-up questions answers. Do the patterns match?

Use your measurements from each trial and your predicted relationships to determine the wavelength of the laser light. Do you obtain a consistent value across different trials? If so, is it comparable to the accepted value for the wavelength of light produced by a Helium Neon laser?

CONCLUSION

Can you tell which features of a two-slit interference pattern are caused by light from one slit interfering with light from the other slit? Can you distinguish them from the features due to light from part of one slit interfering with light from another part of the same slit? Explain.

Do your results allow you to *rule out* the possibility of determining the size of a single virus from the pattern due to several copies of the same virus in close proximity to one another? Explain.

The size of common viruses is on the order of 10^{-6} m to 10^{-8} m. When determining virus size with an interference technique, would it be helpful to use light with a different wavelength from the one you used for this problem? If so, explain why.

PROBLEM #2: INTERFERENCE DUE TO A SINGLE SLIT

Your group is involved in a project investigating some properties of viruses. You need to categorize viruses by size, but have found that they are too small to view with any microscope that uses visible light. You know, however, that for a small object illuminated by coherent light, a diffraction pattern will be formed rather then an image. The size of an object can be determined from its diffraction pattern, and you would like to try an interference technique with viruses.

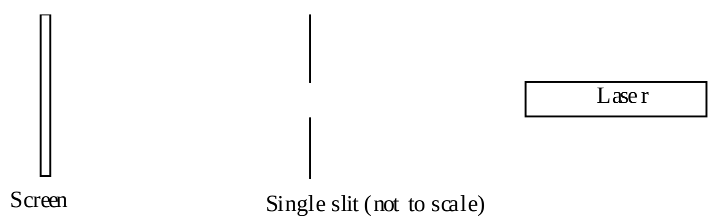
Two issues occur to you. The first issue is, of course, how to determine the size of an object from its diffraction pattern. The second issue has to do with the form in which the viruses will be studied. Your group can isolate a single *type* of virus, but cannot isolate a single *example* of the virus. As a result, you will be forced to study the pattern produced by several viruses in very close proximity to one another. You hope that some information about the size of a single virus can be extracted from the pattern formed by many viruses. If the technique is to be useful, you must be able to distinguish the diffraction pattern due to a *single virus* from the pattern that results from *several copies* of the same type of virus.

In this problem and the previous problem, **Interference Due To A Double Slit**, you study light interference in a simplified system to explore how these two issues can be dealt with. In the present lab problem, you will develop a technique for determining the size of a single object from its diffraction pattern. A diode laser will be the light source and a narrow slit will represent a virus. You are interested in what type of diffraction pattern is formed and how the pattern depends on the width of the slit.

Read Sternheim & Kane sections 21.1-21.4 & 23.6-23.9.

EQUIPMENT

For this problem, you will be provided with a diode laser, a slide with four individual slits of different widths a second slide with four pairs of double slits, a magnetic slide holder, a screen, an optical bench, and a ruler.



If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

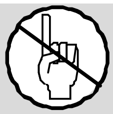
WARM UP

1. Draw a sketch of the arrangement you will use to project a diffraction pattern on the screen. Include laser, laser beam, slit, and screen.
2. Draw another diagram with an enlarged view of the slit and the screen. Show a laser beam wave front reaching the slide. Are the parts of the wave front that reach different parts of the slit in phase? If they are out of phase, determine the phase difference between them.
3. What condition must be met for a maximum to occur in the diffraction pattern for a single slit? What condition must be met for a minimum to occur? How can these conditions be understood in terms of the situation's geometry and the properties of light waves?
4. Indicate the point on the screen that is directly across from the single slit. Label this as *O*. Is *O* a diffraction maximum or minimum? Choose another point *P* on the screen. Indicate on your diagram how you would determine if *P* were a diffraction maximum or minimum. Is this determination simplified if you assume that distance from the slide to the screen is much larger than the slit width? If so, explain.
5. Use your diagram to write an expression for the distances (above or below *O*) to the points where diffraction maxima should be produced. Write another expression for the distances to diffraction minima. Write a third expression for the wavelength of the incident light, based on positions of maxima or minima.
6. Sketch a graph, showing *light intensity vs. position* on the screen. Identify positions of diffraction maxima and minima.
7. What should happen to the distances between bright spots if the width of the slit were doubled? What should happen if the distance from the slits to the screen is doubled?
8. Does the width of the slit place a restriction on the maximum amplitude or wavelength of a light wave that could pass through the slit? If so, illustrate the limits below your diagram, and describe how you expect this might affect the observed diffraction pattern.

PREDICTION

Write an equation describing the single slit diffraction pattern that relates the positions of diffraction maxima on the screen to: the width of the slit, the distance between the slide and the screen, and the wavelength of the laser's radiation.

EXPLORATION



Warning: ***Laser beams may cause permanent vision impairment or blindness.*** **Do NOT allow the laser beam (or its reflection) to point into anybody's eye. To avoid stray beams in the laboratory, make sure beams from your laser terminate on a screen at all times. Laser beams are extremely intense compared to light from any common light source (even compared to sunlight, as viewed from earth). Permanent blindness may result from prolonged exposure to any laser beam, even those from small laser pointers.**

Arrange the laser and the slide with single slits on the optics bench. The laser should be parallel to the optics bench and perpendicular to the slide, and its beam should be aimed at one slit. The screen should be vertical and perpendicular to the optics bench. Adjust the positions so that you clearly observe a diffraction pattern on the screen.

How does the diffraction pattern compare with your predictions? Which features did you predict, and which ones did you not predict?

How does the diffraction pattern change for different slit widths? How does the pattern change when you adjust the distance from the slit to the screen? What happens if you rotate the slit from a vertical to a horizontal position? Do your observations match your predictions?

How does the diffraction pattern of a single slit compare with the diffraction pattern of a pair of slits with the same width? Use a double slit of the same slit width as the single and observe the width of the central region. Does this bode well for the virus project? Do you think the laser is important for this problem? Do you have any other sources of light to try instead of laser? What do you see?

MEASUREMENT

Continuing your exploration, sketch the diffraction patterns for two different slit widths.

Fix a sheet of paper on the screen. Mark maxima of diffraction pattern on the screen. (If the maxima are difficult to locate visually, mark some positions so that the central part of each spot can be precisely determined from the marks.) Be sure to record the slit width and the distance from the slit to the screen.

Repeat this operation for at least two different distances and at least two different slit widths.

Remove the slit from the system, and observe the pattern produced when laser light shines on a human hair. Do you see a diffraction pattern? Measure and record the distance from the hair to the screen, as well as the positions of the diffraction maxima.

ANALYSIS

Compare the sketches you prepared during measurement to the graphs from your warm-up questions answers. Do the patterns match?

Use your measurements and the relationships from the prediction to determine the wavelength of the laser light from each trial. Do you obtain a consistent value across different trials? If so, is it comparable to the accepted value for the wavelength of light produced by a Helium Neon laser?

The diffraction pattern due to a solid object (a hair, for example) is the same as that due to a hole of the same shape. Use your measurements to determine the width of your hair.

CONCLUSION

Do the expressions you predicted match the diffraction patterns you observed? If they do not match perfectly, identify some sources of error, and explain how they could result in the observed errors.

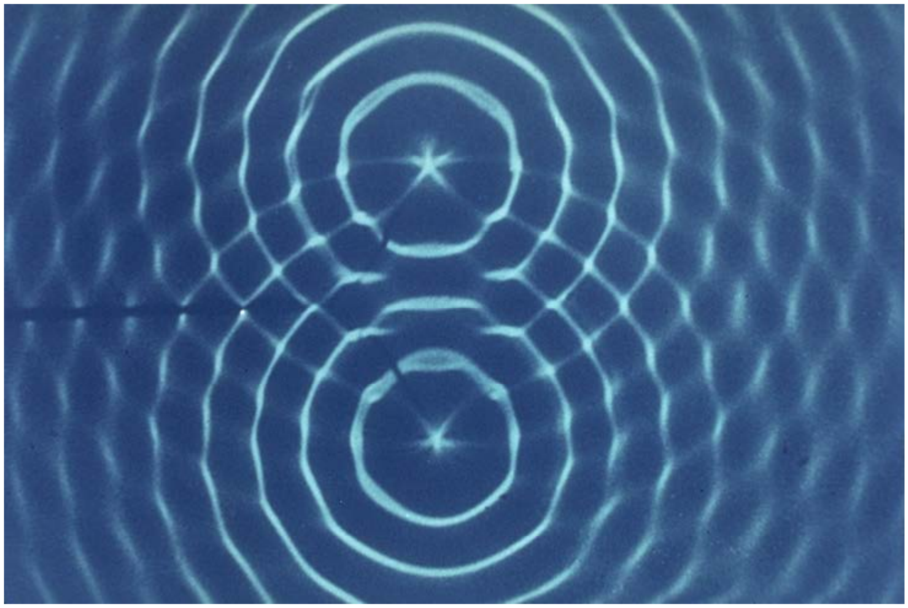
Do your observations provide evidence for the wave nature of light?

Does your measurement of hair thickness match an order-of-magnitude estimate of hair thickness based on direct observation? Explain your estimate.

What do you need to know to determine an object's size from the diffraction pattern it produces?

Compare the results of this problem to the results of the previous problem **Interference Due To a Double Slit**. How closely connected are the features of a single slit diffraction pattern to those of a double slit interference pattern?

☑ CHECK YOUR UNDERSTANDING
LAB 7: WAVE OPTICS



The picture above shows a series of circular water waves emanating outward from two points. The waves interfere with one another. Refer to the picture for questions 1-5 below.

1. On the picture, indicate the wavelength of these waves.

2. Draw lines to show where the waves are *constructively* and *destructively* interfering. How many interference *maxima* are there along the right edge of the picture?

3. What are the phase-difference requirements for constructive or destructive interference? Demonstrate at several points how these requirements are met in the picture above.

4. How would the interference pattern change if the wavelength were shortened?

5. How would the interference pattern change if the wave sources were moved closer together? What would happen if the wave sources were located on top of each other – at a single point?

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: __________

Course, Lab, Problem: ______________________________

Date Performed: ______________________________

Lab Partners' Names: ______________________________

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	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

Physics Lab Report Rubric

LAB 8: NUCLEAR PHENOMENA

Radioactive decay is the emission of particles such as photons, electrons, neutrons, or even other nuclei when atomic nuclei go from a high energy state to a lower energy state. This lower energy state is usually a nucleus of a different element. The particles emitted from the nucleus, given the generic name of radiation, often have a high enough energy to penetrate materials such as organic tissue. This energy is transferred to any object with which the particles collide, including the cells of your body. Radioactive materials are used to kill diseased cells inside a living organism that cannot be reached by other means, as tracers to analyze fluid flow in the body, and in imaging the body's interior. They are also used in industry to examine potential defects in materials. When the particles from radioactive decay collide with cells in a living organism, the resulting collision damages the cell. If enough cells are damaged, the effect can be to overwhelm the organism's repair mechanisms or to cause a mutation. Some food products are treated with radiation to kill existing microorganisms without altering the molecular structure of the food as would happen with heating or chemical treatment.

We live in an environment of particles with energies as high or higher than those produced by radioactive decay. Our bodies are built of some naturally occurring radioactive nuclei such as potassium 40. In addition the earth is bombarded by high energy protons which collide with the atmosphere and produce showers of high energy particles which continuously collide with our cells. Almost all of the common materials in our environment, e.g. carbon or iron, contain radioactive nuclei. This sea of radiation in which we live is usually called background. This radiation constantly kills or alters the cells in our body and our bodies have evolved to handle the repair at the cellular level. Significantly higher levels of radiation however can overwhelm this cellular self-repair mechanism.

In this laboratory, you will solve problems related to the nature of interactions between particles produced by radioactive decay and matter. You will also determine the rate of background radiation for comparison.

OBJECTIVES:

Successfully completing this laboratory should enable you to:

- Quantitatively determine the level of background radiation.
- Understand the statistical nature of radioactive decay and the process of counting.
- Predict the relationship between distance from a radioactive source and the count rate.
- Determine the different types of particles emitted by radioactive decay by the effects of different shielding material.

LAB 8: NUCLEAR PHENOMENA

- Understand how the effectiveness of radiation shielding depends on the shielding thickness, for different shielding materials and different types of radiation.
- Test for relationships among measured quantities by producing a linear graph with data with an non-linear functional dependence.

PREPARATION:

Before you come to lab,

1) Read Sternheim & Kane chapter 30 sections 30.1-30.3 & 30.9.
2) Set up and solve the equation that describes the lifetime of a radioactive nucleus.
3) Use graphical techniques to determine the parameters in that equation.

PROBLEM #1: DISTANCE FROM THE SOURCE

You have a job working in a cancer treatment facility that prepares radioactive isotopes. Although you take great care to handle them properly, you know that some body parts are more sensitive to radiation than others. After all, you may want to have children some day. To address your worry, you decide to use geometry to calculate how the rate of particles emitted from a radioactive source going through a sensitive area of your body depends on the distance from the source. You will test your calculation in the laboratory using a small radioactive source and a Geiger counter to detect the emitted particles. Is this relationship different for different types of particles?

Read Sternheim & Kane chapter 30 sections 30.1-30.3 & 30.9.

EQUIPMENT

You have a Radiation Monitor (Geiger counter) connected to a LabPro Interface device and the LoggerPro software. You will also have different radioactive sources: both a beta source, and a gamma source.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

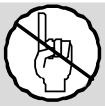
WARM UP

1. Draw a large sphere centered on a small radioactive source. Write down the fraction of the particles produced by the source that pass through the surface of that sphere. Write down the equation for the surface area of that sphere.
2. On the surface of the sphere you've drawn, sketch an area representing a small particle detector. If the source emits radiation evenly in all directions, write an equation for the fraction of its radiation that would pass through the particle detector as a function of the area of the detector and the radius of the sphere.
3. Now draw another even larger sphere still centered on the radioactive source. Draw the same particle detector on the surface of the larger sphere. Now write an equation for the fraction of the source's radiation that would pass through the particle detector as a function of the area of the detector and the radius of the new sphere. Is the rate of particles passing through the detector when it is on the surface of the larger sphere higher or lower than its rate when it is on the smaller sphere?
4. Write an equation for the relationship of a detector's counting rate and its distance from radioactive source. Sketch a graph of this relationship. What assumptions does this relationship require?

PREDICTION

Use geometry to calculate how the particle count rate varies with distance from a small radioactive source. On what assumptions is your calculation based?

EXPLORATION



WARNING: The radioactive sources available for this problem provide low intensity radiation, and are safe if handled with respect for short amounts of time. Do not remove them from the laboratory, and do not attempt to open the plastic disks containing the sources. **If a disk breaks open inform your TA immediately, do not touch it.**

Make sure you read the Equipment and Software appendices to understand the operation of the Geiger counter before trying to operate it. Place a radioactive source near the detector, turn on the counter. Try the controls, and make sure every group member understands how to operate it. Try each of your sources to make sure the equipment is functioning
.

With the detector working you now need to determine how to make your measurement uncertainty as small a practical. Start by using the detector to measure the number of counts from a radioactive source in some short time interval, say 10 or 15 seconds. Repeat this measurement several times, recording the number of counts occurring in each fixed time interval. Compute the average number of counts per second and the difference of each trial from that average. Calculate the average of these differences for all of your trials. That average difference represents your counting uncertainty for the measurement. Now increase your time interval by a factor of 4 and repeat the same number of trials and the same calculation. In which case is the measurement uncertainty a smaller fraction of the measurement? By approximately what factor did the average measurement change when you increased the counting time by a factor of 4? What does this tell you about the time period necessary when taking data? Keep measurement uncertainty in mind when deciding how much time is "enough" to allow comparisons among count rates under different conditions.

Since we live in a “sea” of radiation, you need to determine how that effects your measurements. Remove all radioactive sources from the vicinity of your detector. Record the count rate from the detector for a significant amount of time. You will need to subtract the count rate due to this background radiation from your future measurements. Measure the background rate, and estimate the uncertainty in your measurement.

Try different orientations of each source relative to the detector. Do you achieve a greater counting rate with the label facing up or facing down? Repeat this test for each type of radioactive source.

Come up with a measurement plan that will allow you to accurately determine the relationship between counting rate and the distance between the detector and the source. Your plan should take background radiation into account and a plan to minimize the measurement uncertainty.

MEASUREMENT

Carry out your measurement plan, and adjust if necessary to obtain useful data for each source. You may find Microsoft Excel (available on the computer at your lab station) to be a very useful tool for recording data, doing calculations, and making plots. Be sure to keep copies of your measurements as electronic files (or on paper printouts).

ANALYSIS

Make a plot to show how the particle rate through the detector depends on the distance from the source. If this is not a linear relationship, use your prediction to determine a set of axes that should make your graph a straight line. See the section *Using Linear Relationships to Make Graphs Clear* in the appendix **A Review of Graphs** if you need help.

To see if your predicted relationship fits the data better than some other possibilities, try at least one other linearization that you think might also fit the data.

Whenever your graph is a straight line, record the equation of the best fit line for that graph. Solve that equation for the counting rate as a function of distance from the detector.

CONCLUSION

Describe the relationship between the particle rate from a radioactive source and distance from that source to the detector.

Does your predicted relationship match the relationship you found? If not, can you explain why not?

PROBLEM #2: SHIELD POSITION

As a member of a radiation medicine research group, you are constantly reminded that it is important to limit your dose of radiation. One day while at Starbucks for a coffee break you overhear your coworkers discussing shielding efficacy. One person says that radiation shielding is most effective when it is placed near the radiation source. Another person contends that shielding is most effective when it is worn on the body, which places it as far from the radiation source as possible. Yet a third person states that material of a particular thickness should absorb a certain fraction of incident radiation so the shield's distance from the source is irrelevant. Based on your ideas of what happens when a particle passes through material, you decide which person you believe and explain why. You also decide to test your idea in the laboratory. Since the result might depend on the type of radiation, you use different sources which each emit beta (electrons) or gamma (photons) radiation. It is also possible that result depends on the type of shielding so you try several different kinds of material.

Read Sternheim & Kane chapter 30 sections 30.1-30.3 & 30.9.

EQUIPMENT

You have a Radiation Monitor (Geiger counter) connected to a LabPro Interface device and the LoggerPro software. You will also have a shielding kit and different radioactive sources: both a beta source, and a gamma source

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Sketch two pictures showing a radioactive source that emits radiation in all directions. Add a detector at the same distance from the source in each diagram. Finally, add identical shielding material in each diagram; place the shield near the source in one picture, and near the detector in another diagram. The shielding material should be wider than the detector, so that radiation emitted in a range of directions from the source will have a chance to interact with the shield.
2. Imagine that each shield absorbs half of the radiation incident on it. Show the paths of some example radiation particles in your pictures for this case. How should the count rates for the situations shown in each picture compare to one another? How should the count rates compare to a situation in which no shielding is present?
3. Imagine a situation in which some particles that interact with the shielding material are scattered (leave the shield in a new direction). Add examples of scattered radiation particles to your pictures. Could scattering affect count rates, compared to

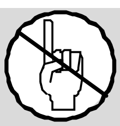
the situations in which particles are only absorbed? Could scattering cause the count rates to depend on the position of the detector?

4. Imagine a situation in which some particles that interact with the shielding material produce several new particles. Add this example to your pictures. Could this cause the count rates to depend on the position of the detector?
5. If no scattering or particle production occurs, do you expect the count rate to change when the position of the shield is changed? If not, why not? If so, do you expect the count rate to be greater when the shield is closer to the source or closer to the detector? Explain.

PREDICTION

Do you think that radiation is shielded more effectively by material that is closer to the radiation source or closer to the detector? How does your conclusion depend on the type of radiation? How does it depend on the type of shielding material? On what do you base your prediction?

EXPLORATION



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Make sure you read the Equipment and Software appendices to understand the operation of the Geiger counter before trying to operate it. Place a radioactive source near the detector, turn on the counter. Try the controls, and make sure every group member understands how to operate it. Try each of your sources to make sure the equipment is functioning

.

With the detector working you now need to determine how to make your measurement uncertainty as small a practical. Start by using the detector to measure the number of counts from a radioactive source in some short time interval, say 10 or 15 seconds. Repeat this measurement several times, recording the number of counts occurring in each fixed time interval. Compute the average number of counts per second and the difference of each trial from that average. Calculate the average of these differences for all of your trials. That average difference represents your counting uncertainty for the measurement. Now increase your time interval by a factor of 4 and repeat the same number of trials and the same calculation. In which case is the measurement uncertainty a smaller fraction of the measurement? By approximately what factor did the average measurement change when you increased the counting time by a factor of 4? What does this tell you about the time period necessary when taking data? Keep measurement uncertainty in mind when deciding how much time is "enough" to allow comparisons among count rates under different conditions.

Since we live in a “sea” of radiation, you need to determine how that effects your measurements. Remove all radioactive sources from the vicinity of your detector. Record the count rate from the detector for a significant amount of time. You will need to subtract the count rate due to this background radiation from your future measurements. Measure the background rate, and estimate the uncertainty in your measurement.

For each source, try different shielding materials and thicknesses until you can reduce the counting rate by a significant fraction. Devise a plan to qualitatively determine whether the position of the shielding material (closer to the radiation source or closer to the detector) has an effect on the counting rate.

MEASUREMENT

Carry out your measurement plan, and adjust if necessary to obtain useful data for each source. Measure count rates for at least three different shield positions for each source.

ANALYSIS

Compare your results for different types of radiation and different types of shielding. Be careful with your logic since there are a lot of materials, radiation types, and distances. To be able to reach any conclusion make sure that only one quantity changes at a time.

Be sure to take the statistical uncertainty in your data into account. If you graph your data (regardless of whether you used a spreadsheet), don’t forget to add error bars!

CONCLUSION

Does your data support your prediction? Why or why not?

Does your data support the assertion that the position of a radiation shield has no effect on the count rate? If there is an effect, how does it depend on the type of incident radiation? Does your data allow you to make any firm statements about whether scattering or particle production occurs for each type of radiation?

