1102 LAB MANUAL
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Acknowledgments

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And all of the teaching assistants who helped to find the 'bugs' in these instructions.

Kenneth & Patricia Heller

WELCOME TO THE PHYSICS LABORATORY!

Physics is our human attempt to explain the workings of the world. The success of that attempt is evident in the technology of our society. The products that result from the application of that understanding surround us: technological inventions including clocks, automobiles, televisions, 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. 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. 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.

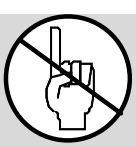
The amount you learn in lab will depend on the time you spend in preparation before coming to lab!

Before coming to lab each week you must read the appropriate sections of your text, the read assigned experiment 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 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. Please do not hesitate to discuss any difficulties with your fellow students or the lab instructor.

Relax! Don't be afraid to explore or make mistakes. **Ask lots of questions**, and have fun.

WHAT TO DO TO BE SUCCESSFUL IN THIS LAB:



Safety always comes first in any laboratory.

If in doubt about any procedure, or if it seems unsafe to you, do not continue. Ask your lab instructor for help.

A. What to bring to each laboratory session:

1. Bring an 8" by 10" graph-ruled lab journal, such as University of Minnesota 2077-S 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.

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. **Before you come to the lab, you must pass a short test covering some basic material in the textbook.**

   These lab prep-tests are on computer and are designed to take about 15 minutes to complete.

2. Each lab contains several different experimental problems. Before you come to a lab, be sure you have completed the assigned *Prediction* and *Warm-Ups*. The Warm-Ups will help you build a prediction for the given problem. It is usually helpful to answer the Warm-Ups before making the prediction. **These individual predictions will be handed in and checked (graded) by your lab instructor previous to the beginning of each lab session (your lab instructor will provide you with the exact details).**

   This preparation is crucial if you are going to get anything out of this laboratory work. There are at least two other reasons for preparing:

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

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

C. Laboratory Problem Reports

At the end of every lab (about once every two weeks) you will be assigned to write up one of the experimental problems. Your report must present a clear and accurate account of what you and your group members did, the results you obtained, and what the results mean. A report is not to be copied or fabricated. Copying someone else’s work 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**. It should describe <u>your</u> predictions, <u>your</u> experiences, <u>your</u> observations, <u>your</u> measurements, and <u>your</u> conclusions. A description of the lab report format is discussed at the end of this introduction. **Each lab report is due, without fail, within two days of the end of that lab.**

D. Attendance

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

E. Grades

Satisfactory completion of the lab is required as part of your course grade. Those not completing **all** lab assignments by the end of the semester at a 60% level or better will receive a grade of F for the **entire course**. Once again, we emphasize that **each lab report is due, without fail, within two days of the end of that lab.**

There are two parts of your grade for each laboratory: (a) your laboratory journal, and (b) your formal problem report. The lab instructor grades your laboratory journal 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 attempts but your lab report is unacceptable, your instructor may allow you to rewrite parts or all of the report. You must hand in a rewrite within two days of its return to you by the instructor, in order to obtain an acceptable grade.

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

1. **In all discussions and group work, full respect for all people is required.** All disagreements about work must stand and 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 where you learn things, and test your ideas and predictions. You learn by collecting data and determining 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 a substantial amount of thinking has gone into your ideas you simply give your best prediction or explanation as you see it. Of course, there is always the possibility that your idea does not accord with the accepted ideas. Then someone says, "No, that's not the way I see it and here's why." Eventually persuasive evidence will be offered for one viewpoint or the other.
   >
   > "Speaking out" your explanations, in writing or vocally, is one of the best ways to learn.

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

   But it is never OK to copy the work of others.

   Helping others is encouraged because it is, in fact, one of the best ways for you to learn. But copying is completely inappropriate and unacceptable. Write out your own calculations and answer questions in your own words. It is OK 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 needs to be either returned to the lab instructor, or left neatly at your station, depending on the circumstances.

   If any lab equipment is missing or broken, submit a problem report to the following email address:

   labhelp@physics.umn.edu

   Be sure to include a complete description of the problem and include the lab room number. You can also file a report containing comments about this lab manual (for example, when you discover errors or inconsistencies in statements).

In summary, the key to making any community successful 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
MECHANICAL OSCILLATIONS

Most of the laboratory problems so far have involved objects moving with constant acceleration because the total force acting on those objects was constant. In this set of laboratory problems, the total force acting on an object, and thus its acceleration, will change with position. When the position and the acceleration of an object change in a periodic manner, we say that the object undergoes oscillations.

You are familiar with many objects that oscillate, such as pendula and the strings of a guitar. At the atomic level, atoms oscillate within molecules, and molecules oscillate within solids. This molecular oscillation gives an object the internal energy that defines its temperature. Springs are a common example of objects that exert the type of force that will cause oscillatory motion.

In this lab you will study oscillatory motion caused by springs exerting a changing force on an object. You will use different methods to determine the *strength* of the total force exerted by different spring configurations, and you will investigate what determines a system's oscillation *frequency*.

OBJECTIVES:

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

- Provide a qualitative explanation of the behavior of oscillating systems using the concepts of restoring force and equilibrium position.
- Identify the physical quantities that influence the period (or frequency) of the oscillatory motion and describe this influence quantitatively.
- Describe qualitatively the effect of additional forces on an oscillator's motion.

PREPARATION:

Read Knight, Jones & Field Chapter 4.

Before coming to lab you should be able to:

- Describe the similarities and differences in the behavior of the sine and cosine functions.
- Recognize the difference between amplitude, frequency, and period for repetitive motion.
- Determine the force on an object exerted by a spring using the concept of a spring constant.

LABORATORY 1
MECHANICAL OSCILLATIONS

PROBLEM #1: MEASURING SPRING CONSTANTS

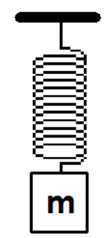
You are selecting springs for use in a large antique clock. In order to determine the force that they exert when stretched, you need to know their spring constants. One book recommends a **static approach**, in which objects of different weights hang from the spring and the displacement from equilibrium is measured. Another book suggests a **dynamic approach**, in which an object hanging from the end of a spring is set into motion and its oscillation frequency is measured. You wish to determine if these different approaches yield the same value for the spring constant. You decide to take both static and dynamic measurements and then compare.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 4 Sections 1 and 2.

EQUIPMENT

You have springs, a table clamp, rod, meterstick, stopwatch, mass set and computer. You can hang the spring from a rod that is extended from a table clamp.



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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

Method #1 (Static Approach)

1. Make two pictures of the situation, one before you attach an object to a spring, and one after an object is suspended from the spring and is at rest. Draw a coordinate system. On each picture, label the position where the spring is unstretched, the distance from the unstretched position to the stretched position, the mass of the object, and the spring constant.

2. Draw a force diagram for an object hanging from a spring at rest. Label the forces acting on the object. Use Newton's second law to write the equation of motion for the object.
3. Solve the equation of motion for the spring constant in terms of the other values in the equation. What does this tell you about the slope of a displacement (from the unstretched position) versus weight of the object graph?

Method #2 (Dynamic Approach): Suppose you hang an object from the spring, start it oscillating, and measure the *period* of oscillation.

1. Make three pictures of the oscillating system: (1) when the mass is at it maximum displacement *below* its equilibrium position, (2) after one half period, and (3) after one period. On each picture put arrows to represent the object’s velocity and acceleration.
2. Write down an equation that is the relationship between the object’s period, its mass, and the spring constant. Solve the equation for the spring constant in terms of the object’s mass and period.

PREDICTION

1. Write an expression for the relationship between the spring constant and the displacement of an object hanging from a spring.

2. Write an expression for the relationship between the spring constant and the period of oscillation of an object hanging from a spring.

EXPLORATION

DO NOT STRETCH THE SPRINGS PAST THEIR ELASTIC LIMIT (ABOUT 40 CM) OR YOU WILL DAMAGE THEM.