PROBLEM #3: SHIELD THICKNESS

You are working for a company interested in irradiating turkeys for long-term storage. The management has asked your team for preliminary estimates of the minimum dose of the radiation necessary to kill enough of the microorganisms to retard spoilage. You quickly realize that the radiation dose to be determined is the minimum necessary at the center of the turkey. Of course, turkeys come in different sizes so your first task is to calculate how the radiation dose varies with depth inside the turkey. Your team decides to test your calculation in the lab by modeling the turkey with sheets of shielding material, as they are easier to handle than slabs of raw turkey meat. Since the company has not decided between using beta or gamma radiation for the process, you will have to test your idea on both types of radiation.

Read Sternheim & Kane chapter 30 sections 30.1-30.3 & 30.9.

EQUIPMENT

You have a Radiation Monitor (Geiger counter) connected to a LabPro Interface device and the LoggerPro software. You will also have a shielding kit and different radioactive sources: both a beta source, and a gamma source

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a diagram with a source of radiation, a detector, and several identical sheets of equal thickness material between them.
2. Imagine that you measure the amount of radiation incident on the first sheet of material and the fraction that passes through that sheet. The surviving radiation now passes through a second sheet of material. Based on your first set of measurements, write an expression for the amount of radiation that passes through the second sheet. Continue this procedure for a third sheet. You should be able to continue for any number of sheets.
3. Try some numbers. Suppose that the initial radiation was 1000 particles and only half of the incident particles pass through each sheet of material, calculate the number of particles that survive the first sheet. How many survive the second sheet? The third sheet? On what quantity(ies) does the number of particles surviving a sheet of material depend? Make a graph of the number of surviving particles versus the number of sheets of material. Since each sheet is a specific thickness of material, you now have a graph of how the surviving amount of radiation depends on the thickness of material. Try to guess what functions could

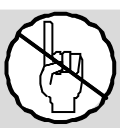
represent this graph. Check your guesses by graphing them to see if they match your points.

4. Imagine that all of the sheets of material are very thin and are pushed together to make one thick piece of material. As the particles pass through a thin sheet, the number entering the next sheet is reduced. On what quantity(ies) does this change in the number of particles depend? Write an equation for the change of the number of radiation particles per small amount of thickness (dN/dT). Solve this equation for the surviving number of particles as a function of material thickness. Check to see if this function matches your graph in question 3.
5. Compare the mathematics for your hypothetical description of the shielding of radioactive particles by material to that of radioactive decay described in your textbook. How are they similar? Different?

PREDICTION

Write down a mathematical function that describes the effect of material thickness on the intensity of radiation that passes through that material. Describe the reasoning that leads you to that function.

EXPLORATION



WARNING: The radioactive sources available for this problem provide low intensity radiation, and are safe if handled with respect for short amounts of time. Do not remove them from the laboratory, and do not attempt to open the plastic disks containing the sources. **If a disk breaks open inform your TA immediately, do not touch it.**

Make sure you read the Equipment and Software appendices to understand the operation of the Geiger counter before trying to operate it. Place a radioactive source near the detector, turn on the counter. Try the controls, and make sure every group member understands how to operate it. Try each of your sources to make sure the equipment is functioning
.

With the detector working you now need to determine how to make your measurement uncertainty as small a practical. Start by using the detector to measure the number of counts from a radioactive source in some short time interval, say 10 or 15 seconds. Repeat this measurement several times, recording the number of counts occurring in each fixed time interval. Compute the average number of counts per second and the difference of each trial from that average. Calculate the average of these differences for all of your trials. That average difference represents your counting uncertainty for the measurement. Now increase your time interval by a factor of 4 and repeat the same number of trials and the same calculation. In which case is the measurement uncertainty a smaller fraction of the measurement? By approximately what factor did the average measurement change when you increased the counting time by a factor of 4? What does this tell you about the time period necessary when taking data? Keep measurement uncertainty in mind when deciding how much time is "enough" to allow comparisons among count rates under different conditions.

Since we live in a “sea” of radiation, you need to determine how that effects your measurements. Remove all radioactive sources from the vicinity of your detector. Record the count rate from the detector for a significant amount of time. You will need to subtract the count rate due to this background radiation from your future measurements. Measure the background rate, and estimate the uncertainty in your measurement.

Try different types and thicknesses of material for the beta and gamma sources while noting the counting rates. Find a material that gives a noticeably different counting rate as you add more sheets? How many sheets will you need to get a good enough graph to check your prediction?

Some of the material, such a lead sheets, may not be able to support themselves when you stack them. If you use such material, be sure that the support system you devise will not significantly affect your measurement.

Decide as a group how long you will count for each increment of material thickness.

Come up with a measurement plan that will allow you to do this.

MEASUREMENT

Carry out your measurement plan, and adjust if necessary to obtain useful data. Don’t forget to include measurements that will help you determine your uncertainties.

ANALYSIS

Make a graph of the number of particles entering your detector (corrected for background count rate) vs. material thickness for each source. Match the data to your prediction for each type of radiation on a graph.

If it is difficult to tell whether or not a graph supports your predicted function, linearize the graph based on your prediction. Also try at least one other linearization of another function that might represent the data. See the section *Using Linear Relationships to Make Graphs Clear* in the appendix **A Review of Graphs** if you need help.

CONCLUSION

Describe the relationship between radiation survival and material thickness. Does this relationship hold for both types of radiation?

Does your data support your prediction? Why or why not?

PROBLEM #4: HALF LIFE

You work for a nuclear medicine company that uses radioactive isotopes to diagnose and treat cancers and other diseases. Because certain radioisotopes are attracted to specific organs, their emissions can provide information about a particular disease or cancer. Nuclear techniques can provide data about the function of organs, not just their structure. One consequence of nuclear medicine is a plethora of contaminated waste: syringes, glass, gloves, and vials of radioactive pharmaceuticals. Unlike defense-related waste, most refuse from nuclear medicine won't be radioactive for millennia. For example, one radioactive isotope of indium, ^{111}In, is used as a "tracer" to identify tumors and has a half-life of 2.8 days, much shorter than that of plutonium. In this exercise, you and your partners will look at the relationship between time and radioactivity on a short lived isotope. This relationship can be used to determine the half-life of a radioactive sample.

Read Sternheim & Kane chapter 30 sections 30.1-30.3 & 30.9.

EQUIPMENT

You have a Radiation Monitor (Geiger counter) connected to a LabPro Interface device and the LoggerPro software. You will also have a Cs/Ba-137m isotope generator kit.

If you need assistance, send an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

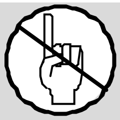
WARM UP

1. Write an expression that represents the number of counts for a source with an unknown decay constant and a specified number of radioactive nuclei to start with.
2. Set the number of counts equal to half the original amount. Can you solve for the decay constant? Can you think of a way to determine the decay constant from the actual counts of a sample?
3. Solve your decay equation for the time when the number of counts is half the original amount. This is referred to as the "half-life" of the radioactive material.
4. How is the half-life of a material related to its decay constant? If a material has a very long half-life, is the decay constant large or small?

PREDICTION

Write down a mathematical function that describes the half-life of a radioactive sample.

EXPLORATION



WARNING: The radioactive sources available for this problem provide low intensity radiation, and are safe if handled for short amounts of time. Do not remove them from the laboratory, and handle with care.

Make sure you read the Equipment and Software appendices to understand the operation of the Geiger counter before trying to operate it. Place a radioactive source near the detector, turn on the counter. Try the controls, and make sure every group member understands how to operate it. Try each of your sources to make sure the equipment is functioning
.

With the detector working you now need to determine how to make your measurement uncertainty as small a practical. Start by using the detector to measure the number of counts from a radioactive source in some short time interval, say 10 or 15 seconds. Repeat this measurement several times, recording the number of counts occurring in each fixed time interval. Compute the average number of counts per second and the difference of each trial from that average. Calculate the average of these differences for all of your trials. That average difference represents your counting uncertainty for the measurement. Now increase your time interval by a factor of 4 and repeat the same number of trials and the same calculation. In which case is the measurement uncertainty a smaller fraction of the measurement? By approximately what factor did the average measurement change when you increased the counting time by a factor of 4? What does this tell you about the time period necessary when taking data? Keep measurement uncertainty in mind when deciding how much time is "enough" to allow comparisons among count rates under different conditions.

Since we live in a “sea” of radiation, you need to determine how that effects your measurements. Remove all radioactive sources from the vicinity of your detector. Record the count rate from the detector for a significant amount of time. You will need to subtract the count rate due to this background radiation from your future measurements. Measure the background rate, and estimate the uncertainty in your measurement.

How will you know when you have enough data?

MEASUREMENT

Place the sample as close to the screen of the radiation monitor as possible. Do not move the sample until you have completed taking data. It should take about 5 minutes to take the needed data.

When you and your partners are done taking measurements, you must ascertain how many radioactive events occurred in each one-minute interval.

ANALYSIS

Plot your results on a graph of counts vs. time. You should discover that, as you took your measurements, the radioactivity of the sample decreased. Also make a graph of (*ln* counts) vs. time. From your prediction equation, what does the slope of this line represent? Record this value. Is the value of this slope positive or negative?

Use your prediction equation to calculate the half-life of the radioactive sample.

CONCLUSION

Report the value for the half-life you measured. How certain are you of the result? What is the uncertainty in your measurements and analysis? How does the half-life of this compare to other radioactive wastes?

Physics Lab Report Rubric

Name: ______________________________ ID#: __________
Course, Lab, Problem: ______________________________
Date Performed: ______________________________
Lab Partners' Names: ______________________________
____
____

	Possible	Earned
Warm-Up Questions		
Laboratory Notebook		
Participation		

Earns No Points	Earns Full Points	Possible	Earned
Argument			
• no or unclear argument • logic does not flow • gaps in content • leaves reader with questions	• complete, cogent, flowing argument • content, execution, analysis, conclusion all present • leaves reader satisfied		
Technical Style			
• vocabulary, syntax, etc. inappropriate for scientific writing • necessary nonverbal media absent or poorly constructed • subjective, fanciful, or appealing to emotions • jarringly inconsistent • no or confusing sections	• language appropriate for scientific writing • nonverbal media present where appropriate, well-constructed, well incorporated • objective, indicative, logical style • consistent • division into sections is helpful		
Use of Physics			
• predictions unjustified • experiment physically unjustified • experiment tests wrong phenomenon • theory absent from consideration of premise, predictions, and results	• predictions justified with physical theory • experiment is physically sound and tests phenomenon in question • results interpreted with theory to clear, appropriate conclusion		
Quantitativeness			
• statements are vague or arbitrary • analysis is inappropriately qualitative • uncertainty analysis not used to evaluate prediction or find result • numbers, equations, units, uncertainties missing or inappropriate	• consistently quantitative • equations, numbers with units, uncertainties throughout • prediction confirmed or denied, result found by some form of uncertainty analysis • results, conclusions based on data		
Total			

PHYSICS LAB REPORT RUBRIC

ELECTROSTATIC PAPER AND ACCESSORIES:

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

- Lay the electrostatic paper flat. .
- Distribute the pieces of metal (called "electrodes") on the paper, in the configuration whose field you wish to examine. The tips of the long brass rods may also be used as electrodes, to create point-like charges.
- Connect the electrodes to a source of charge. This is done by connecting a wire from the positive ("+") side of the battery or power supply to one electrode and the wire from the negative ("–") side to the other as shown in Figure 1.
- You may wish to place a wooden block on top of the brass rods to increase contact pressure with the paper. This can increase the magnitude of the electric field created on the paper. It also helps to place an extra sheet of paper under the electrostatic paper.

Figure 1: Electrostatic paper Setup

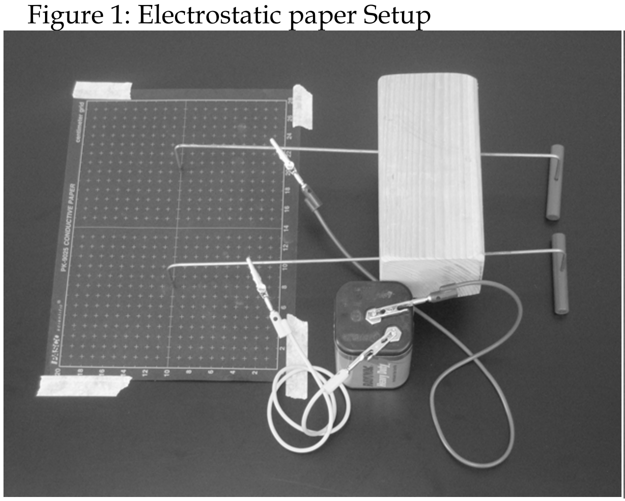
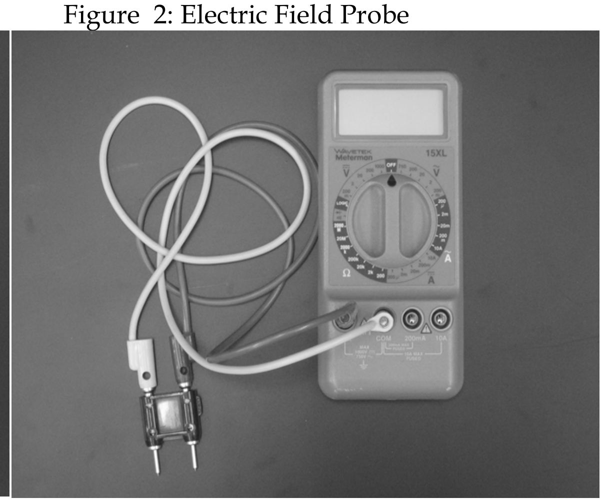


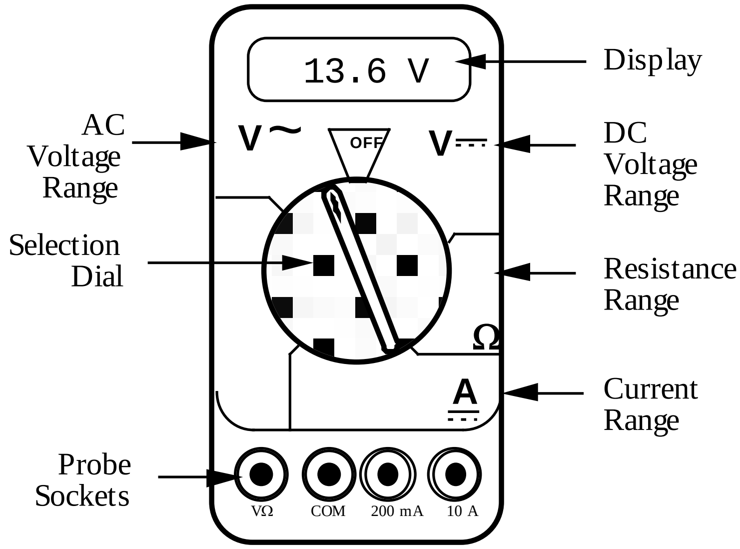
Figure 2: Electric Field Probe



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

THE DIGITAL MULTIMETER (DMM)

The DMM is a common piece of lab equipment that can be used to measure various electrical quantities, most often current, resistance, and potential. The DMM's you will be using are capable of measuring both "direct current" (DC) and "alternating current" (AC) circuits. Be careful about knowing which type of measurement you need to make, then set your DMM accordingly. Some DMM's might be slightly different from the one pictured to the right.

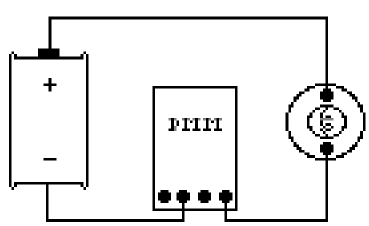


> The DMM can measure currents anywhere from 10 amps to a microamp (10^{-6} amps). This versatility makes the DMM fragile, since measuring a large current while the DMM is prepared to measure a small one will certainly harm the DMM. For example, measuring a 1 ampere current while the DMM is on the 2 milliamp scale will definitely blow a fuse! If this happens, your instructor can change the fuse. However, if you damage the DMM beyond repair, you will have to finish the lab without the DMM.

Measuring Current:

1. Set the selection dial of the DMM to the **highest** current measurement setting (10 amps). Insert one wire into the socket labeled '10A' and a second wire into the socket labeled 'COM'.

2. Attach the DMM into the circuit as shown below:



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

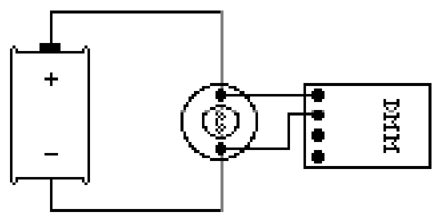
3. If no number appears while the DMM is at the 10A setting, move the wire from the 10A socket to the 200mA socket and then turn the selection dial to the 200 milliamp (200m) setting. If there is still no reading, change the dial to the 20 milliamp setting, etc.

4. When you have taken your measurement, return the DMM selection dial to the highest current setting (10 amps) and move the wire back to the 10A socket.

Measuring Voltage:

1. Set the DMM selection dial to read DC volts (V⎓). Insert one wire into the socket labeled 'V?' and a second wire into the socket labeled 'COM'.

2. Set the selection dial of the DMM to the **highest** voltage measurement setting. Connect the two wires from the DMM to the two points between which you want to measure the voltage, as shown below.



   To measure voltage, the DMM must be placed in the circuit so that the potential difference across the circuit element you want to measure is **across** the DMM.

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

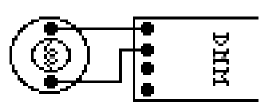
Measuring Resistance:

The element whose resistance you are measuring ***must*** *be free from all other currents (due to other batteries, power supplies, etc.) for the DMM to work*. That means you must **remove** it from a circuit.

To measure resistance:

1. Set the DMM selection dial to measure ohms (Ω). Insert one wire into the socket labeled 'VΩ' and a second wire into the socket labeled 'COM'.

2. *Make sure that the circuit element whose resistance you wish to measure is free of any currents*.
3. Attach the wires across the circuit element, as shown in the example below.



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

A Brief Introduction to RMS Measurements:

A problem arises when one wishes to measure an alternating current or potential. All measuring instruments sample a signal over some period of time. A device that samples over a time longer than one period of the signal (such as the DMM) essentially measures the average signal. For sine or cosine functions, the average is zero, which doesn't tell you much about the signal strength.

The solution to this difficulty is to use root-mean-square (RMS) averaging. To eliminate the cancellation of the positive and negative parts of the sine function, it is squared, then the average is taken[1], and the square root of this average yields the RMS value.

For example, to find the RMS value of an AC current that has a maximum value of I_O:

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

$$\langle I^2 \rangle = \frac{1}{2\pi} \int_0^{2\pi} I_0^2 \sin^2(\omega t)\, d(\omega t)$$
$$= \frac{I_0^2}{2\pi} \int_0^{2\pi} \sin^2(\omega t)\, d(\omega t) = \frac{1}{2} I_0^2$$

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

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

1 When a quantity that varies with time is averaged, as in this case, the average value is often designated by putting angle brackets around the quantity. For example, the time average of a sinusoidally varying current is:

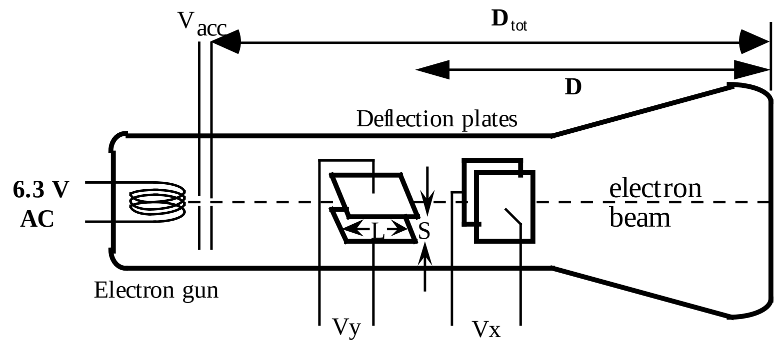
$$\langle I \rangle = \frac{I_0}{2\pi} \int_0^{2\pi} \sin(t)\, dt = 0$$

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 cm
L = 2.0 cm
S = 0.30 cm
D_{tot} = 9.6 cm



<u>How the CRT works:</u>
Within the electron gun:

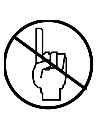
- A thin filament (represented above as a coil of wire), similar to a light-bulb filament, is heated by a current. When the CRT is operating, this filament can be seen as an orange, glowing wire. This hot filament ejects slow-moving electrons.
- Some slow electrons drift toward the high-voltage "acceleration plates." These plates are labeled as Vacc in Figure 3. The electric field between the charged plates accelerates the electrons to high velocities in the direction of the fluorescent screen. The final velocity of an accelerated electron is much greater than its initial "drift" velocity, so the initial electron velocity can be ignored in calculations.

After the electron gun:

- Before hitting the screen, the high-velocity electrons may be deflected by charged plates along the length of the CRT. These charged plates are usually called the "x-deflection" and "y-deflection" plates.
- When the electrons reach the end of the tube, their energy causes the material that coats the end of the tube to glow. This material is similar to the material inside fluorescent light bulbs. The end of the CRT is called the fluorescent screen.

To supply the necessary electric potentials to the CRT you will use a power supply. The power supply provided has the proper potential differences to heat the CRT filament and to accelerate the electrons. The power supplies we use also have built-in circuit breakers. Should you attempt to draw too much current from your power supply, it will shut itself off with an audible "click." If this happens, check to make sure all of your wires are connected properly, then press in the small white button on the side of the power supply.

Note that the CRT and power supply come as a set, and many of the connections are color-coordinated to avoid potentially damaging misconnections. You will also have an assortment of batteries, which will be used to control the electric field between the CRT x- and y-deflection plates.



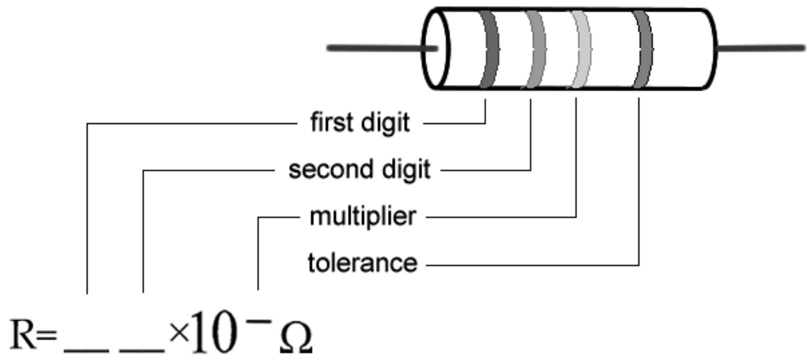
WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply.