Method #1 - Static Approach:
Select a series of masses that give a usable range of displacements**.** The largest mass should not pull the spring past its elastic limit, for two reasons: (1) beyond the elastic limit there is no well-defined spring constant, and (2) a spring stretched beyond the elastic limit will be damaged.

Clamp the metal rod to the table, and hang the spring from the rod. Decide on a procedure that allows you to measure the distance a spring stretches when an object hangs from it in a consistent manner. Decide how many measurements you will need to make a reliable determination of the spring constant.

Method #2 - Dynamic Approach:
Secure the spring to the metal rod and select a mass that gives a regular oscillation without excessive wobbling. The largest mass you choose should not pull the spring past its elastic limit and the smallest mass should be much greater than the mass of the spring. Practice starting the mass in motion smoothly and consistently.

Decide how to measure the period of oscillation of the object-spring system most accurately. How can you minimize the uncertainty introduced by your reaction time in starting and stopping the stopwatch? How many times should you measure the period to get a reliable value? How will you determine the uncertainty in the period?

MEASUREMENT

For both methods, make the measurements that you need to determine the spring constant. **DO NOT STRETCH THE SPRINGS PAST THEIR ELASTIC LIMIT (ABOUT 40 CM) OR YOU WILL DAMAGE THEM.** Analyze your data as you go along so you can decide how many measurements you need to make to determine the spring constant accurately and reliably with each method.

ANALYSIS

Method #1: Graph displacement versus weight for the object-spring system. From the slope of this graph, calculate the value of the spring constant. Estimate the uncertainty in this measurement of the spring constant.

Method #2: Graph period versus mass for the object-spring system. If this graph is not a straight line, see the section *Using Linear Relationships to Make Graphs Clear* in the ***Graphing*** appendix to help linearize the graph. From the slope of the straight-line graph, calculate the value of the spring constant. Estimate the uncertainty in this measurement of the spring constant.

CONCLUSION

For each method, does the graph have the characteristics you predicted? How do the values of the spring constant compare between the two methods? Which method do you feel is the most reliable? Justify your answers.

PROBLEM #2: OSCILLATION FREQUENCY WITH TWO SPRINGS

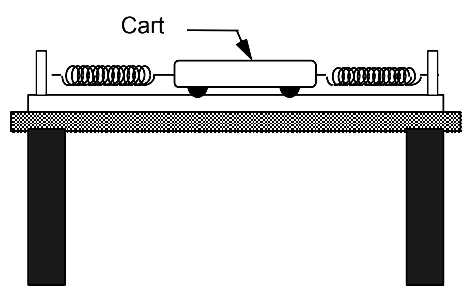
You have a summer job with a research group at the University. Because of your physics background, your supervisor asks you to design equipment to measure earthquake aftershocks. A calibration sensor needs to be isolated from the earth movements, yet it must be free to move. You decide to place the sensor on a low friction cart on a track and attach a spring to both sides of the cart. To make any quantitative measurements with the sensor you need to know the frequency of oscillation for the cart as a function of the spring constants and the mass of the cart.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 4 Sections 1 and 2.

EQUIPMENT

You have a track, two track endstops, two oscillation springs, a meterstick, stopwatch, cart and the video analysis equipment.



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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Make two pictures of the oscillating cart (1) one at its equilibrium position and (2) one at some other position and time while it is oscillating. On your pictures, show the direction of the velocity and acceleration of the cart and the forces on the cart.

2. Draw a force diagram of the oscillating cart when it is at a position away from its equilibrium position. Label the forces.

3. Write down an equation for the total force on the cart in terms of the two spring constants and its displacement from the equilibrium position.

4. Now imagine that only one spring was attached to the cart, but it exerted the same force at the same displacement as the two-spring system. How would the motion of these two systems compare? What is the relationship between the spring constant of the single spring system and the two for the two-spring system?