To properly connect the CRT to the power supply:

1. Turn the power supply off.
2. Connect the power supply ports marked "AC 6.3V" (they are green; the voltage differs slightly from one supply to another, but should be clearly marked) to the ports marked "HEATER" or "FILAMENT" on the CRT (these are also green).
3. Connect the appropriate accelerating potential across the cathode and anode. For instance, if your experiment calls for a 500 volt accelerating potential, connect the cathode to the port marked "–250 V" (which may be black or white) and the anode to the port marked "+ 250 V" (which is red). This gives a total potential difference of 500 volts.
4. Turn the power supply on.

RESISTOR CODES

A resistor is a circuit element manufactured to have a constant resistance. The resistance is coded onto the side of the resistor in colored bands, where the color and position of the bands tell you what the resistance is.



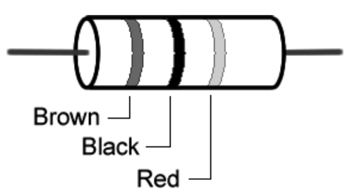
To read the color bands on the resistor, begin by finding the gold or silver band on one end of the resistor; this is the back of the resistor. You begin reading from the other end. Most resistors (including those you will use in lab) are coded to two significant digits. The first two color bands correspond to these two significant digits.

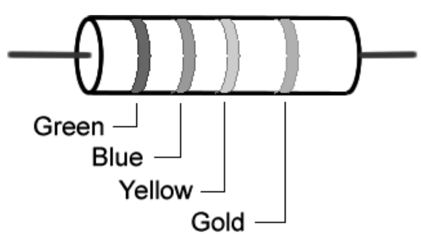
The third color band is called the multiplier. The number coded by this band represents a power of ten which you multiply by the number from the first two bands to get the total resistance.

The fourth color band tells you the tolerance, or error bounds for the coded resistance: gold means ±5% tolerance, silver means ±10% tolerance and no fourth band means ±20%.

Some resistors have a fifth color band, which represents the reliability of the resistor, and can just be ignored for the purposes of these labs.

Examples:





$R = 10 \times 10^2 \Omega \pm 20\%$

$R = 56 \times 10^4 \Omega \pm 5\%$

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

POWER SUPPLIES

The 18volt 5 amp power supply is an all-purpose power supply for the production of constant currents and voltages.

At the top is the main display that reads either current in Amperes or voltage in Volts. There is a switch there that allows you to switch between them.

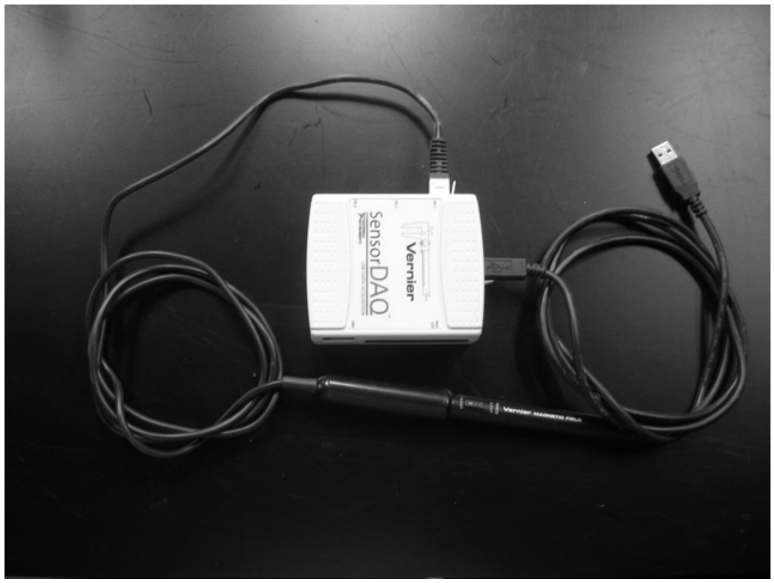
The current and voltage controls are located in the middle. In between the constant current and constant voltage knobs is a switch that allows you to toggle from high currents to low currents. **It is highly recommended that you use only the low current mode.**

This power supply normally operates in the constant voltage mode. As such, you can only change the voltages by using the constant voltage knobs. **In the event that too much is being pulled from the power supply (as in a short), it will automatically switch to the constant current mode, where the amount of current flowing is greatly reduced.** This is a signal that something is amiss with your circuit.

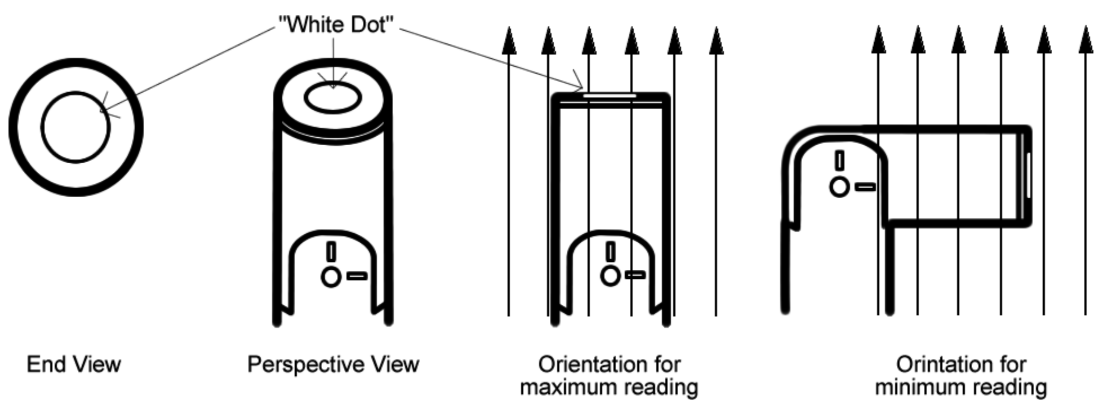
There is a *mater-slave* switch on the back of the power supply. This should always be set to master for the DMM to function properly. If you experience any problems, this is the first place to check.

THE MAGNETIC FIELD SENSOR (HALL PROBE)

To measure magnetic field strength, you will need a measurement probe (the magnetic field sensor) that connects to a computer through the Vernier sensor*DAQ* lab interface..

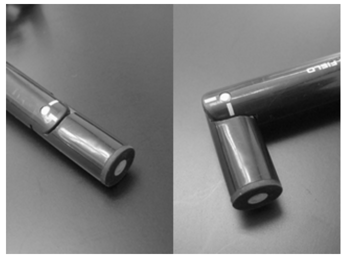


The tip of the measurement probe is embedded with a Hall Effect transducer chip (shown above as the white dot on the end of the probe). The chip produces a voltage that is linear with the magnetic field. The maximum output of the chip occurs when the plane of the white dot on the sensor is perpendicular to the direction of the magnetic field, as shown below:



The sensor*DAQ* allows the computer to communicate with the probe. In order to measure magnetic fields, the wire leading out of the probe must be plugged into the port labeled "CH 1".

The Range switch on the side of the probe is to allow you to measure a greater range of magnetic field strengths. Each setting represents the maximum field strength that the probe can measure: either ±6.4mT or ±0.3mT. When measuring stronger magnetic fields, you should use the 6.4mT setting, but for fields weaker than 0.3mT the lower setting will give you a more accurate reading.



The measurement probes have swiveling tips to allow for more convenient data collection. Note: **that these tips are only meant to swivel in one direction. They will break of they are bent in the other direction, and they are very fragile, so it does not take much to do this.** Please be very careful as these are costly to replace.

RE-MAGNETIZING A BAR MAGNET

The magnetizer should be used if you have a bad bar magnet that isn't a simple dipole, polarity doesn't match the labels, or the magnet is too weak.

Important to know is that the magnetizer is poorly labeled. The N and S do not indicate the end of the magnet that goes into the magnetizer! We believe the company is trying to imply that magnets inserted into the side labeled N will be north attracting and vice versa. You need to insert the S pole of the bar magnet into the side labeled N and the N pole of the bar magnet into the side labeled S.

MEASURING RADIATION
(Geiger Counter)

To measure radiation you will need a ***Geiger Counter***. The tube detects incoming radiation (alpha, beta, or gamma decay) and produces a voltage spike which the counter unit records. To use the Geiger Counter in conjunction with the computer plug the connecting cord into the round hole on the right side of the counter, and plug the other end of the connecting cord into the LabPro Interface port labeled "DIG/SONIC 1". The computer uses the software LoggerPro in conjunction with the Geiger Counter to measure radiation. For a description of the LoggerPro software see *Appendix E*.

To begin measuring radiation amounts the power switch on the Geiger Counter must be moved to the "ON" position, or the "AUDIO" position. The Geiger Counter's red light will flash whenever it makes a radiation count. When in the "AUDIO" position the counter will also make a beep noise whenever it makes a radiation count.

There is a switch on the Geiger Counter that controls its detection sensitivity. The switch has positions labeled 1X, 10X, etc. For the lab problems in this manual the 1X position will most likely be the best setting.

Counts recorded by the detector are the result of radioactive decay, which is a randomly occurring event. Events that are the result of random processes have inherent uncertainty. This means that if the count rate for a certain sample is recorded several times, the number of counts recorded will fluctuate around an average. In a set of N counts, if N is small the uncertainty in N will follow Poisson Statistics. If N is large the uncertainty will follow Gaussian Statistics. (These terms are explained in any math reference book, for example see http://mathworld.wri.com). Keep uncertainty in mind when deciding how many counts are "enough" to allow comparisons among count rates under different conditions.

MAGNETLAB - MEASURING CONSTANT MAGNETIC FIELD

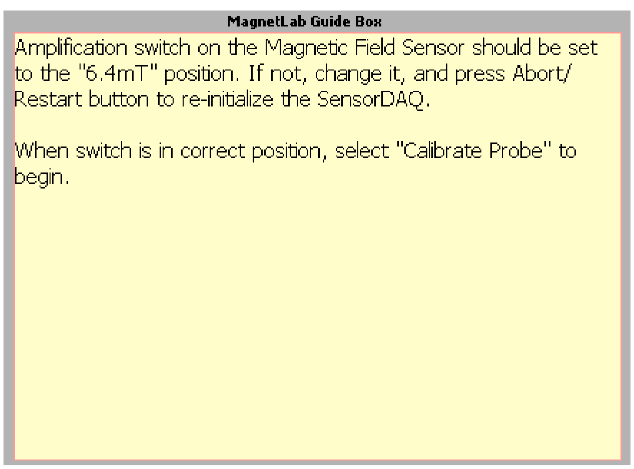
Application Basics

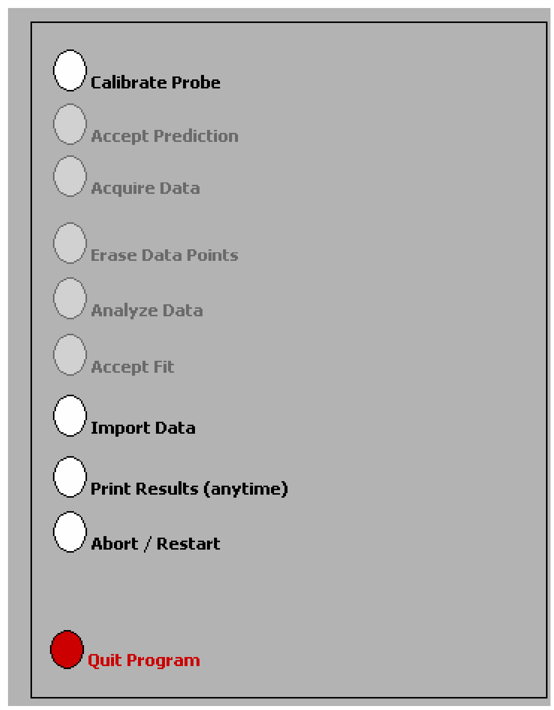
Before you begin, you should ensure that you have read the relevant sections of Appendix A to familiarize yourself with the equipment.

The software package that works in tandem with your magnetic field sensor is written in LabVIEW™. It allows you to measure and record magnetic field strength as a function of a number of different variables.

After logging into the computer, execute the application by double clicking the "MAGNETLAB" icon located in the PhysLab folder on the desktop.

Before you start using the program, you should take a moment to identify several key elements. The two most important of these are the Command Panel, shown to the right, and the Guide Box, shown below.





The Guide Box will give you directions and tasks to perform. It will also tell you when to select a command in the Command Panel. After selecting a command, it will "gray out" and the next command will become available.

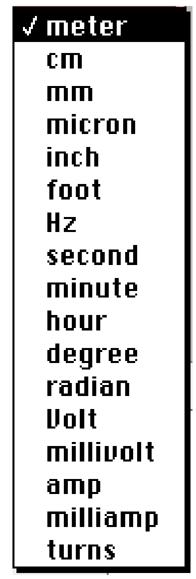
You can also print and/or quit from the Command Panel or abort your analysis and try again.

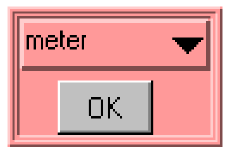
The primary data output you get is by generating pdf files of your results, so be careful not to quit without printing pdf files or exporting your data to be emailed amongst your lab group.

Calibration

The first command is to calibrate the Magnetic Field Sensor. Before selecting this command, you need to set the probe to the 6.4mT setting.

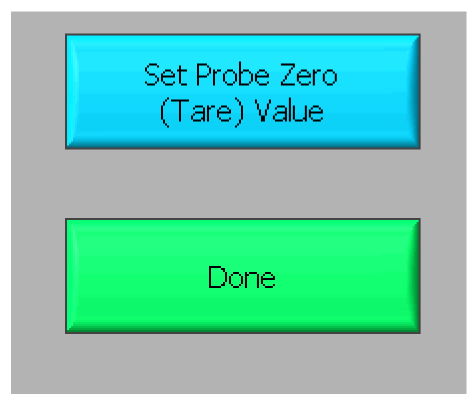
After selecting the "Calibrate Probe" command, you will be asked to do *two* tasks. First, you will need to choose the quantity on the x-axis of your data graph. This is accomplished by moving the cursor over to the word "meter" in the red-colored area (shown below) and then pressing the mouse button.





You should get a list of choices as shown to the right. By selecting any of these units, you will be making a choice about what you wish to measure. For example, if you choose to use "cm", you will make a graph of magnetic field strength as a function of distance (B vs. x). It is likely you will want to choose a small unit (cm's or mm's) to measure the distance in, since many magnetic fields are not very strong over long distances Selecting "degree" will make a plot of magnetic field strength as a function of angle (B vs. θ). Click "OK" when you are ready to proceed.

Second, you will need to eliminate the effect of the background magnetic fields. This process is called "zeroing the Hall probe" in the Guide Box. **Place the magnetic field sensor wand in the position you would like to take your measurement, but be sure that there are no magnets nearby.** Note that power supplies and computers generate magnetic fields, so it is a good idea to keep away from them! When you are ready, select the "Set Probe Zero" as shown below. Then select the "Done" button. The calibration process is now complete.



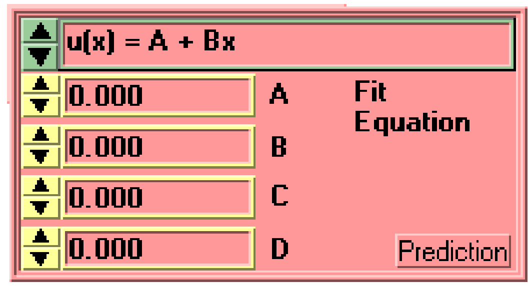
Predictions

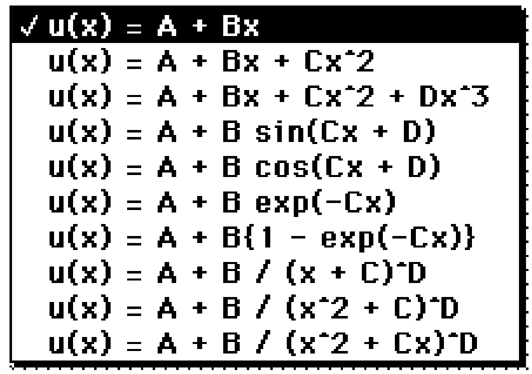
This type of analysis relies on your graphical skills to interpret the data. You should be familiar with both appendices, **A Review of Graphs** and Accuracy, **Precision and Uncertainty**.

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 prediction, you first need to decide on your coordinate axes and scale (units) for your measurements. *Record these in your lab journal.*

Next, you will need to select the generic equation, u(x), which describes the graph you expect for the data. Clicking the equation currently showing in the box will bring up a list of equations to choose from; see the diagrams to the right.





After selecting your generic equation, you 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.

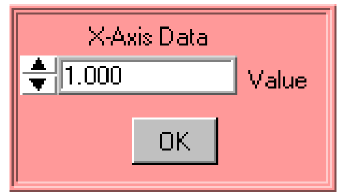
Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes or use the *AutoScale* feature (see Finding Data below). When you are satisfied, select the *Accept Prediction* option from the Command Panel. Once you have done this you cannot change your prediction except by starting over.

Exploration

After you have entered your prediction, you can explore the limitations of your magnetic field sensor before you take data. The value of the magnetic field strength is displayed directly under the Guide Box. When you are ready to take data, select *Acquire Data* from the Command Panel.

Data Acquisition

Collecting data requires that you enter the x-axis data before the computer reads in a value for the magnetic field strength. You enter this data using the panel shown. For every x-axis data value you enter, the analysis program will record the magnetic field strength in gauss on the y-axis of the "Plot". Press "OK" to collect the next data point.



Each data point should appear on the graph on the computer screen as you take it. If it doesn't, adjust the scales of your graph axes or use the *AutoScale* feature (see Finding Data below). If you are satisfied with your data, choose *Analyze Data* from the Command Panel.

Finding Data on the Graph

You can find your data on the graph by adjusting the scales of your X-axis and Y-axis plots manually. This scaling is accomplished by entering values into the legend of the graph. Click on the upper or lower legend value and enter a new value, then hit enter. If you cannot locate your data, you can select both "AutoScale Y-axis" and "AutoScale X-Axis" to let the program find the data for you. You can then adjust your axis scales to give you a convenient graph for analysis. Be careful, the AutoScale option will often set the scales in such a way that small fluctuations in the data are magnified into huge fluctuations.

Data Fits

Deciding which equation best fits your data is the most important part of using this analysis program. While the actual mechanics of choosing the equation and parameter 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.

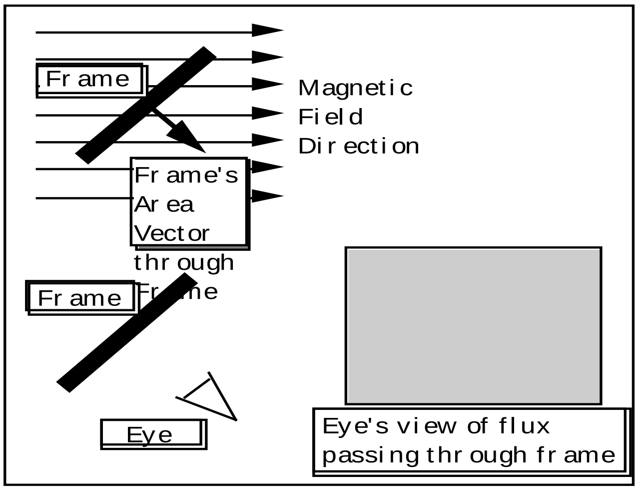
To save your data, simply select *Export Data* and follow the instructions in the windows. Your file should be saved in the **LabData** folder. To retrieve this file, restart *MagnetLab* from the desktop and select *Import Data.*

Last Words

These directions are not meant to be exhaustive. You will discover more features as you analyze more data. Be sure to record these features in your lab journal.

FLUX SIMULATOR

A computer movie called 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.

Slider

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

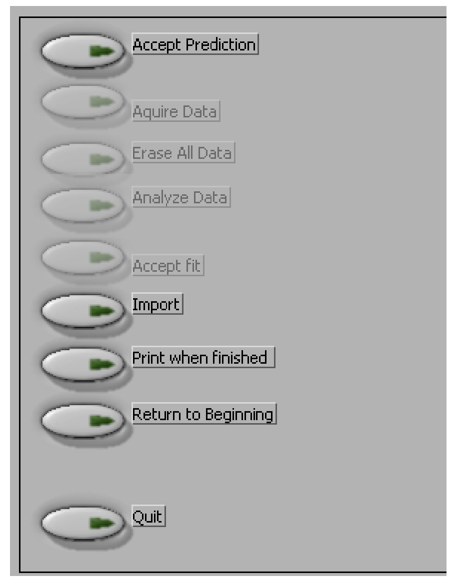
VoltageTimeLAB - MEASURING TIME-VARYING VOLTAGES

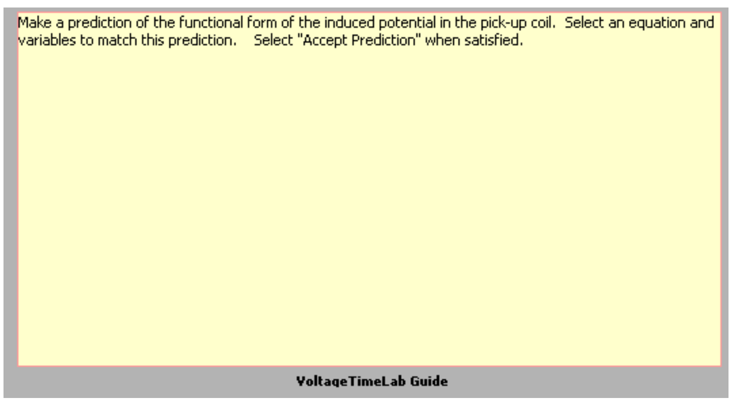
The Basics:

This software package, written in LabVIEW™, allows you to measure and record potential differences as a function of time. The software and voltage interface act much like an oscilloscope.

After logging into the computer, execute the application by double clicking the "VoltageTimeLab" icon located in the PhysLab folder on the desktop.

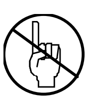
Before you start using the program, you should take a moment to identify several key elements. The two most important of these are the Command Panel, shown to the right, and the Guide Box, shown below.





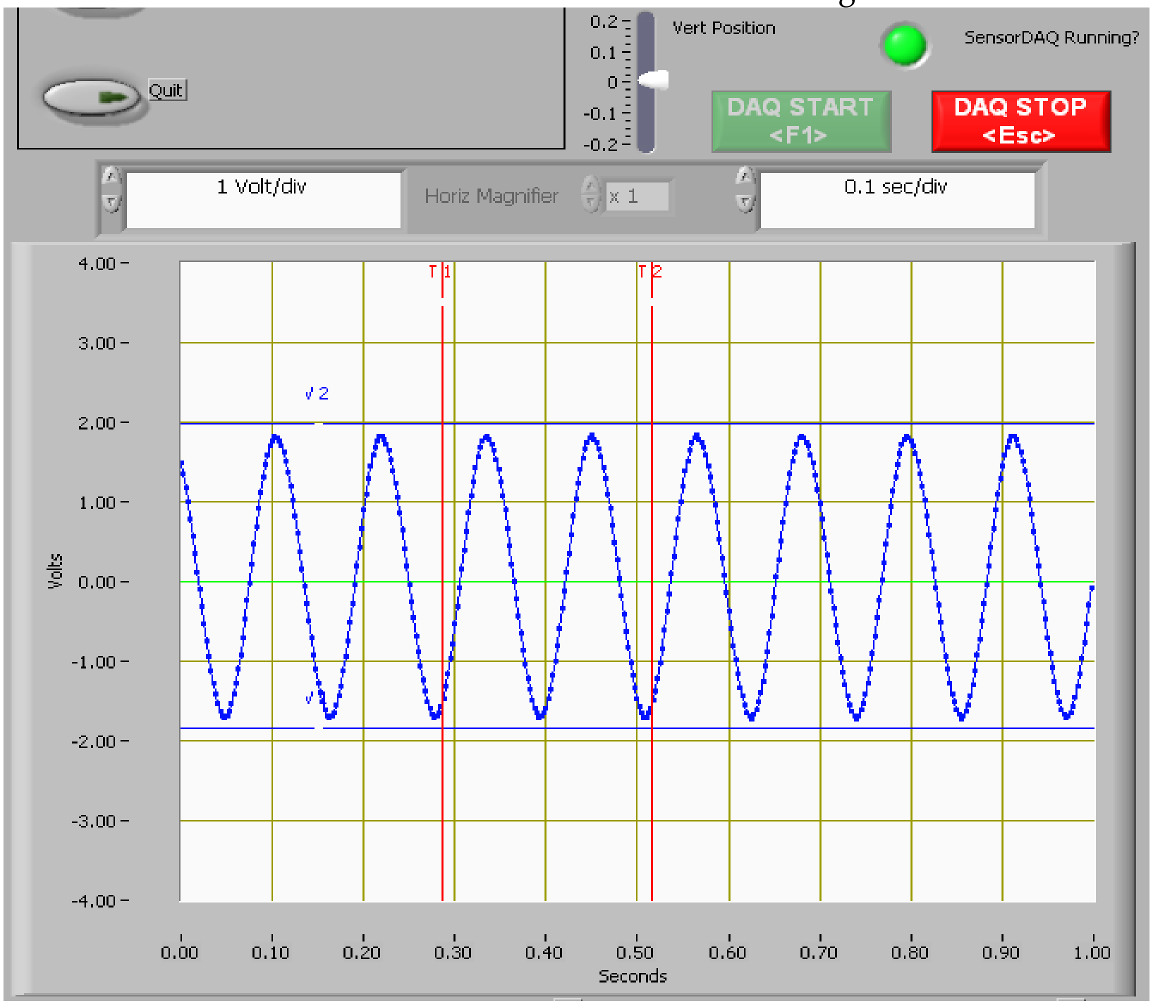
The Guide Box will give you directions and tasks to perform. It will also tell you when to select a command in the Command Panel.

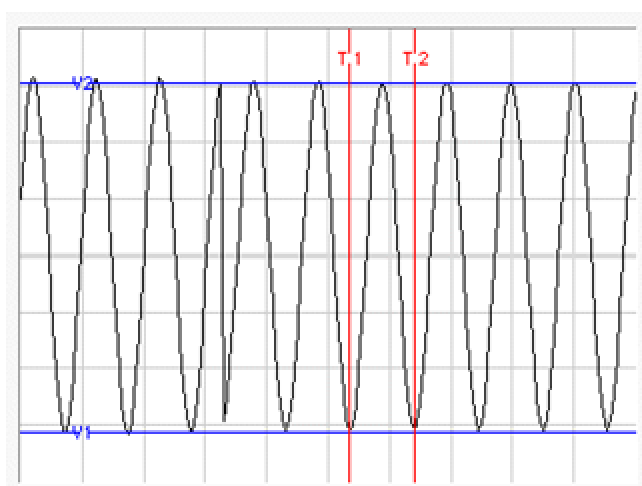
You can also print and/or quit from the Command Panel or abort your analysis and try again.



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

Since the application to measure time-varying voltage is a slight modification of the application to measure magnetic field, you are already familiar with how to use much of it. The basic difference between the TimeVoltageLab and the MagnetLab applications is an additional display that is much like an oscilloscope. The potential difference versus time display is shown on the next page. The DAQ (Data Acquisition) control buttons are located directly above this display. The "DAQ START" and "DAQ STOP" buttons do as they suggest, stop and start data streaming from the probe to the voltage versus time display. When you first start the application you will need to click the "DAQ START" button to start streaming the probe readings. You will use the "DAQ STOP" to freeze the data screen for taking measurements. A green indicator is used to indicate whether the interface is running or not.





The vertical axis is a measure of the potential difference (voltage) between the two leads of the voltage probe. The horizontal axis measures time. You should also notice that the display has a grid on it. The scale of each axis is shown at the bottom of the display. As you might suspect, it is possible to change the grid size of each axis. To change the scale of the axis, simply click on the highest or lowest number on that axis and type in a new value. The axis will automatically adjust to create even increments over the newly defined range.

The red and blue lines that are on the display are movable simply by putting your mouse pointer over one of the lines. When the mouse pointer changes shape, hold the mouse button down and drag the lines to mark a voltage or time as shown. The lines mark the voltage and time boundaries of the data that will be considered for analysis.

If you are unable to see the lines, it is possible that you changed the axes scale and "zoomed in" too far. Try changing the axes to "zoom out" again, and determine if you can locate the blue and red lines. Move the lines to within the values of the new scale, and they should remain visible on the screen when you zoom in.

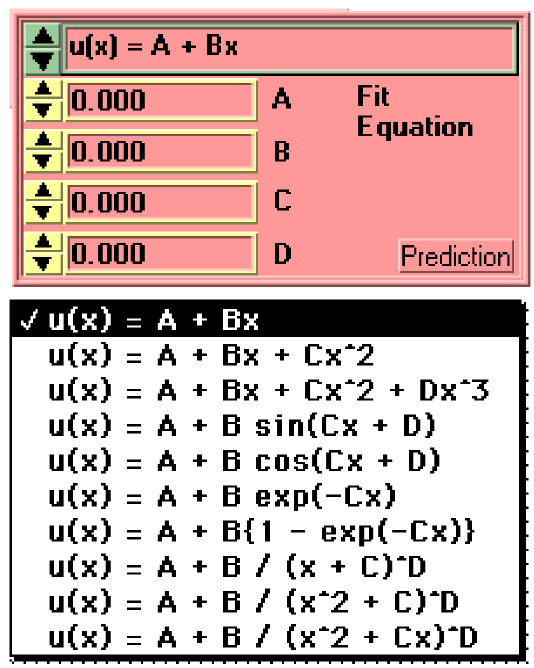
Predictions

This type of analysis relies on your graphical skills to interpret the data. You should be familiar with both appendices, **A Review of Graphs** and Accuracy, **Precision and Uncertainty**.

The first task is to enter your prediction of the mathematical function you expect to represent your data. Making a prediction before taking data is the best way to determine if anything is going wrong (remember Murphy's Law). It's also a good way to make sure you have learned something, but only if you stop to think about the discrepancies or similarities between your prediction and the results.

You will need to select the generic equation, u(x), which describes the graph you expect for the data. Clicking the equation currently showing in the box will bring up a list of equations to choose from; see the diagrams to the right.

After selecting your generic equation, you next need to enter your best approximation for the parameters A, B, C, and/or D. These values should come directly from your prediction equation you did for class. As you enter these values, you should see the red line in the "Plot" box changing.



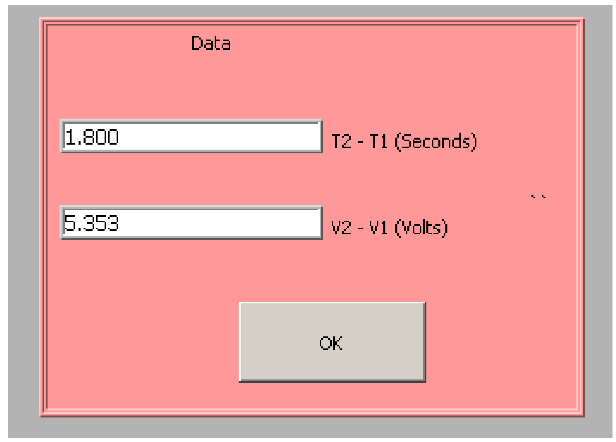
Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes (see Finding Data below). When you are satisfied, select the *Accept Prediction* option from the Command Panel. Once you have done this you cannot change your prediction except by starting over.

Exploration

After you have entered your prediction, you can explore the limitations of your voltage probe sensor before you take data. The value of the voltage is displayed directly on the voltage vs. time display. When you are ready to take data, select *Acquire Data* from the Command Panel.

Data Acquisition

Collecting data requires that you position the moveable red and blue lines on the voltage vs. time display. The blue lines will generate potential difference data and the red lines will generate time/period data. The data values are shown in the data box. The data box appears once you have selected *"Acquire Data"* from the Command Panel. Press "*OK*" to collect each data point. Each data point should appear on the graph on the computer screen as you take it. If it doesn't, adjust the scales of your graph axes. If you are satisfied with your data, choose *Analyze Data* from the Command Panel.



Finding Data on the Graph

You can find your data on the graph by adjusting the scales of your X-axis and Y-axis plots manually. This scaling is accomplished by entering values into the legend of the graph. Click on the upper or lower legend value and enter a new value, then hit enter. If you cannot locate your data, you can select both "AutoScale Y-axis" and "AutoScale X-Axis" to let the program find the data for you. You can then adjust your axis scales to give you a convenient graph for analysis. Be careful, the AutoScale option will often set the scales in such a way that small fluctuations in the data are magnified into huge fluctuations.

Data Fits

Deciding which equation best fits your data is the most important part of using this analysis program. While the actual mechanics of choosing the equation and parameters are similar to what you did for your predictions, fitting data is somewhat more complicated.

By looking at the behavior of the data on the graph, determine the best possible function to describe this data. After you have decided on the appropriate equation, you need to determine the constants of this equation so that it best fits the data. Although this can be done by trial and error, it is much more efficient to think of how the behavior of the equation you have chosen depends on each parameter. Calculus can be a great help here. *This can be a time-consuming task, so be patient.*

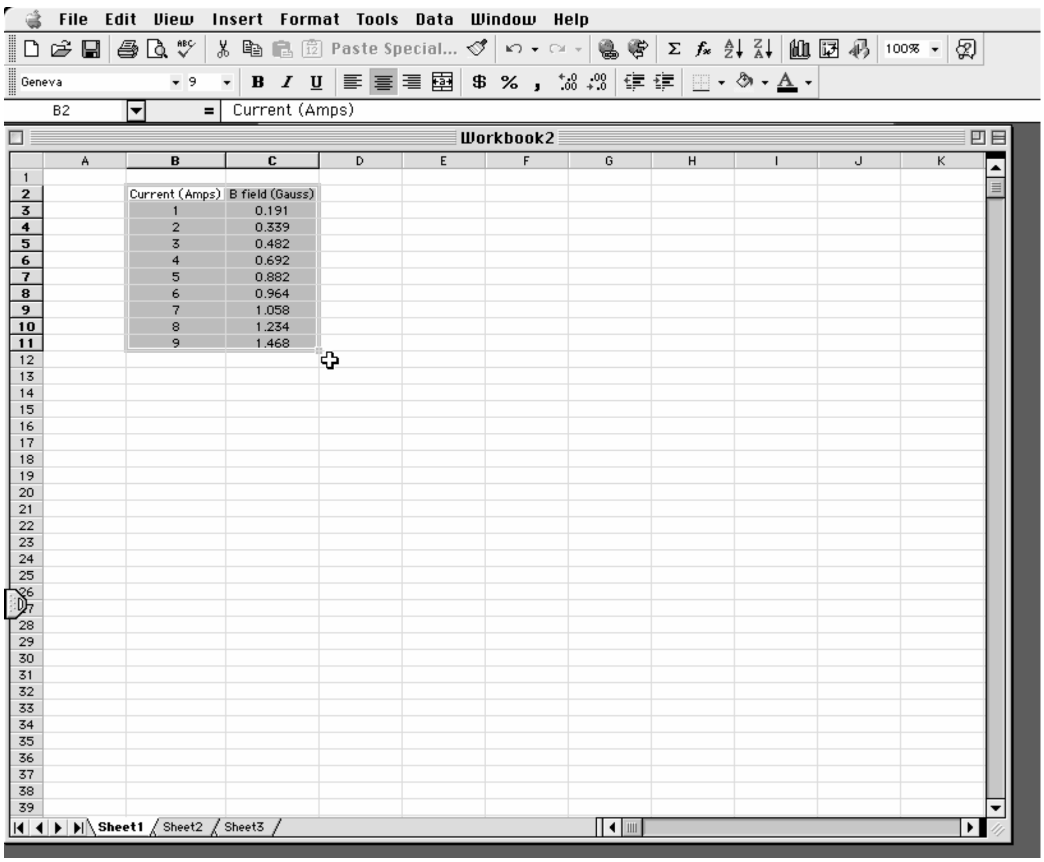
Now you need to estimate the uncertainty in your fit by deciding the range of other lines that *could* also fit your data. This method of estimating your uncertainty is described in the appendix Accuracy, Precision and Uncertainty. Slightly changing the values for each constant in turn will allow you 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.

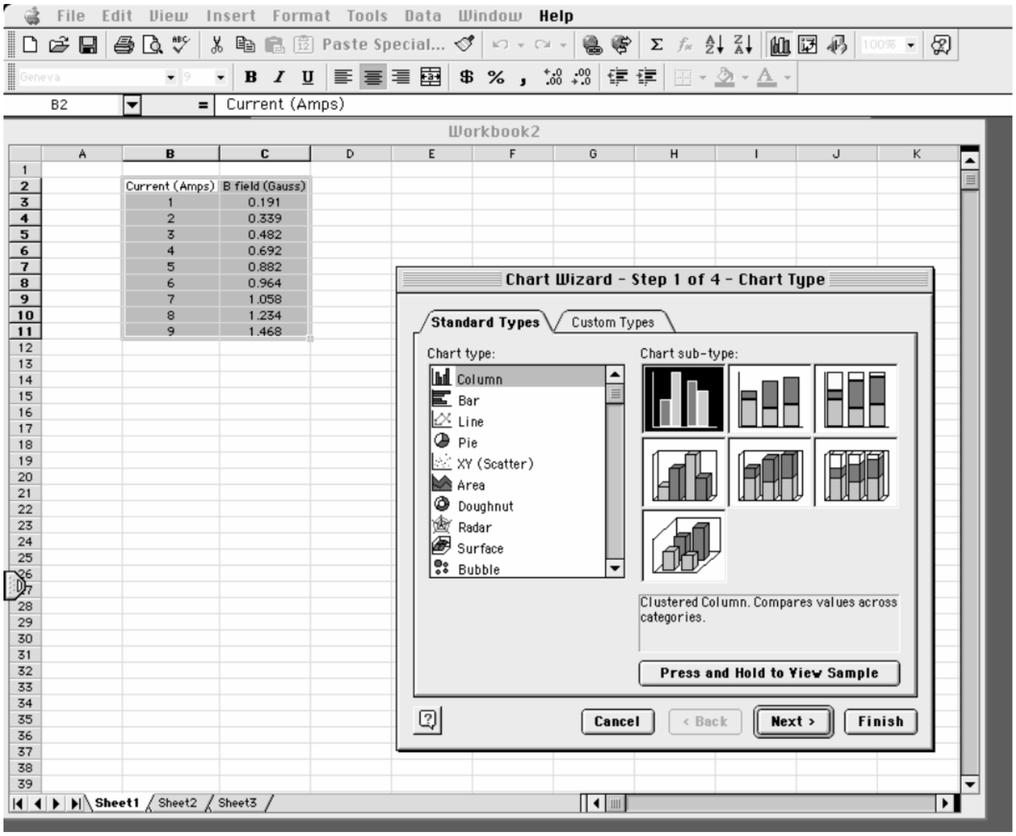
Excel - MAKING GRAPHS

You will find that numerous exercises in this manual will require graphs. Microsoft Excel is a spreadsheet program that can create fourteen types of graphs, each of which have from two to ten different formats. This results in a maze of possibilities. There are help screens in Excel; however, this overview is covers the type of graph you should include in your lab reports. This is meant to be a brief introduction to the use of Microsoft Excel for graphing scientific data. If you are acquainted with Excel already, you should still skim through this appendix to learn about the type of graph to include in reports.

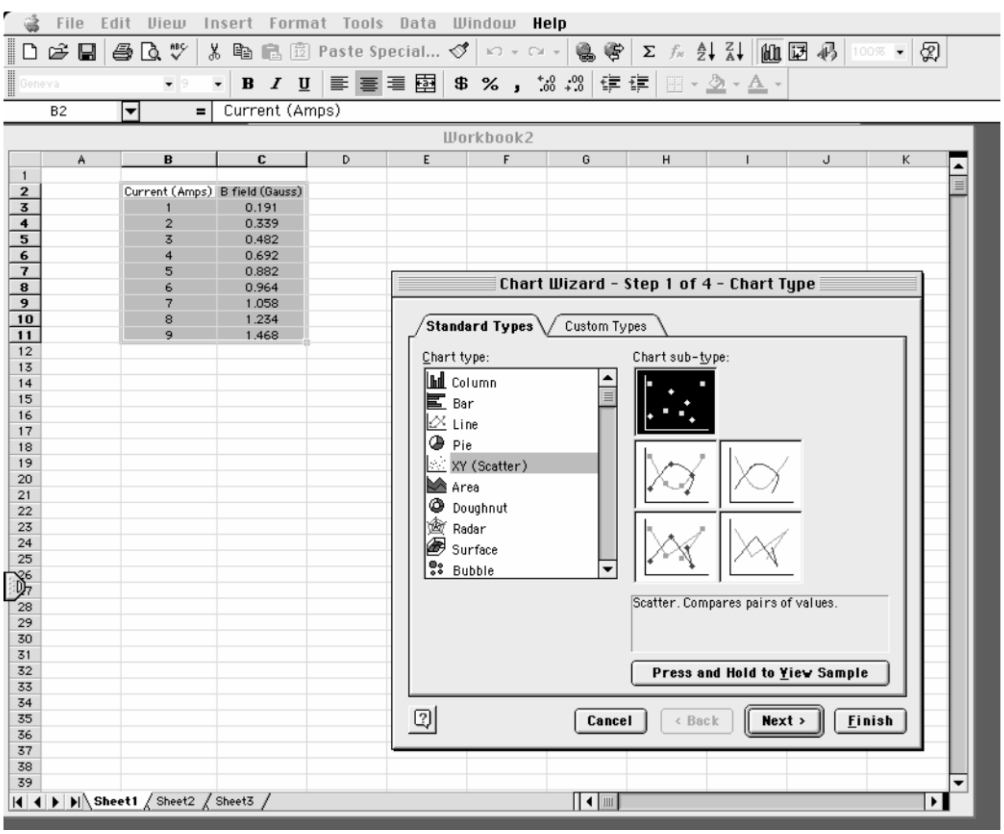
Step 1. Input your measurements and highlight the data using your cursor.



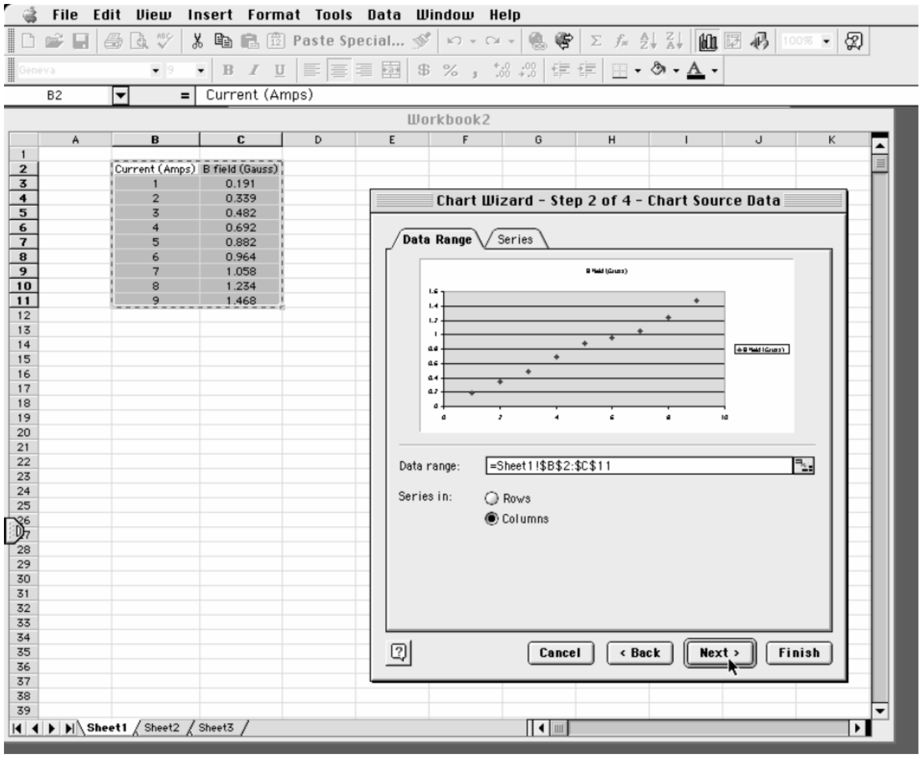
Step 2. Click on the "Chart Wizard" on the toolbar.