5. Write down an equation for the frequency of the imaginary one spring system. How does it compare with the frequency of the two-spring system?

PREDICTION

Write an expression for the frequency of the cart in terms of its mass and the two spring constants.

EXPLORATION

Decide the best method to determine the spring constants based on your results of the earlier problem **Measuring Spring Constants**.

DO NOT STRETCH THE SPRINGS PAST THEIR ELASTIC LIMIT (ABOUT 40 CM) OR YOU WILL DAMAGE THEM.

Find the best place for the adjustable end stop on the track. *Do not stretch the springs past 40 cm*, but stretch them enough so the cart oscillates smoothly. Find the most appropriate cart mass.

Practice releasing the cart smoothly. How long does it take for the oscillations to stop? What effect will this have on your measured values compared to your predicted values? How can you affect this time? What amplitude will you use to take your measurements? Between what positions should you measure a cycle? Over how many cycles should you measure to get a precise result?

MEASUREMENT

Determine the spring constants. Record these values. What is the uncertainty in these measurements?

Measure the period of oscillation for the cart. How many times should you take this measurement to be sure that it is reliable? What is the uncertainty in your measurement?

ANALYSIS

Analyze your video to find the period of oscillation. Calculate the frequency (with uncertainty) of the oscillations from your measured period. Calculate the frequency (with uncertainty) using your Prediction equation. How does your measured frequency compare with your predicted frequency?

CONCLUSION

What is the frequency of the oscillating cart? Did your measured frequency agree with your predicted frequency? Why or why not? What are the limitations on the accuracy of your measurements and analysis?

If you completed the earlier problem, **The Effective Spring Constant**: What is the effective spring constant of this configuration? How does it compare with the effective spring constants of the side-by-side and end-to-end configurations?

EXPLORATORY PROBLEM #3: DRIVEN OSCILLATIONS

You are now prepared to calibrate your seismic detector discussed in the problem **Oscillation Frequency with Two Springs**. You need to determine how the amplitude of the oscillations of the detector will vary with the frequency of the earthquake aftershocks, so you replace the end stop on the track with a device that moves the end of the spring back and forth, simulating the earth moving beneath the track. The device, called a mechanical driver, is designed so you can change the frequency of oscillation.

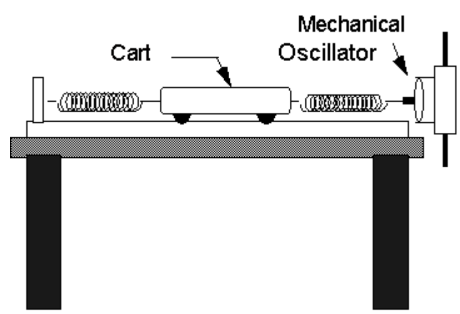
Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 4 Sections 1 to 7

EQUIPMENT

You have a track, endstop, two springs, a meterstick, stopwatch, cart, mechanical oscillator, rod, table clamp, function generator, two banana cables and the video analysis equipment.

The oscillator is connected to a function generator which allows it to oscillate back and forth with adjustable frequencies.



If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

You should follow the Warm Up for the problem **Oscillation Frequency with Two Springs** if you have not already done so.

To qualitatively decide on the behavior of the system with the mechanical oscillator attached and turned on, think about an experience you have had putting energy into an oscillating system. For example, think about pushing someone on a swing. When is the best time to push to get the maximum height for the person on the swing? How does the frequency of your push compare to the natural frequency of the person on the swing? How does the maximum height of the swinger compare to the size of your push?

PREDICTION

Make your best-guess sketch of how you think a graph of the amplitude of the cart versus the frequency of the mechanical driver will look. Assume the driver has a constant amplitude of a few millimeters.

EXPLORATION

Examine the mechanical driver. Mount it at the end of the track, using the clamp and metal rod so its shaft is aligned with the cart's motion. Connect it to the signal generator, using the output marked **Lo** (for ``low impedance''). Use the smallest amplitude that is sufficient to observe the oscillation of the cart at the lowest frequency possible.