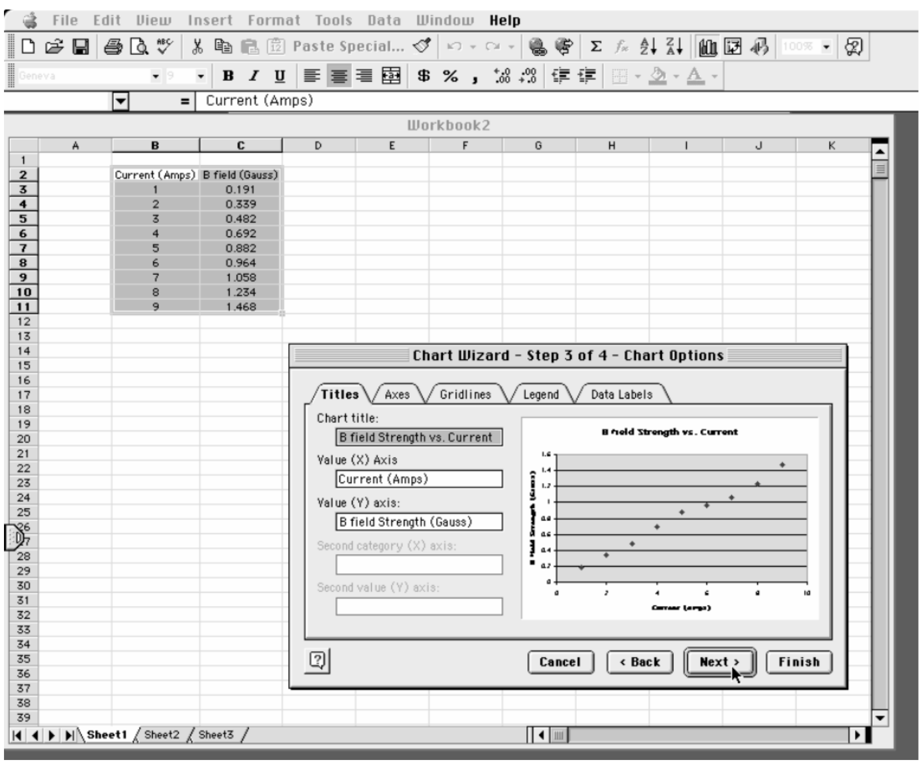
Step 3. Choose XY Scatter, not Line, from the list and click the "Next" button.



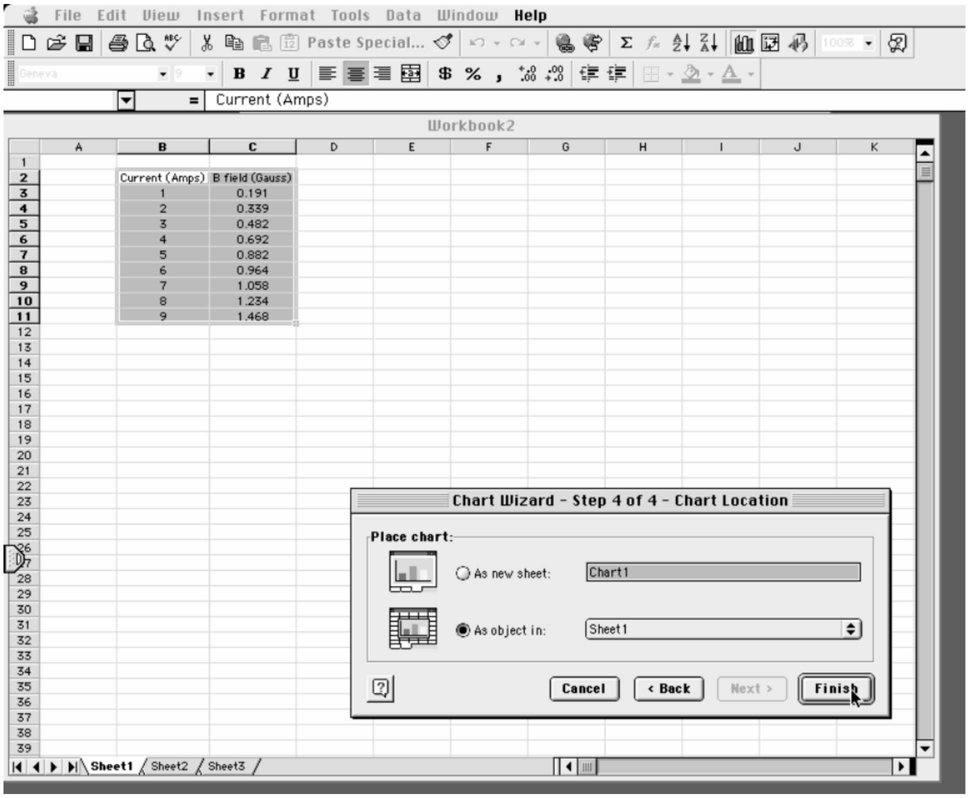
Step 4. Select the “Series in: Columns” option and click the “Next” button.



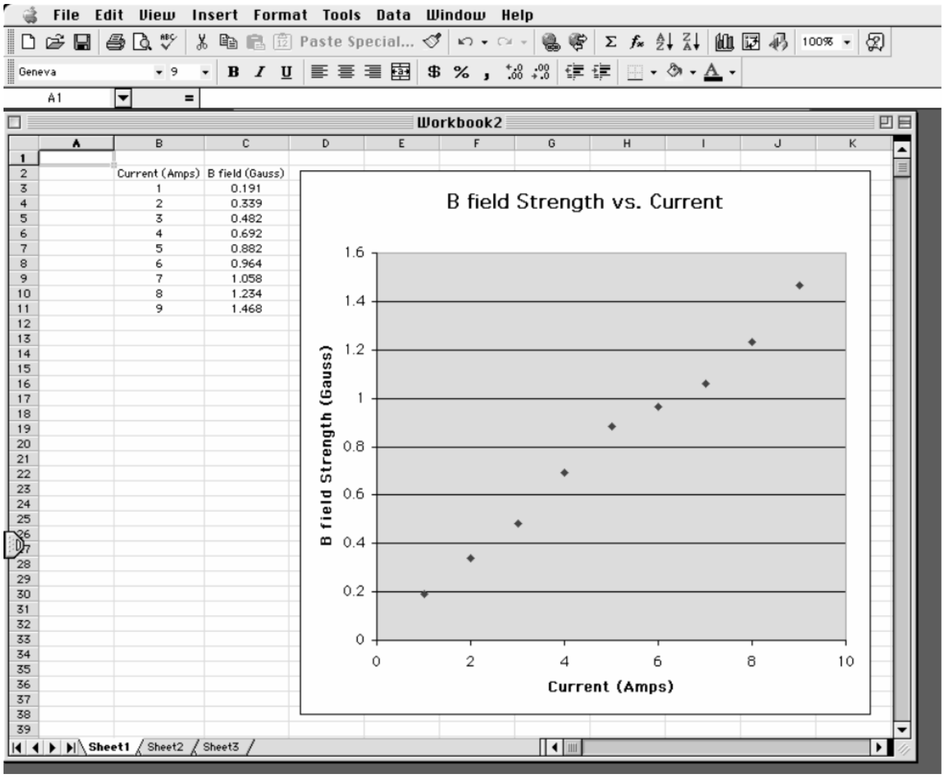
Step 5. Fill in the chart title and axis labels, and click the “Next” button.



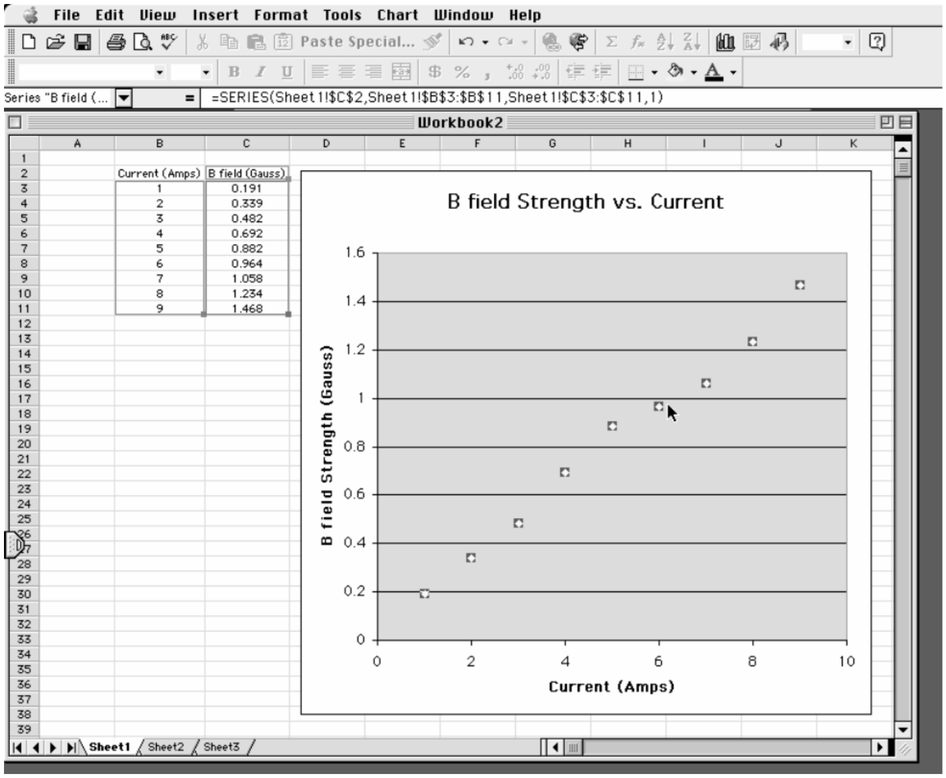
Step 6. Click the "Finish" button.



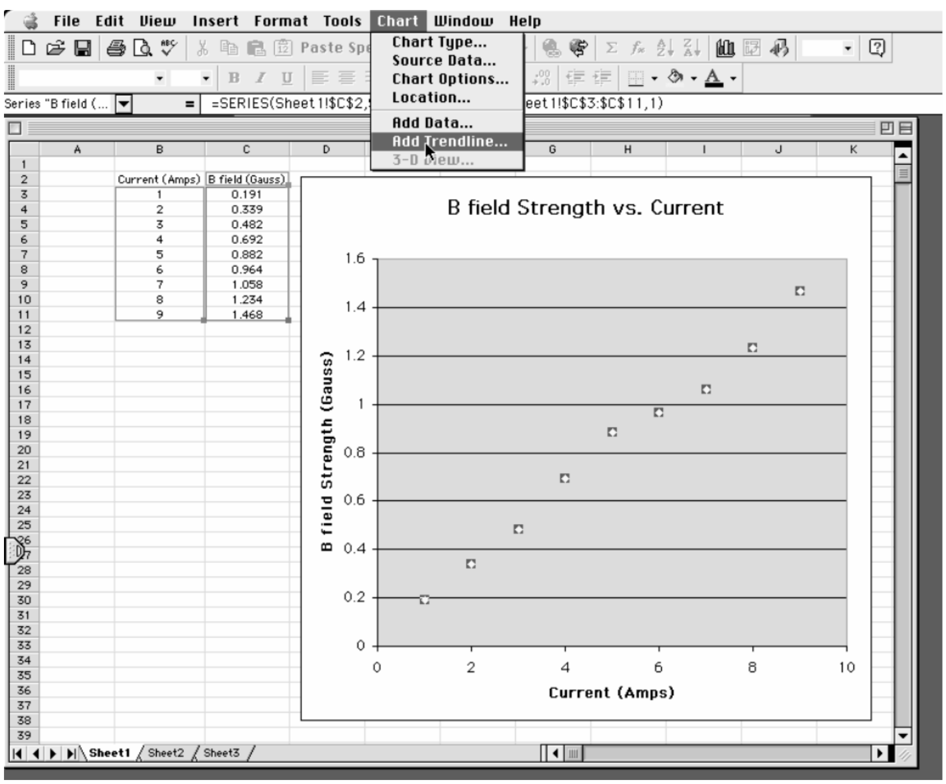
Step 7. Your graph will appear on the worksheet.



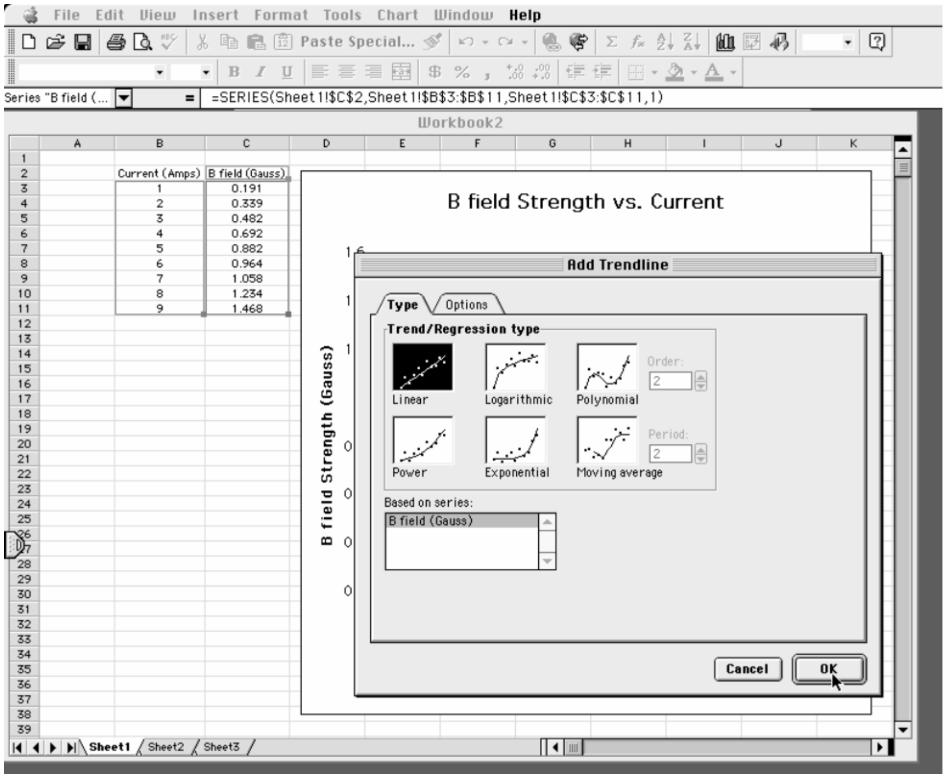
Step 8. Click on the data points to highlight them.



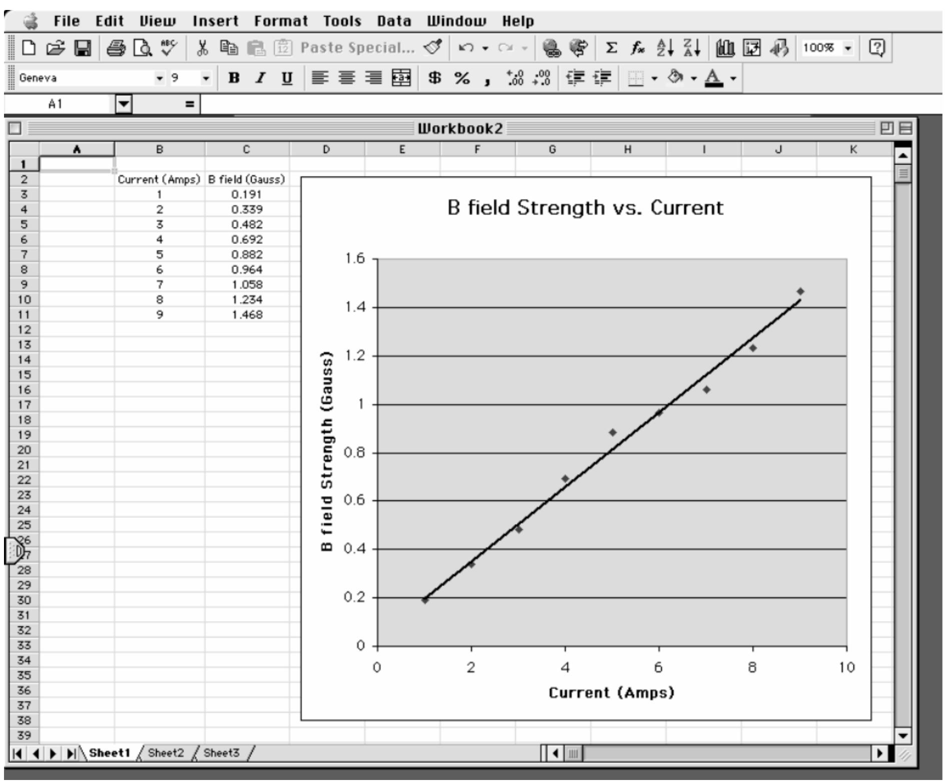
Step 9. Select "Add a Trendline" from the "Chart" menu.



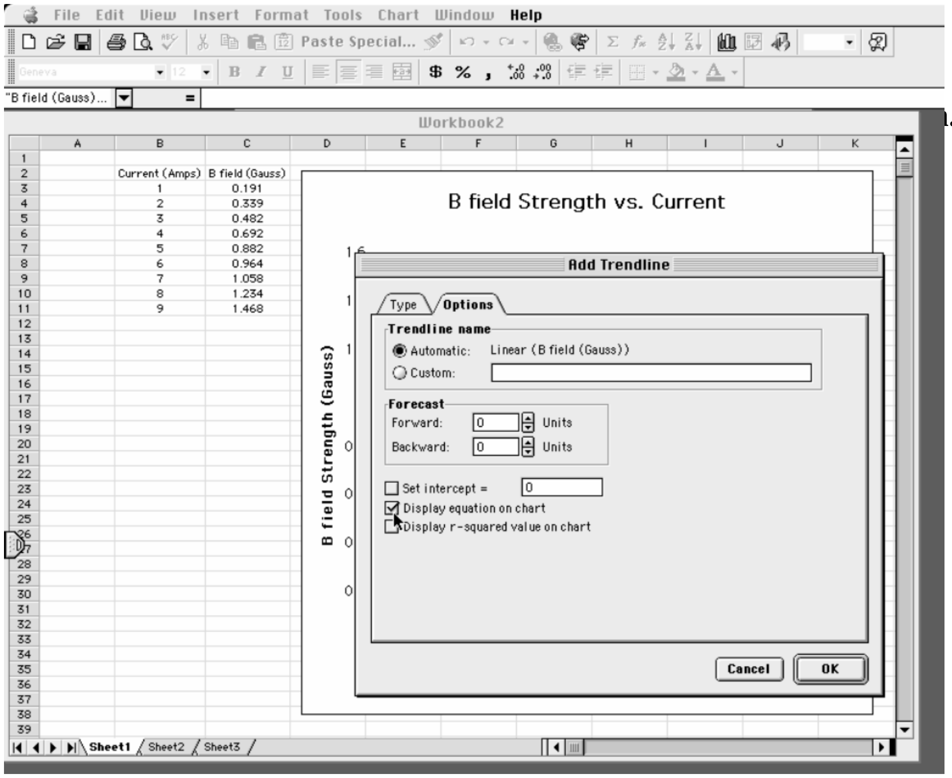
Step 10. Choose the best type of trend line for your data.

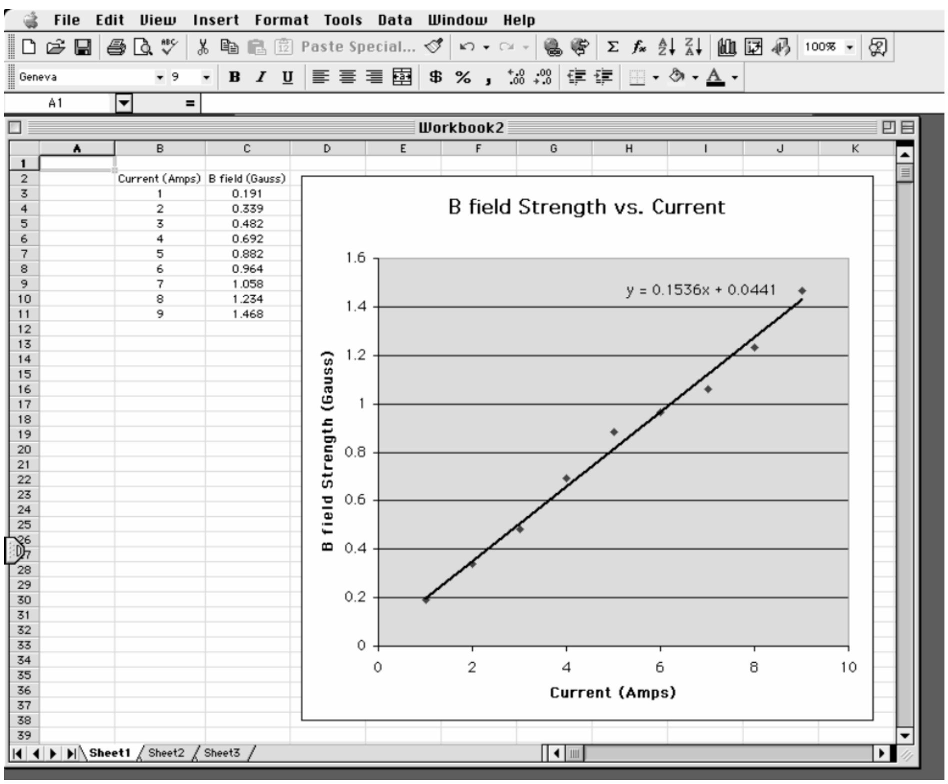


Step 11. The trend line will appear – is it a good fit to your data?



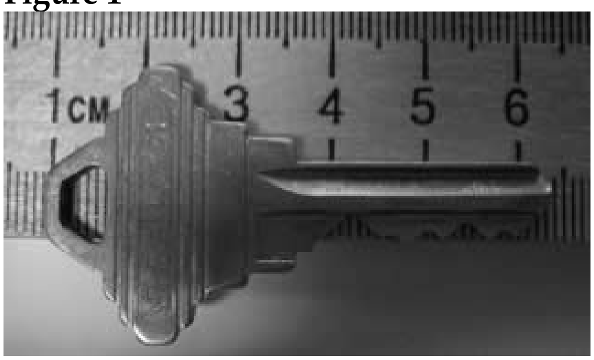
Step 12. If the equation of the line is needed, choose "Display equation on chart."





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 1, you could not measure more precisely than a quarter or half or a third of a mm. Reporting a number like 5.37142712 cm would not only be meaningless, it would be misleading.

Figure 1



In your measurement, you can precisely determine the distance down to the nearest millimeter and then improve your precision by estimating the next figure. It is always assumed that the last figure in the number recorded is uncertain. So, you would report the length of the key as 5.37 cm. Since you estimated the 7, it is the uncertain figure. If you don't like estimating, you might be tempted to just give the number that you know best, namely 5.3 cm, but it is clear that 5.37 cm is a better report of the measurement. An estimate is always necessary to report the most precise measurement. When you quote a measurement, the reader will always assume that the last figure is an estimate. Quantifying that estimate is known as **estimating uncertainties**. Appendix C 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 1 gives some examples.

Table 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 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 C and below) will be good enough.

Addition and subtraction

When adding or subtracting numbers, the number of decimal places must be taken into account.

*The result should be given to as many decimal places as the term in the sum that is given to the **smallest** number of decimal places.*

Examples:

Addition	Subtraction
6.24**2**	5.87**5**
+4.2**3**	-3.3**4**
+0.01**3**	2.5**35**
10.4**85**	
10.4**9**	2.5**4**

The uncertain figures in each number are shown in **bold-faced** type.

Multiplication and division

When multiplying or dividing numbers, the number of significant figures must be taken into account.

*The result should be given to as many significant figures as the term in the product that is given to the **smallest** number of significant figures.*

The basis behind this rule is that the least accurately known term in the product will dominate the accuracy of the answer.

As shown in the examples, this does not always work, though it is the quickest and best rule to use. When in doubt, you can keep track of the significant figures in the calculation as is done in the examples.

Examples:

Multiplication

15.8**4**	17.2**7**
x 2.**5**	x 4.**0**
7920	69.**080**
316**8**	
3**9.600**	
40	69

Division

1**17**	2**5**
23)269**1**	7**5**)187**5**
23	15**0**
3**9**	3**75**
23	**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}:

3. Multiply: 34.2 and 1.5×10^{4}

Appendix: Accuracy, Precision and Uncertainty - ERROR ANALYSIS

How tall are you? How old are you? When you answered these everyday questions, you probably did it in round numbers such as "five foot, six inches" or "nineteen years, three months." But how true are these answers? Are you exactly 5' 6" tall? Probably not. You estimated your height at 5′ 6" and just reported two significant figures. Typically, you round your height to the nearest inch, so that your actual height falls somewhere between 5' 5½" and 5' 6½" tall, or 5' 6" ± ½". This ± ½" is the **uncertainty,** and it informs the reader of the precision of the **value** 5' 6".

What is uncertainty?

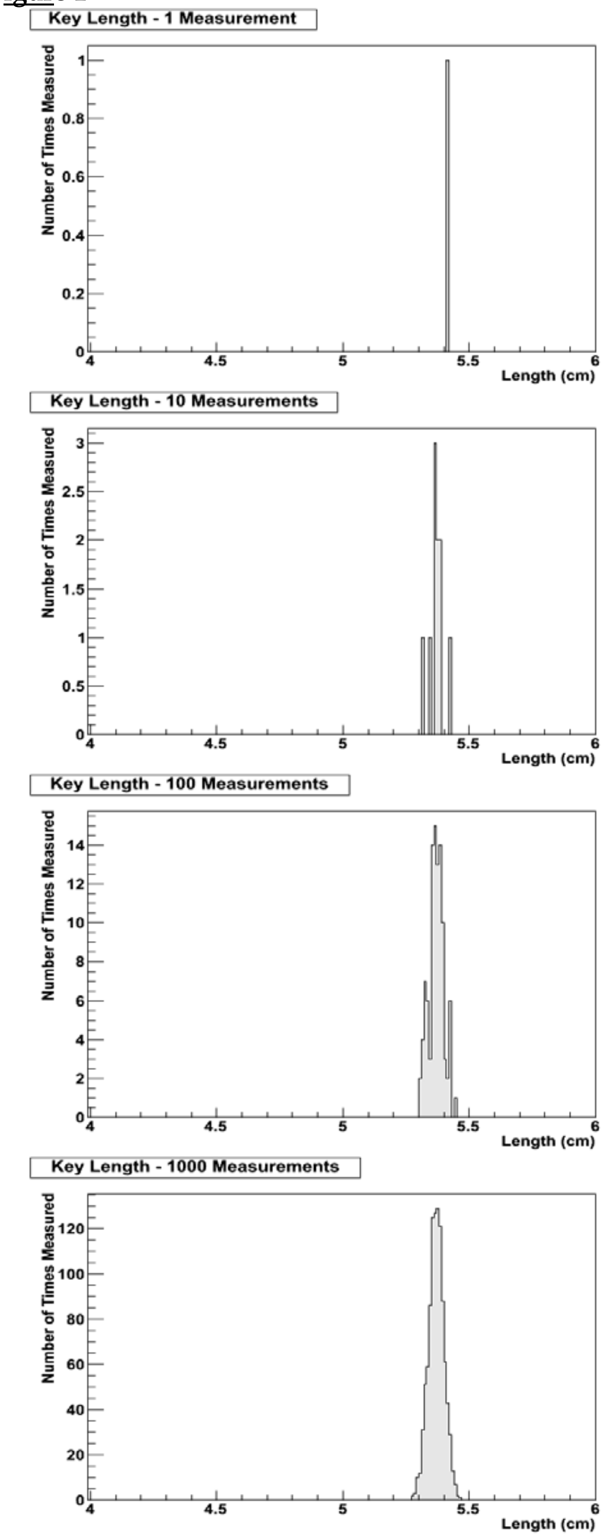
Whenever you measure something, there is always some uncertainty. There are two categories of uncertainty: **systematic** and **random**.

(1) **Systematic uncertainties** are those that consistently cause the value to be too large or too small. Systematic uncertainties include such things as reaction time, inaccurate meter sticks, optical parallax and miscalibrated balances. In principle, systematic uncertainties can be eliminated if you know they exist.

(2) **Random uncertainties** are variations in the measurements that occur without a predictable pattern. If you make precise measurements, these uncertainties arise from the estimated part of the measurement. Random uncertainty can be reduced, but never eliminated. We need a technique to report the contribution of this uncertainty to the measured value.

Uncertainties cause every measurement you make to be **distributed**. For example, the key in Figure 2 is approximately 5.37cm long. For the sake of argument, pretend that it is exactly 5.37cm long. If you measure its length many times, you expect that most of the measurements will be close to, but not exactly, 5.37cm, and that there will be a few measurements much more than or much less than 5.37cm. This effect is due to random uncertainty. You can never know how accurate any single measurement is, but you expect that many measurements will cluster around the real length, so you can take the average as the "real" length, and more measurements will give you a better answer; see Figure 1.

Figure 1



You must be very careful to estimate or eliminate (by other means) systematic uncertainties well because they cannot be eliminated in this way; they would just shift the distributions in Figure 1 left or right.

Roughly speaking, the average or "center" of the distribution is the "measurement," and the width or "deviation" of the distribution is the random uncertainty.

How do I determine the uncertainty?

This Appendix will discuss three basic techniques for determining the uncertainty: **estimating the uncertainty,** measuring the **average deviation**, and finding the **uncertainty in a linear fit**. Which one you choose will depend on your situation, your available means of measurement, and your need for precision. If you need a precise determination of some value, and you are measuring it directly (e.g., with a ruler or thermometer), 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 2.

Figure 2

If the true value were not as important as the magnitude of the value, you could say that the key's length was 5cm, give or take 1cm. This is a crude estimate, but it may be acceptable. A better estimate of the key's length, as you saw in Appendix A, would be 5.37cm. This tells us that the worst our measurement could be off is a fraction of a mm. To be more precise, we can estimate it to be about a third of a mm, so we can say that the length of the key is 5.37 ± 0.03 cm.

Another time you may need to estimate uncertainty is when you analyze video data. Figures 3 and 4 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 3

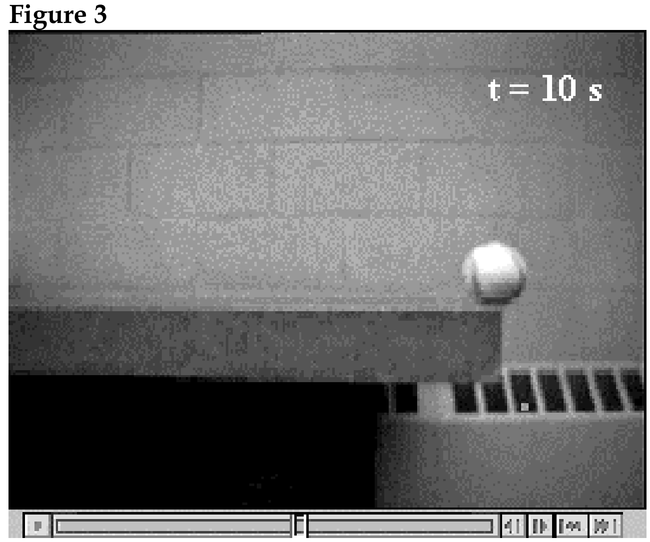
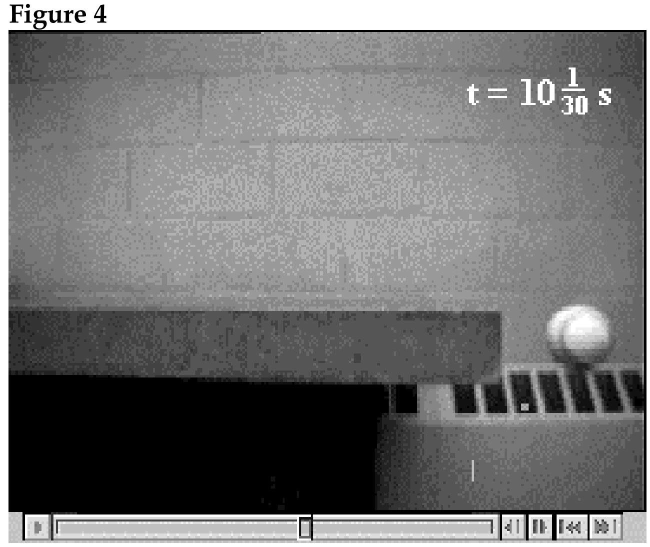


Figure 4



The exact moment the ball left the table lies somewhere between these frames. We can estimate that this moment occurs midway between them ($t = 10\frac{1}{60}\,s$). Since it must occur at some point between them, the worst our estimate could be off by is $\frac{1}{60}s$. We can therefore say the time the ball leaves the table is $t = 10\frac{1}{60} \pm \frac{1}{60}s$.

How do I find the average deviation?

If estimating the uncertainty is not good enough for your situation, you can experimentally determine the un-certainty by making several 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 3.120 3.121 average.
The deviations are: 0.011g, 0.004g, 0.001g, 0.005g, 0.001g, 0.001g
Sum of deviations: 0.023g
Average deviation: (0.023g)/6 = 0.004g
Mass of penny A: 3.121 ± 0.004g

Class 2: Penny B massed by six different students on six different balances

Mass (grams)
3.140 3.133 3.144 3.118 3.126 3.125 3.131 average
The deviations are: 0.009g, 0.002g, 0.013g, 0.013g, 0.005g, 0.006g
Sum of deviations: 0.048g
Average deviation: (0.048g)/6= 0.008g
Mass of penny B: 3.131 ± 0.008g

Finding the Uncertainty in a Linear Fit

Sometimes, you will need to find the uncertainty in a linear fit to a large number of measurements. The most common situation like this that you will encounter is fitting position or velocity with respect to time from MotionLab.

When you fit a line to a graph, you will be looking for the "best fit" line that "goes through the middle" of the data; see the appendix about graphs for more about this procedure. To find the uncertainty, draw the lines with the greatest and least slopes that still roughly go through the data. These will be the upper and lower limits of the uncertainty in the slope. These lines should also have lesser and greater y-intercepts than the "best fit" line, and they define the lower and upper limits of the uncertainty in the y-intercept.

Note that when you do this, the uncertainties above and below your "best fit" values will, in general, **not** be the same; this is different than the other two methods we have presented.

For example, in Figure 5, the y-intercept is 4.25 +2.75/-2.00, and the slope is 0.90 +0.20/-0.25.

Figure 5a

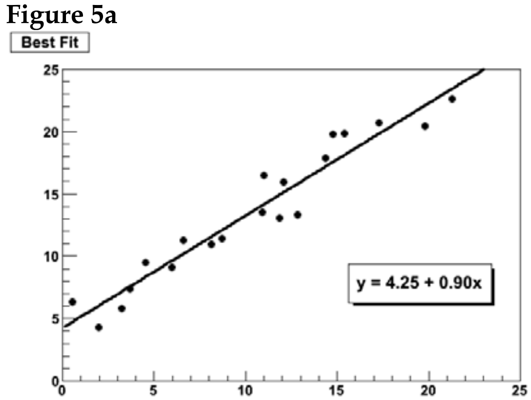


Figure 5b

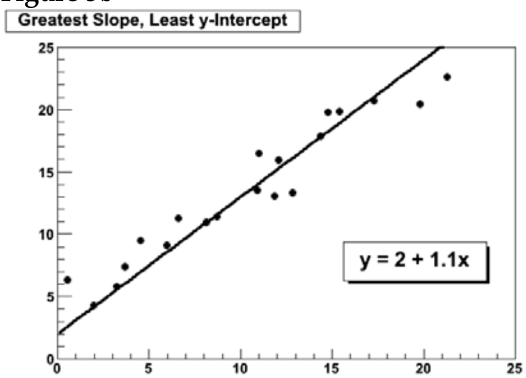
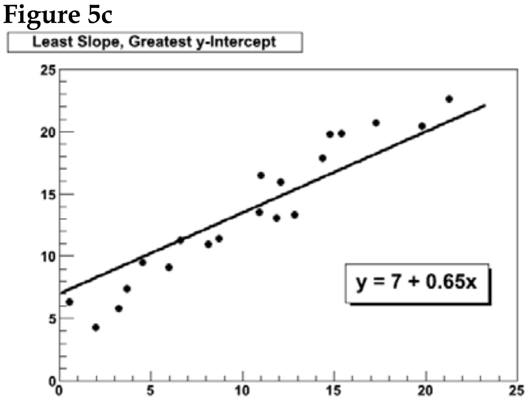


Figure 5c

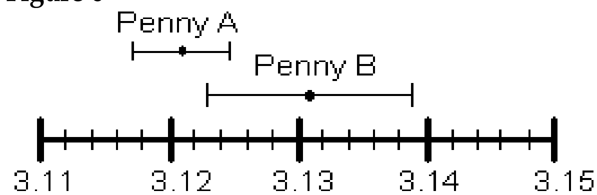


However you choose to determine the uncertainty, you should always state your method clearly in your report.

How do I know if two values are the same?

Go back to the pennies. 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 6, 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 6



Mass of pennies (in grams) with uncertainties

An important application of this is determining agreement between experimental and theoretical values. If you use a formula to generate a theoretical value of some quantity and use the method below to generate the uncertainty in the calculation, and if you generate an experimental value of the same quantity by measuring it and use the method above to generate the uncertainty in the measurement, you can compare the two values in this way. If the ranges overlap, then the theoretical and experimental values agree. If the ranges do not overlap, then the theoretical and experimental values do not agree.

Which result is more precise?

Suppose you use a meter stick to measure the length of a table and the width of a hair, each with an uncertainty of 1 mm. Clearly you know more about the length of the table than the width of the hair. Your measurement of the table is very precise but your measurement of the width of the hair is rather crude. To express this sense of precision, you need to calculate the percentage uncertainty. To do this, divide the uncertainty in the measurement by the value of the measurement itself, and then multiply by 100%. For example, we can calculate the precision in the measurements made by class 1 and class 2 as follows:

Precision of Class 1's value:
(0.004 g ÷ 3.121 g) x 100% = 0.1 %
Precision of Class 2's value:
(0.008 g ÷ 3.131 g) x 100% = 0.3 %

Class 1's results are more precise. This should not be surprising since class 2 introduced more uncertainty in their results by using six different balances instead of only one.

Which result is more accurate?

Accuracy is a measure of how your measured value compares with the real value. Imagine that class 2 made the measurement again using only one balance. Unfortunately, they chose a balance that was poorly calibrated. They analyzed their results and found the mass of penny B to be 3.556 ± 0.004 g. This number is more precise than their previous result since the uncertainty is smaller, but the new measured value of mass is very different from their previous value. We might conclude that this new value for the mass of penny B is different, since the range of the new value does not overlap the range of the previous value. However, that conclusion would be **wrong** since our uncertainty has not taken into account the inaccuracy of the balance. To determine the accuracy of the measurement, we should check by measuring something that is known. This procedure is called calibration, and it is absolutely necessary for making accurate measurements.

Be cautious! It is possible to make measurements that are extremely precise and, at the same time, grossly inaccurate.

How can I do calculations with values that have uncertainty?

When you do calculations with values that have uncertainties, you will need to estimate (by calculation) the uncertainty in the result. There are mathematical techniques for doing this, which depend on the statistical properties of your measurements. A very simple way to estimate uncertainties is to find the *largest possible uncertainty* the calculation could yield. **This will always overestimate the uncertainty of your calculation**, but an overestimate is better than no estimate or an underestimate. The method for performing arithmetic operations on quantities with uncertainties is illustrated in the following examples:

Addition:	***Multiplication:***
(3.131 ± 0.008 g) + (3.121 ± 0.004 g) = ?	(3.131 ± 0.013 g) x (6.1 ± 0.2 cm) = ?
First, find the sum of the values:	First, find the product of the values:
3.131 g + 3.121 g = 6.252 g	3.131 g x 6.1 cm = 19.1 g-cm
Next, find the largest possible value:	Next, find the largest possible value:
3.139 g + 3.125 g = 6.264 g	3.144 g x 6.3 cm = 19.8 g-cm
The uncertainty is the difference between the two:	The uncertainty is the difference between the two:
6.264 g – 6.252 g = 0.012 g	19.8 g-cm - 19.1 g-cm = 0.7 g-cm
Answer: 6.252 ± 0.012 g.	**Answer: 19.1 ± 0.7g-cm.**
Note: This uncertainty can be found by simply adding the individual uncertainties:	*Note: The percentage uncertainty in the answer is the sum of the individual percentage uncertainties:*
0.004 g + 0.008 g = 0.012 g	$\frac{0.013}{3.131} \times 100\% + \frac{0.2}{6.1} \times 100\% = \frac{0.7}{19.1} \times 100\%$

Subtraction:

(3.131 ± 0.008 g) – (3.121 ± 0.004 g) = ?

First, find the difference of the values:

3.131 g - 3.121 g = 0.010 g

Next, find the largest possible difference:

3.139 g – 3.117 g = 0.022 g

The uncertainty is the difference between the two:

0.022 g – 0.010 g = 0.012 g

Answer: 0.010±0.012 g.

Note: This uncertainty can be found by simply adding the individual uncertainties:

0.004 g + 0.008 g = 0.012 g

Notice also, that zero is included in this range, so it is possible that there is no difference in the masses of the pennies, as we saw before.

Division:

(3.131 ± 0.008 g) ÷ (3.121 ± 0.004 g) = ?

First, divide the values:

3.131 g ÷ 3.121 g = 1.0032

Next, find the largest possible value:

3.139 g ÷ 3.117 g = 1.0071

The uncertainty is the difference between the two:

1.0071 - 1.0032 = 0.0039

Answer: 1.003 ± 0.004

Note: The percentage uncertainty in the answer is the sum of the individual percentage uncertainties:

$$\frac{0.008}{3.131}\times 100\% + \frac{0.004}{3.121}\times 100\% = \frac{0.0039}{1.0032}\times 100\%$$

Notice also, the largest possible value for the numerator and the smallest possible value for the denominator gives the largest result.

The same ideas can be carried out with more complicated calculations. Remember this will always give you an overestimate of your uncertainty. There are other calculation techniques, which give better estimates for uncertainties. If you wish to use them, please discuss it with your instructor to see if they are appropriate.

These techniques help you estimate the random uncertainty that always occurs in measurements. They will not help account for mistakes or poor measurement procedures. There is no substitute for taking data with the utmost of care. A little forethought about the possible sources of uncertainty can go a long way in ensuring precise and accurate data.

PRACTICE EXERCISES:

B-1. Consider the following results for different experiments. Determine if they agree with the accepted result listed to the right. Also calculate the precision for each result.

a) $g = 10.4 \pm 1.1$ m/s^2 — $g = 9.8$ m/s^2

b) $T = 1.5 \pm 0.1$ sec — $T = 1.1$ sec

c) $k = 1368 \pm 45$ N/m — $k = 1300 \pm 50$ N/m

B-2. The area of a rectangular metal plate was found by measuring its length and its width. The length was found to be 5.37 ± 0.05 cm. The width was found to be 3.42 ± 0.02 cm. What is the area and the average deviation?

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.

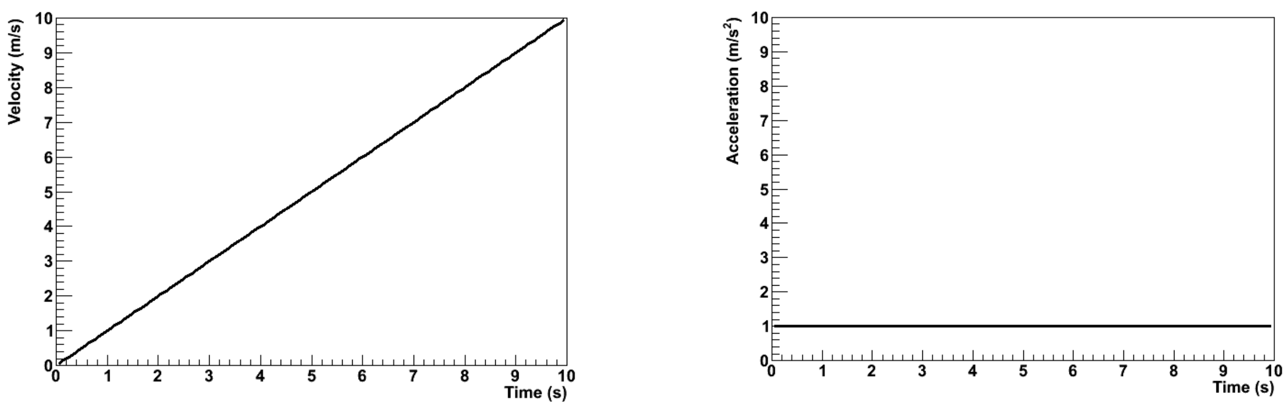
Cart (grams)	**Mass set 1** (grams)	**Mass set 2** (grams)
201.3	98.7	95.6
201.5	98.8	95.3
202.3	96.9	96.4
202.1	97.1	96.2
199.8	98.4	95.8
200.0	98.6	95.6

Appendix: Review of Graphs

Graphs are visual tools used to represent relationships (or the lack thereof) among numerical quantities in mathematics. In particular, we are interested in the graphs of functions.