Devise a scheme to accurately determine the amplitude of a cart on the track, and practice the technique. For each new frequency, should you restart the cart at rest?

When the driver is at or near the undriven frequency (natural frequency) of the cart-spring system, try to simultaneously observe the motion of the cart and the shaft of the driver. What is the relationship? What happens when the driver frequency is twice as large as that frequency?

MEASUREMENT

If you do not know the frequency of your system when it is not driven, determine it using the technique used in the **Oscillation Frequency with Two Springs** problem.

Collect enough cart amplitude and driver frequency data to test your prediction. Be sure to collect several data points near the undriven frequency of the system.

ANALYSIS

Make a graph the oscillation amplitude of the cart versus driver frequency.

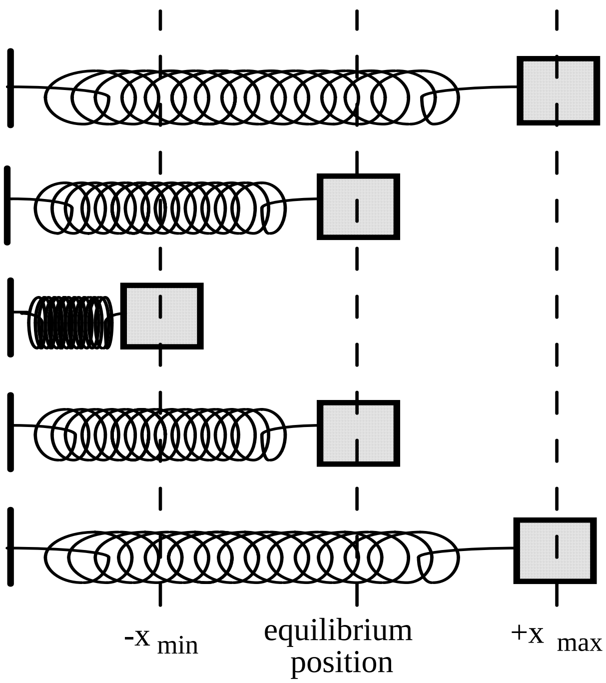
CONCLUSION

Is the graph what you had anticipated? Where is it different? Why? What are the limitations on the accuracy of your measurements and analysis?

Can you explain your results? Is energy conserved? What will you tell your boss about your design for a seismic detector?

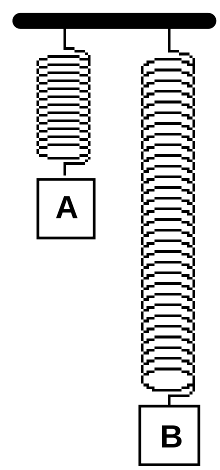
☑ CHECK YOUR UNDERSTANDING
MECHANICAL OSCILLATIONS

1. The diagram below shows an oscillating mass/spring system at times 0, T/4, T/2, 3T/4, and T, where T is the period of oscillation. For each of these times, write an expression for the displacement (x), the velocity (v), the acceleration (a), the kinetic energy (KE), and the potential energy (PE) *in terms of the amplitude of the oscillations (A), the angular velocity (w), and the spring constant (k)*.



t	x	v	a	KE	PE
0					
$\frac{T}{4}$					
$\frac{T}{2}$					
$\frac{3T}{4}$					
T					

2. Identical masses are attached to identical springs that hang vertically. The masses are pulled down and released, but mass B is pulled further down than mass A, as shown at right.



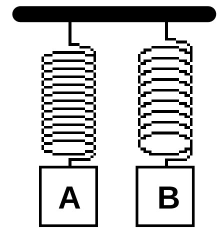
   a. Which mass will take a longer time to reach the equilibrium position? Explain.

   b. Which mass will have the greater acceleration at the instant of release, or will they have the same acceleration? Explain.

   c. Which mass will be going faster as it passes through equilibrium, or will they have the same speed? Explain.

   d. Which mass will have the greater acceleration at the equilibrium point, or will they have the same acceleration? Explain.