What is a graph?

In this course, we will be dealing almost exclusively with graphs of functions. When we graph a quantity A with respect to a quantity B, we mean to put B on the horizontal axis and A on the vertical axis of a two-dimensional region and then to draw a set of points or curve showing the relationship between them. We do not mean to graph any other quantity from which A or$B$can be determined. For example, a plot of acceleration versus time has acceleration itself, $a(t)$, on the vertical axis, not the corresponding velocity $v(t)$; the time t, of course, goes on the horizontal axis. See Figure 1.



(a) (b)

Figure 1: Graphs of acceleration a and velocity v for an object in 1-dimensional motion with constant acceleration.

Traditionally, we call the vertical axis the "y-" axis; the horizontal axis, the "x-" axis. Please note that there is nothing special about these variables. They are not fixed, and they have no special meaning. If we are graphing, say, a velocity function $v(t)$ with respect to time t, then we do not bother trying to identify $v(t)$ with y or $t$with x; in that case, we just forget about y and x. This can be particularly important when representing position with the variable x, as we often do in physics. In that case, graphing $x(t)$ with respect to t would give us an x on both the vertical and horizontal axes, which would be extremely confusing. We can even imagine a scenario wherein we should graph a function x of a variable y such that y would be on the horizontal axis and $x(y)$ would be on the vertical axis. In particular, in MotionLab, the variable z, not x, is always used for the horizontal axis; it represents time. Both x and y are plotted on vertical axes as functions of the time z.

There are graphs which are not graphs of functions, e.g. pie graphs. These are not of relevance to this course, but much of what is contained in this document still applies.

Data, Uncertainties, and Fits

When we plot empirical data, it typically comes as a set of ordered pairs (x, y). Instead of plotting a curve, we just draw dots or some other kind of marker at each ordered pair.

Empirical data also typically comes with some uncertainty in the independent and dependent variables of each ordered pair. We need to show these uncertainties on our graph; this helps us to interpret the region of the plane in which the true value represented by a data point might lie. To do this, we attach error bars to our data points. Error bars are line segments passing through a point and representing some confidence interval about it.

After we have plotted data, we often need to try to describe that data with a functional relationship. We call this process "fitting a function to the data" or, more simply, "fitting the data." There are long, involved statistical algorithms for finding the functions that best fit data, but we won't go into them here. The basic idea is that we choose a functional form, vary the parameters to make it look like the experimental data, and then see how it turns out. If we can find a set of

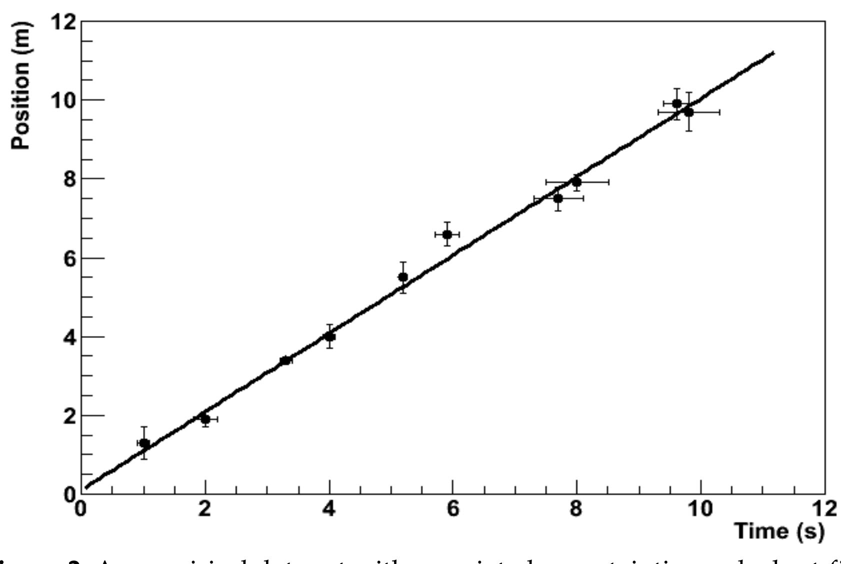


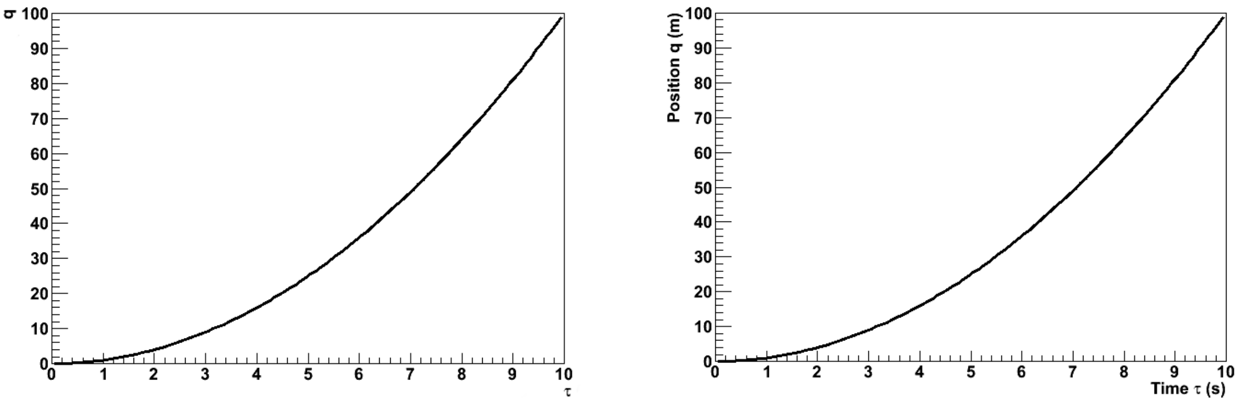
Figure 2: An empirical data set with associated uncertainties and a best-fit line.

parameters that make the function lie very close to most of the data, then we probably chose the right functional form. If not, then we go back and try again. In this class, we will be almost exclusively fitting lines because this is easiest kind of fit to perform by eye. Quite simply, we draw the line through the data points that best models the set of data points in question. The line is not a "line graph;" we do not just connect the dots (That would almost never be a line, anyway, but just a series of line segments.). The line does not actually need to pass through any of the data points. It usually has about half of the points above it and half of the points below it, but this is not a strict requirement. It should pass through the confidence intervals around most of the data points, but it does not need to pass through all of them, particularly if the number of data points is large. Many computer programs capable of producing graphs have built-in algorithms to find the best possible fits of lines and other functions to data sets; it is a good idea to learn how to use a high-quality one.

Making Graphs Say Something

So we now know what a graph is and how to plot it; great. Our graph still doesn't say much; take the graph in Figure 4(a). What does it mean? Something called q apparently varies quadratically with something called τ, but that is only a mathematical statement, not a physical one. We still need to attach physical meaning to the mathematical relationship that the graph communicates. This is where labels come into play.

Graphs should always have labels on both the horizontal and vertical axes. The labels should be terse but sufficiently descriptive to be unambiguous. Let's say that q is position and τ is time in Figure 4. If the problem is one-dimensional, then the label "Position" is probably sufficient for the vertical axis (q). If the problem is two-dimensional, then we probably need another qualifier. Let's say that the object in question is moving in a plane and that q is the vertical component of its position; then "Vertical Position" will probably do the trick. There's still a problem with our axis labels. Look more closely; where is the object at $\tau = 6s$? Who knows? We don't know if the ticks represent seconds, minutes, centuries, femtoseconds, or even some nonlinear measure of time, like humans born. Even if we did, the vertical axis has no units, either. We need for the units of each axis to be clearly indicated if our graph is really to say something. We can tell from Figure 4(b) that the object is at $q = 36m$ at $\tau = 6s$. A grain of salt: our prediction graphs will not always need units. For example, if we are asked to draw a graph predicting the relationship of, say, the acceleration due to gravity of an object with respect to its mass, the label "Mass" will do just fine for our horizontal axis. This is because we are not expected to give the precise functional dependence in this situation, only the overall behavior. We don't know exactly what the acceleration will be at a mass of $10g$, and we don't care. We just need to show whether the variation is increasing, decreasing, constant, linear, quadratic, etc. In this specific case, it might be to our advantage to include units on the vertical axis, though; we can probably predict a specific value of the acceleration, and that value will be meaningless without them.



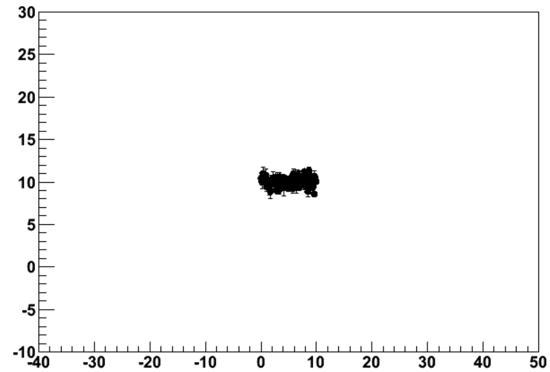
(a)

(b) Position q with respect to time τ for a mass of 3kg. The acceleration is constant.

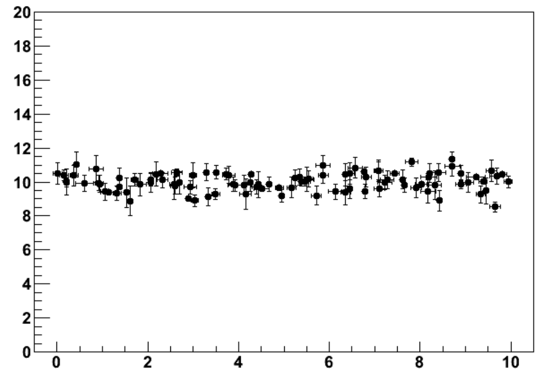
Figure 4: Poorly- versus well-labeled and -captioned graphs. The labels and caption make the second graph much easier to interpret.

Every graph we make should also have some sort of title or caption. This helps the reader quickly to interpret the meaning of the graph without having to wonder what it's trying to say. It particularly helps in documents with lots of graphs. Typically, captions are more useful than just titles. If we have some commentary about a graph, then it is appropriate to put this in a caption, but not a title. Moreover, the first sentence in every caption should serve the same role as a title: to tell the reader what information the graph is trying to show. In fact, if we have an idea for the title of a graph, we can usually just put a period after it and let that be the first "sentence" in a caption. For this reason, it is typically redundant to include both a title and a caption. After the opening statement, the caption should add any information important to the interpretation of a graph that the graph itself does not communicate; this might be an approximation involved, an indication of the value of some quantity not depicted in the graph, the functional form of a fit line, a statement about the errors, etc. Lastly, it is also good explicitly to state any important conclusion that the graph is supposed to support but does not obviously demonstrate. For example, let's look at Figure 4 again. If we are trying to demonstrate that the acceleration is constant, then we would not need to point this out for a graph of the object's acceleration with respect to time. Since we did not do that, but apparently had some reason to plot position with respect to time instead, we wrote, "The acceleration is constant."

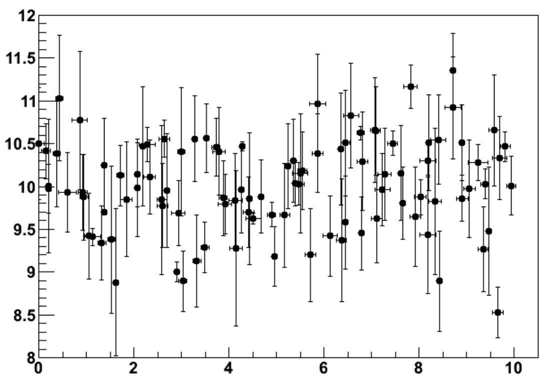
Lastly, we should choose the ranges of our axes so that our meaning is clear. Our axes do not always need to include the origin; this may just make the graph more difficult to interpret. Our data should typically occupy most of the graph to make it easier to interpret; see Figure 5. However, if we are trying to demonstrate a functional form, some extra space beyond any statistical error helps to prove our point; in Figure 5(c), the variation of the dependent with respect to the independent variable is obscured by the random variation of the data. We must be careful not to abuse the power that comes from freedom in



(a)



(b)



(c)

Figure 5: Graphs with too much (a), just enough (b), and too little space (c) to be easy to interpret.

plotting our data, however. Graphs can be and frequently are drawn in ways intended to manipulate the perceptions of the audience, and this is a violation of scientific ethics. For example, consider Figure 6. It appears that Candidate B has double the approval of Candidate A, but a quick look at the vertical axis shows that the lead is actually less than one part in seventy. The moral of the story is that our graphs should always be designed to communicate our point, but not to create our point.

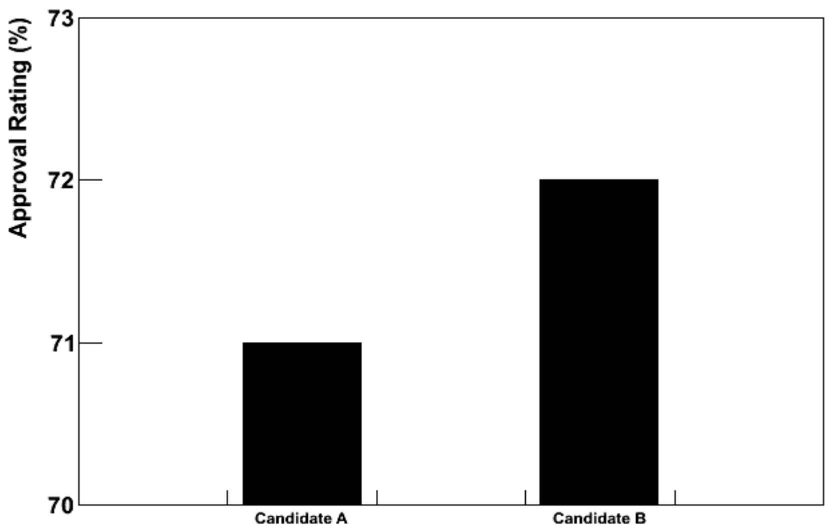


Figure 6: Approval ratings for two candidates in a mayoral race. This graph is designed to mislead the reader into believing that Candidate B has a much higher approval rating than Candidate A.

Using Linear Relationships to Make Graphs Clear

The easiest kind of graph to interpret is often a line. Our minds are very good at interpreting lines. Unfortunately, data often follow nonlinear relationships, and our minds are not nearly as good at interpreting those. It is sometimes to our advantage to force data to be linear on our graph. There are two ways that we might want to do this in this class; one is with calculus, and the other is by cleverly choosing what quantities to graph.

The "calculus" method is the simpler of the two. Don't let its name fool you: it doesn't actually require any calculus. Let's say that we want to compare the constant accelerations of two objects, and we have data about their positions and velocities with respect to time. If the accelerations are very similar, then it might be difficult to decide the relationship from the position graphs because we have a hard time detecting fine variations in curvature. It is much easier to compare the accelerations from the velocity graphs because we then just have to look at the slopes of lines; see Figure 7. We call this the "calculus" method because velocity is the first derivative with respect to time of position; we have effectively chosen to plot the derivative of position rather than position itself. We can sometimes use these calculus-based relationships to graph more meaningful quantities than the obvious ones.

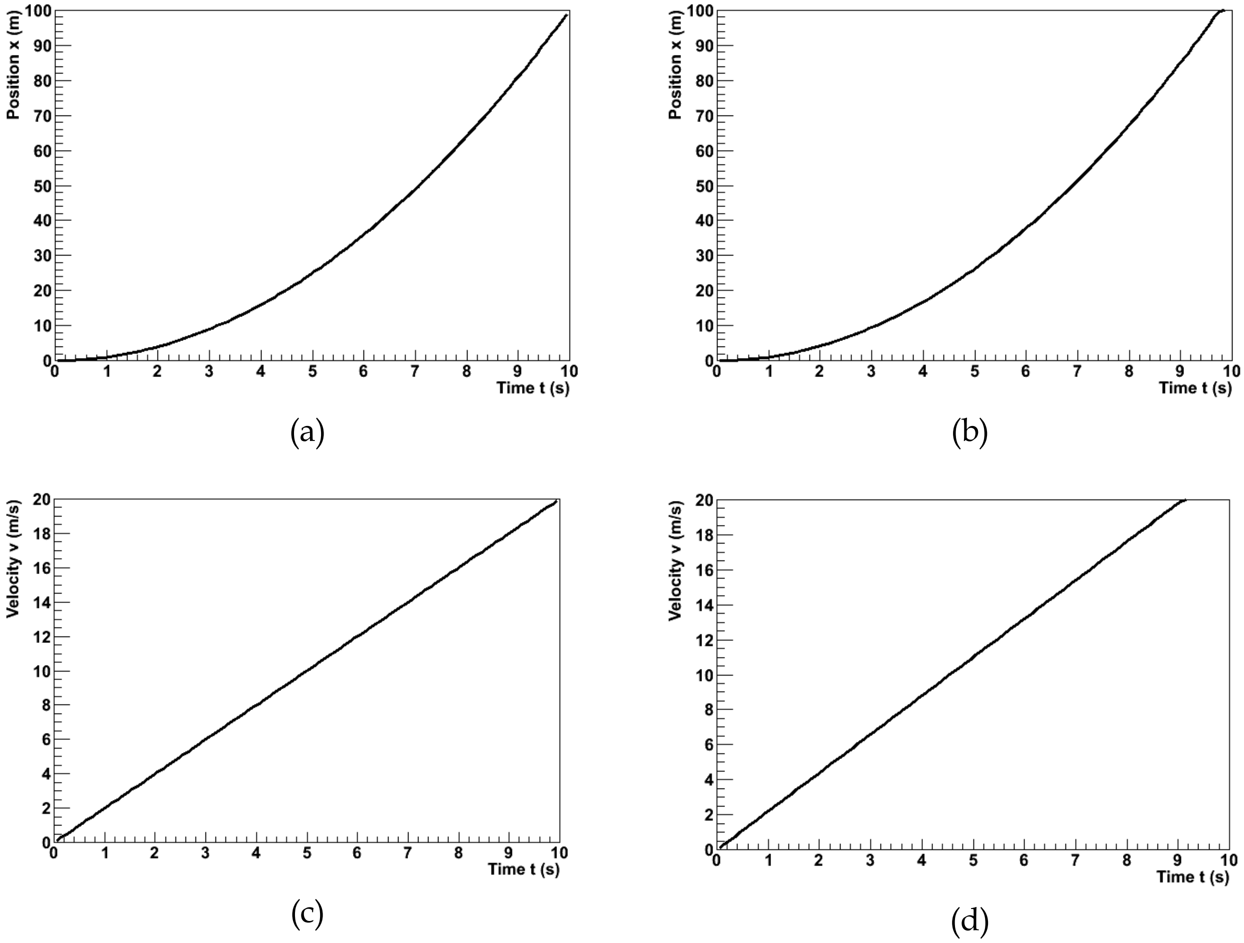


Figure 7: Position and velocity with respect to time for an objects with slightly different accelerations. The difference is easier to see in the velocity graphs.

The other method is creatively named "linearization." Essentially, it amounts to choosing non-obvious quantities for the independent and/or dependent variables in a graph in such a way that the result graph will be a line. An easy example of this is, once again, an object moving with a constant acceleration, like one of those in Figure 7. Instead of taking the derivative and plotting the velocity, we might have chosen to graph the position with respect to $t^2/2$; because the initial velocity for this object happened to be 0, this would also have produced a graph with a constant slope.

The Bottom Line

Ultimately, graphs exist to communicate information. This is the objective that we should have in mind when we create them. If our graph can effectively communicate our point to our readers, then it has accomplished its purpose.

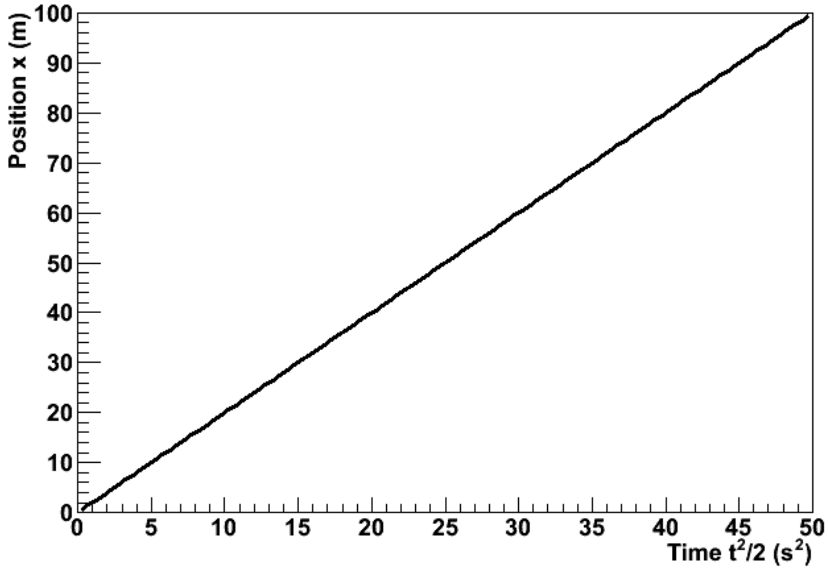


Figure 8: The position of the first object from Figure 7 plotted with respect to $t^2/2$. The relationship has been linearized.

Appendix: **Guide to Writing Lab Reports** (120x)

Many students have a great deal of trouble writing lab reports. They don't know what a lab report is; they don't know how to write one; they don't know what to put in one. This document seeks to resolve those problems. We will address them in that order.

This manual includes examples of a good and of a bad lab report; examine them in conjunction with this document to aid your understanding.

What Is a Lab Report?

Everyone seems to understand that a lab report is a written document about an experiment performed in lab. Beyond that, a lab report's identity is less obvious and more disputed. Let's save ourselves some misery by first listing some things that a lab report is not. A lab report is not

- ... a worksheet; you may not simply use the example like a template, substituting what is relevant for your experiment.
- ... the story of your experiment; although a description of the experimental procedure is necessary and very story-like, this is only one part of the much greater analytical document that is the report.
- ... rigid; what is appropriate for a report about one experiment may not be appropriate for another.
- ... a set of independent sections; a lab report should be logically divided, but its structure should be natural, and its prose should flow.

So what, then, is a lab report? A lab report is a document beginning with the proposal of a question and then proceeding, using your experiment, to answer that question. It explains not only what was done, but why it was done and what it means. To try to specify the content in much more detail than this is too constraining; you must simply do whatever is necessary to accomplish these goals. However, a lab report usually accomplishes them in four phases. First, it introduces the experiment by placing it in context, usually the motivation for performing it and some question that it seeks to answer. Second, it describes the methods of the experiment. Third, it analyzes the data to yield some scien- tifically meaningful result. Fourth, it discusses the result, answering the original question and explaining what the result means.

There are, of course, other senses of what a lab report is — it is quantitative, it is persuasive, etcetera — but we will come to those along the way.

How Do I Write a Lab Report?

Now that we have a vague idea of what a lab report is, let's discuss how to write it. By this, we do not mean its content, but its audience, style, etcetera.

Making an Argument

We already mentioned that a lab report uses an experiment to answer a question, but merely answering it isn't enough; your report must convince the reader that the answer is correct. This makes a lab report a persuasive document. Your persuasive argument is the single most important part of any lab report. You must be able to communicate and demonstrate a clear point. If you can do this well, your report will be a success; if you cannot, it will be a failure.

At some point, you have certainly written a traditional, five-paragraph essay. The first paragraph introduces a thesis, the second through fourth defend the thesis, and the fifth paragraph concludes by restating the thesis. This is a little too simple for a lab report, but the basic idea is the same; keep it in mind. Begin by introducing and stating your prediction in — logically enough — the Introduction and Prediction sections. Test your prediction in the Procedure, Data, and Analysis sections. Restate and critically evaluate both your prediction and your result in your Conclusion section.

Audience

If you are successfully to persuade your audience, you must know something about her. What sorts of things does she know about physics, and what sorts of things does she find convincing? For your lab report, she is an arbitrary scientifically-literate person. She is not quite your professor, not quite your TA, and not quite your labmates, but she is this same sort of person. The biggest difference is that she doesn't know what your experiment is, why you are doing it, or what you hope to prove until you tell her. Use physics and mathematics freely in your report, but explain your experiment and analysis in detail.

Technical Style

A lab report is a technical document. This means that it is stylistically quite different from other documents you may have written. What characterizes technical writing, at least as far as your lab report is concerned? Here are some ofthe most prominent features, but for a general idea, read the sample good lab report included in this manual.

A lab report does not entertain. When you read the sample reports, you may find them boring; that's OK. The science in your report should be able to stand for itself. If your report needs to be entertaining, then its science is lacking.

A lab report is a persuasive document, but it does not express opinions. Your prediction should be expressed as an objective hypothesis, and your experiment and analysis should be a disinterested effort to confirm or deny it. Your result may or may not coincide with your prediction, and your report should support that result objectively.

A lab report is divided into sections. Each section should clearly communicate one aspect of your experiment or analysis.

A lab report may use either the active or the passive voice. Use whichever feels natural and accomplishes your intent, but you should be consistent.

A lab report presents much of its information with media other than prose. Tables, graphs, diagrams, and equations frequently can communicate far more effectively than can words. Integrate them smoothly into your report.

A lab report is quantitative. If you don't have numbers to support what you say, you may as well not say it at all.

Some of these points are important and sophisticated enough to merit sections of their own, so let's discuss them some more.

Nonverbal Media

A picture is worth a thousand words. Take this old sentiment to heart when you write your lab report, but do not limit yourself to pictures. Make your point as clearly and tersely as possible; if a graph will do this better than words will, use a graph.

When you incorporate these media, you must do so well, in a way that serves the fundamental purpose of clear communication. Label them “Figure 1” and “Table 2.” Give them meaningful captions that inform the reader what information they are presenting. Give them context in the prose of your report. They need to be functional parts of your document’s argument, and they need to be well-integrated into the discussion.

Students sometimes think that they are graded “for the graphs,” and TAs sometimes over-emphasize the importance of these media. Avoid these pitfalls by keeping in mind that the purpose of these things is communication. If you can make your point more elegantly with these tools, then use them. If you cannot, then stick to tried-and-true prose. Use your best judgment.

Quantitativeness

A lab report is quantitative. Quantitativeness is the power of scientific analysis. It is objective. It holds a special power lacking in all other forms of human endeavor: it allows us to know precisely how well we know something. Your report is scientifically valid only insofar as it is quantitative.

Give numbers for everything, and give the numerical errors in those numbers. If you find yourself using words like “big,” “small,” “close,” “similar,” etcetera, then you are probably not being sufficiently quantitative. Replace vague statements like these with precise, quantitative ones.

You will frequently need to give equations as well as numbers. If so, say something about whence the equation came and why it’s there. You can’t find the error in an equation, but you can propagate the error in the inputs to get the errors in the outputs. Do this.

Error analysis is a very important part of quantitativeness. This lab manual contains an appendix about error analysis; read it, understand it, and take it to heart.

To be quantitative, i.e., to give numbers and to analyze errors, you are going to need to do a lot of math. This is inescapable, but it’s not so bad. For your purposes, you can think of mathematics as a particular language used to express ideas about physics. Think to yourself about what information you have and what information you want. Try (briefly!) to put into your own words, on a scrap piece of paper, how the information you have tells you the information you want, then use what you know about calculus and algebra to translate that idea into the math you need in your report. For example, “the vertical component of the acceleration (=a_x) of the ball in free-fall due to gravity is the change (=derivative) in time (=t) of the vertical component of its velocity (=v_y)” would become

$$a_y = \frac{dv_y}{dt}$$

One way you could find this value is as the slope of Vy versus z in your MotionLabdata.

What Should I Put in My Lab Report?

Structure your report like this.

Abstract

Think of the abstract as your report in miniature. Make it only a few sentences long. State the question you are trying to answer, the method you used to answer it, and your results. It is not an introduction. Your report should make sense in its absence. You do not need to include your prediction here.

Introduction

Do three things in your introduction. First, provide enough context so that your audience can understand the question that your report tries to answer. This typically involves a brief discussion of the hypothetical real-world scenario from the lab manual. Second, clearly state the question. Third, provide a brief statement of how you intend to answer it.

It can sometimes help students to think of the introduction as the part justifying your report to your company or funding agency. Leave your reader with an understanding of what your experiment is and why it is important.

Predictions

Include the same predictions in your report that you made prior to the beginning of the experiment. They do not need to be correct. You will do the same amount of work whether they are correct or incorrect, and you will receive far more credit for an incorrect, well-refuted prediction than for a correct, poorly-supported one.

Your prediction will often be an equation or a graph. If so, discuss it in prose.

Procedure

Explain what your actual experimental methodology was in the procedure section. Discuss the apparatus and techniques that you used to make your measurements.

Exercise a little conservatism and wisdom when deciding what to include in this section. Include all of the information necessary for someone else to repeat the experiment, but only in the important ways. It is important that you measured the time for a cart to roll down a ramp through a length of one meter; it is not important who released the cart, how you chose to coordinate the person releasing it with the person timing it, or which one meter of the ramp you used. Omit any obvious steps. If you performed an experiment using some apparatus, it is obvious that you gathered the apparatus at some point. If you measured the current through a circuit, it is obvious that you hooked up the wires. One aspect of this which is frequently problematic for students is that a step is not necessarily important or non-obvious just because they find it difficult or time-consuming. Decide what is scientifically important, and then include only that in your report.

Students approach this section in more incorrect ways than any other. Do not provide a bulleted list of the equipment. Do not present the procedure as a series of numbered steps. Do not use the second person or the imperative mood. Do not treat this section as though it is more important than the rest of the report. You should rarely make this the longest, most involved section.

Data

This should be your easiest section. Record your empirical measurements here: times, voltages, fits from MotionLab, etcetera.

Do not use this as the report's dumping ground for your raw data. Think about which measurements are important to your experiment and which ones are not. Only include data in processed form. Use tables, graphs, and etcetera, with helpful captions. Do not use long lists of measurements without logical grouping or order.

Give the units and uncertainties in all of your measurements.

This section is a bit of an exception to the "smoothly integrate figures and tables" rule. Include little to no prose here; most of the discussion belongs in the Analysis section. The distinction between the Data and Analysis sections exists mostly for your TA.

Analysis

Do the heavy lifting of your lab report in the Analysis section. Take the data from the Data section, scientifically analyze it, and finally answer the question you posed in your Introduction. Do this quantitatively.

Your analysis will almost always amount to quantifying the errors in your measurements and in any theoretical calculations that you made in the Predictions section. Decide whether the error intervals in your measurements and predictions are compatible. This manual contains an appendix about error analysis; read it for a description of how to do this.

If your prediction turns out to be incorrect, then show that as the first part of your analysis. Propose the correct result and show that it is correct as the second part of your analysis.

Finally, discuss any shortcomings of your procedure or analysis, such as sources of systematic error for which you did not account, approximations that are not necessarily valid, etcetera. Decide how badly these shortcomings affect your result. If you cannot confirm your prediction, then estimate which are the most important.

Conclusion

Consider your conclusion the wrapping paper and bow tie of your report. At this point, you should already have said most of the important things, but this is where you collect them in one place. Remind your audience what you did, what your result was, and how it compares to your prediction. Tell her what it means. Leave her with a sense of closure.

Quote your result from the Analysis section and interpret it in the context of the hypothetical scenario from the Introduction. If you determined that there were any major shortcomings in your experiment, you might also propose future work to overcome them.

If the Introduction was your attempt to justify your past funding, then theConclusion is your attempt to justify your future funding.

What Now?

Read the sample reports included in this manual. There are two; one is an example of these instructions implemented well, and the other is an example of these instructions implemented poorly. Then, talk to your TA. He can answer any remaining questions that you might have.

There is a lot of information here, so using it and actually writing your lab report might seem a little overwhelming. A good technique for getting started is this: complete your analysis and answer your question before you ever sit down to write your report. At that point, the hard part of the writing should be done: you already know what the question was, what you did to answer it, and what the answer was. Then just put that down on paper.

GOOD SAMPLE LAB

Lab II, Problem 5: Velocity and Force

Athos

July 14, 2011

Physics 1201W, Professor: Porthos, TA: Aramis

Abstract

The final velocity of a gravity-driven launch cart for a pterosaur model was determined. The mechanism was tested for four driving masses at similar launch heights. The final velocity predicted by Newton's second law and kinematics was confirmed to within experimental error.

Introduction

A research group is investigating the hypothesis that modern birds are the descendants of pterosaurs. As part of this investigation, the flight of pterosaurs is being studied via models. The models are to be launched by a mechanism consisting of a cart accelerated down a straight, level track by a string. The string runs horizontally, over a pulley, and then vertically to a hanging mass which is pulled downward by gravity. To ensure the desired launch parameters for the flight, it is necessary to be able reliably to predict the final velocity of the cart. This experiment studied the final velocity as a function of the driving mass and the height of its release.

Prediction

The final velocity can be easily calculated by application of Newton's second law and kinematics. Let the mass of the cart be M; the hanging mass, m; and the release height, h. The force on the system is the downward force of gravity on the hanging mass, $F = mg$; using Newton's second law for the compound system,

$$a = g\frac{m}{m+M}$$

Letting the initial position be 0m and the initial velocity by 0m/s, kinematics then yields the final velocity:

$$v_f = \sqrt{2gh\frac{m}{m+M}} \qquad (1)$$

The final velocity of the cart is predicted to be that given by Equation 1.

Procedure

A cart was placed on a straight, level, elevated track with a pulley at one end. A string was tied to the cart and run over a pulley. A mass was tied to the other end and allowed to hang down over the edge of the track. The string was pulled taught, and the mass was allowed to fall from rest, pulling

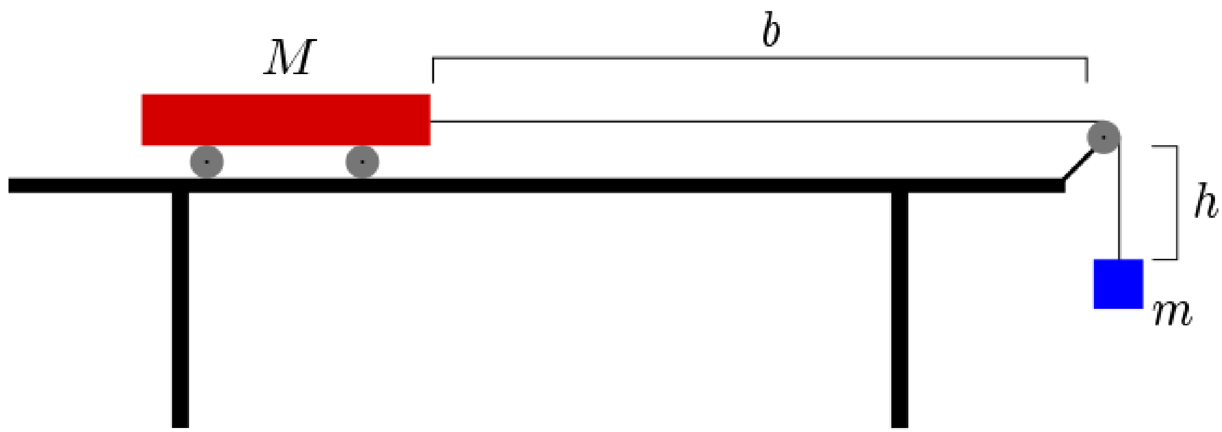


Figure *1*: The test mechanism used for this experiment. $b > h$.

the cart with it. Its initial height was less than the length of string between cart and pulley so that the cart would undergo an initial, accelerating phase and a final, coasting phase in its motion. This mechanism is depicted in Figure 1. The motion of the cart was recorded with a video camera. MotionLab software was used to plot the position and velocity of the cart with respect to time. The position and velocity were then fit by eye in two stages, one for the accelerating and one for the coasting phase. The final velocity was taken to be the parameter in a zeroth-order monomial fit to the coasting phase of the velocity measurements.

Data

m(g)	h(m)	experimental v_f(m/s)	theoretical v_f(m/s)
50.0	0.46	$1.25^{+0.20}_{-0.35}$	$1.24^{+0.04}_{-0.03}$
70.0	0.41	$1.35^{+0.25}_{-0.15}$	$1.34^{+0.04}_{-0.03}$
100.0	0.47	$1.65^{+0.15}_{-0.30}$	$1.64^{+0.04}_{-0.04}$
150.0	0.48	$1.90^{+0.25}_{-0.20}$	$1.94^{+0.04}_{-0.04}$

Table *1*: The masses m, release heights h, and experimental and theoretical values of the cart's final velocity v_f. The error in all of the masses is 0.3g. The error in all of the release heights is 0.02m.

Analysis

The experimental measurements and theoretical predictions of the final velocity are given in Table 1 in the Data section. The errors in the experimental measurements were calculated by the parameters in a minimum zeroth-order monomial greater than and a maximum zeroth-order monomial less than all measured data points in the coasting phase. The errors in the theoretical predictions were calculated by the "worst case" propagation of error technique, using the errors quoted above and $g = (9.80 \pm 0.02)$m/s. The entire error intervals of the theoretical predictions are within the respective error intervals of the experimental measurements, so this experiment did confirm the predictions to within error.

There are numerous sources of error not addressed in this experiment. One is the compound effect of friction and drag retarding the motion of the cart and pulley. This was unquantified. Another was the acceleration produced by any deviation from the horizontal of the track; this was determined to be zero within the static friction in the axles of the cart in that it was incapable of accelerating the cart from rest. Another was the distortion in the videos due to the camera. Another was the masses of the string and the pulley, which were assumed to be massless in the theoretical calculation. All of these, and any other sources of error not mentioned here, are believed to be insignificant in comparison to the random error in that the error interval is much wider than the difference between the theoretical and experimental values of the final velocity.

Conclusion

A proposed launching mechanism for a pterosaur model to be used in the investigation of the ancestry of modern birds was modeled by a cart on a track. The cart was accelerated from rest by each of four hanging masses pulled by gravity via a string run over a pulley. The final velocity of the cart after the hanging mass reached the ground was measured and compared to the predictions of kinematics and Newton's second law. The predictions were confirmed in that they and the measurements both lay within one another's error intervals. The research group is justified in using the predicted formula for v_f to calculate the final velocity of the cart used to launch the model. However, it must take into account the mass of the model by using the sum of the model's and the cart's masses rather than just the mass of the cart in its calculations.

BAD SAMPLE LAB

Lab II, Problem 5

Comte de Rochefort

July 15, 2011

Abstract

We try to study the flight of pterosaurs because of their possible relationship to modern birds. To do so, we need to launch a model at a reproducible velocity. We simulate the launch mechanism with a cart on a track driven by a falling mass pulling it with a string. We test for a number of various masses. We compare the result to a prediction formulated by the application of Newton's second law and basic kinematics. The result is that theory agrees with experiment. The statistical and systematic errors are not significant.

Introduction

We are working as part of a research group studying pterosaurs, a kind of flying reptile from the Mesozoic era. Our group believes that pterosaurs might be related to modern birds. We need to determine the possibility of this evolutionary ancestry, so we are investigating their respective mechanisms of flight as one way of demonstrating this lineage.

As part of the study, we are designing a mechanism which can be employed to propel models of pterosaurs into gliding. The mechanism is a cart on a straight, eminently horizontal, aluminum track. The cart is connected to a string. The string lies over a pulley and then dives straight down. The terminal end of the string is affixed to a set of lab masses. The masses fall under the uniform influence of gravity and pull the string, accelerating the cart from motionlessness. The mechanism needs to have a reliable launch velocity. We must therefore confirm that we can predict the velocity for given values of initial height for the falling mass and of the magnitude of that mass itself.

Prediction

We can calculate the final velocity. We start with Newton's second law for the hanging mass.

$$F = mg - T = ma$$

We do the same for the cart

$$F = T = Ma$$

We set the Ts equal to each other and simplify.

$$T = Ma = mg - ma$$
$$Ma + ma = mg$$
$$(M + m)a = mg$$
$$a = \frac{mg}{M + m}$$

We now have a. We also have the formula

$$x = x_0 + v_0 t + at^2$$

With x = y, v0 = 0, and y0=0, we get

$$y = \frac{1}{2}at^2$$

We set y=h. We already have a.

$$h = \frac{1}{2}\frac{m}{m + M}gt^2$$

We now need t.

$$\frac{2h(M+m)}{mg} = t^2$$

$$t = \sqrt{\frac{2h(m+M)}{mg}}$$

We can use

$$v = v_0 + at$$

to find vf. We already said v0=0.

$$v_f = at = \left(\frac{m}{m+M}g\right)\left(\sqrt{\frac{2h(m+M)}{mg}}\right) = \sqrt{\frac{2hgm}{m+M}}$$

And thus we have theoretically derived our prediction.

Procedure

1. Collect materials: meter stick, lab masses on hook, string, track, video camera, tripod, computer, pulley
2. Set up track on table with pulley at one end.
3. Attach string to cart on one end and hook on the other.
4. Put cart on track and string over pulley so that hook hangs off edge of table.
5. Add mass to hook.
6. Face video camera at cart on track.
7. Let mass fall and pull cart from rest. Record motion with VideoRecorder.
8. Open MotionLab.
9. Set t=0.
10. Calibrate length.
11. Define coordinate system.
12. Predict x(t) and y(t).
13. Acquire data.
14. Fit x(t) and y(t).
15. Predict Vx(t) and Vy(t).
16. Fit Vx(t) and Vy(t).
17. Print data.
18. Repeat for new mass and height.

Data

Masses

Trial 1: 50.0+/-0.05g
Trial 2: 70.0+/-0.05g
Trial 3: 100.0+/-0.05g
Trial 4: 150.0+/-0.05g

Heights

Trial 1: 46.0+/-0.05cm
Trial 2: 41.0+/-0.05cm
Trial 3: 47.0+/-0.05cm
Trial 4: 48.0+/-0.05cm

MotionLab Fits — Accelerating Phase

Trial 1:
x(t)=0.82t2
Vx(t)=1.6t

Trial 2:

x(t)=1.08t2
Vx(t)=2.1t

Trial 3:
x(t)=1.33t2
Vx(t)=2.66t

Trial 4:
x(t)=1.65t2
Vx(t)=3.3t

MotionLab Fits — Non-accelerating Phase

Trial 1:
x(t)=1.25t
Vx(t)=1.25

Trial 2:
x(t)=1.35t
Vx(t)=1.35

Trial 3:
x(t)=1.65t
Vx(t)=1.65

Trial 4:
x(t)=1.90t
Vx(t)=1.90

Analysis

The final velocities for the assorted trials can be directly extracted from the final velocity fit functions from the MotionLab data presented in the preceding section. These give us vf=1.25m/s for Trial 1, vf=1.35m/s for Trial 2, vf=1.65m/s for Trial 3, and vf=1.90m/s for Trial 4.

We have to compare these with the results of the theoretical prediction. These give us vf=1.24m/s for Trial 1, vf=1.34m/s for Trial 2, vf=1.64m/s for Trial 3, and vf=1.94m/s for Trial 4.

The analysis in this case is trivial. The measured final velocities differ by only insignificant amounts from the theoretical final velocities. We have not yet discussed a plethora of critical sources of error in this experiment. We have assumed that the cart and the pulley are frictionless. We have also assumed that the pulley and string are massless. The track may not have been perfectly straight or level. The camera lens produced a poor image near its edges. Then there was human error. The errors were not more than 0.04m/s for any of the trials.

Conclusion

We showed in the analysis section that the deviation between empirical measurements and theoretical calculations are no more than 0.04m/s for this scenario. We also saw that the errors were not statistically significant. This proves that the prediction in Equation 13 was the physically correct one. Our experiment was therefore successful, and the launcher mechanism can be built as planned.