☑ CHECK YOUR UNDERSTANDING
MECHANICAL OSCILLATIONS



3. Two different masses are attached to different springs that hang vertically. Mass A is larger, but the period of simple harmonic motion is the same for both systems. They are pulled the same distance below their equilibrium positions and released from rest.

   a. Which spring has the greater spring constant? Explain.

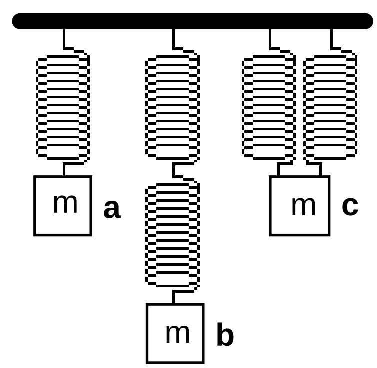
   b. Which spring is stretched more at its equilibrium position? Explain.

   c. The instant after release, which mass has the greater acceleration? Explain.

   d. If potential energy is defined to be zero at the equilibrium position for each mass, which system has the greater total energy of motion? Explain.

   e. Which mass will have the greater kinetic energy as it passes through its equilibrium position? Explain

   f. Which mass will have the greater speed as it passes through equilibrium? Explain.



4. Five identical springs and three identical masses are arranged as shown at right.

   a. Compare the stretches of the springs at equilibrium in the three cases. Explain.

   b. Which case, a, b, or c, has the greatest effective spring constant? The smallest effective spring constant? Explain.

   c. Which case would execute simple harmonic motion with the greatest period? With the least period? Explain.

Physics Lab Report Rubric

Name: ____ ID#: ______________

Course, Lab, Problem: ____

Date Performed: ____

Lab Partners' Names: ____

____

____

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			

LABORATORY 2
WAVES

Mechanical waves allow us to transfer energy from one position to another without actually moving an object between those two positions. Waves are an important part of every day experience. The gentle ripples in an ocean surface that can become pounding waves on the shore are waves. The music you hear consists of waves that are vibrations of the air. Mechanical waves govern the sounds of musical instruments, and mechanical waves carry the destructive forces of earthquakes. In this lab you will have the opportunity to explore various wave phenomena to help you organize your experiences with mechanical waves.

We will build on our experiences from the last laboratory by using springs as the medium for our waves. Anything that can vibrate, such as wires, water, molecules, and air, can carry waves. In these problems you will investigate what determines the speed of a wave, how to create wave patterns, and the relationship between wavelength, frequency, and speed for a given wave.

OBJECTIVES:

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

- Identify real systems with the mathematical description of waves.
- Identify the properties of the medium that determine the wave velocity.
- Determine the relationship between the wavelength, frequency, and speed of a wave.
- Identify the properties of a system that determine the pattern of standing waves.

PREPARATION:

Read Knight, Jones & Field, Chapter 5
Before coming to lab you should be able to:

- Use the properties of sine and cosine.
- Distinguish between frequency and period.
- Distinguish between amplitude and wavelength.
- Distinguish between transverse and longitudinal waves.
- Distinguish between standing and traveling waves.
- Define nodes and antinodes for a standing wave.

LABORATORY 2
WAVES

- Distinguish between waves and pulses.
- Use a stopwatch to determine the speed of a wave.
- Use a meter stick to determine a wavelength.

PROBLEM #1: WAVE SPEED

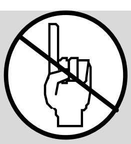
You are part of a team that is designing the power lines that bring electricity to the city from a wind farm. The specifications require that the power line supports be able to withstand the transverse and longitudinal pulses that might be caused by high winds. Pulses that travel too fast can damage the wire. You have been asked to determine how the tension of the wire affects the pulse speed. You also need to know if this effect is different for transverse and longitudinal waves. To make the waves more observable you decide to use a spring to test your ideas.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field, Chapter 5, Sections 1 & 2

EQUIPMENT

This problem is done using a tightly coiled metal spring approximately 2 meters in length. ***Do not stretch the spring past its elastic limit of 8 meters!*** You also have a meterstick, stopwatch, and force scale. Hold the stretched spring tightly. Releasing the spring quickly or unexpectedly can cause pain and injury to your partner. **Safety goggles must be worn to protect your eyes in the event of an accidental release of one end of a stretched spring. Gloves should be worn to protect your hands.**



WARNING: Never release one end of a spring that is under tension. Doing so might create a snapping motion that could injure somebody. Always release the tension slowly. **Wear** safety goggles while in the vicinity of the springs. **Wear** a glove on the hand holding the spring.

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

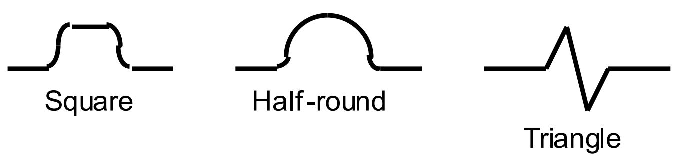
PREDICTION

How do you think the speed of a pulse depends on the tension of the spring? Make an educated guess using dimensional analysis (Hint: break the units of tension down into a combination of kilograms, meters, and seconds). Then predict which type of pulse, longitudinal or transverse, is faster on the spring.

EXPLORATION

Once your group has discussed the predictions and examined the equipment, find a good place to work with the spring. You may need to go out into the halls. Don't forget the **goggles and gloves**. Everyone must wear goggles anytime you are in the vicinity of stretched springs. Two group members will grasp the ends of the tightly coiled spring. Use the force scales to determine how the tension depends on the length of the spring. **Do not** stretch the tightly coiled spring past 8 meters.

Sit on the floor and practice making pulses of different shapes. You need to know if the pulse speed depends on its shape. Try some very different shapes. Be sure everyone in your group gets an opportunity to work with the spring. Learn how to make the following transverse pulses before continuing. Some of these shapes may require several people to make. Record in your journal what you did to make each pulse shape. Which pulse is the easiest one to make?



Observe how your wave pulse evolves with time. Discuss your observations with your partners as you work. Can you make a pulse do a round trip? Note what happens to the pulse when it is reflected from the end of the spring. If you keep the spring tension the same, does the speed depend on the pulse shape?

Practice making longitudinal pulses. Are they easier or more difficult to make than the transverse pulses?

For this part of the exploration, you will examine what the velocity of a wave means. First, you will examine the average velocity of a single coil of the spring. To help you observe the behavior of a single coil, place a flap of tape on a coil in the middle of the spring while the spring is stretched. Send a pulse down the spring and observe the motion of this piece of tape. Try a transverse pulse and a longitudinal pulse. What is the average velocity of the tape? Does the tape wiggle back and forth, or does it travel towards one end? What does this tell you about the medium of a wave and the wave itself? Record your observations and measurements in your journal.

Next you will examine how much time it takes for a pulse to travel the length of the spring. How will you know when the pulse has reached the end? Do you want to time the pulse using its front, middle, or back? How do you use this time measurement to get the velocity? How does this velocity compare to the velocity of a single coil of the spring?

What happens to the velocity of the waves if you change the amount that you stretch the spring? What happens to spring tension? Does this imply anything about your prediction? Can you explain? Try some extreme cases. **Remember: Do not stretch the coiled spring past 8 meters!**

Find a good way of timing the motion of the pulse. Be sure you have a plan that works for both longitudinal and transverse pulses. Record this plan in your journal. Rotate partners until everyone in the group has had the opportunity to make pulses and work the stopwatch.

MEASUREMENT

Collect enough data to test your predictions. Be sure to collect data at various tensions for both longitudinal and transverse pulses.

ANALYSIS

Do the necessary analysis to confirm your predictions. What are the limitations on the accuracy of your measurements and analysis?

CONCLUSION

Can you explain your results? What will you tell your supervisor about the speed of the pulses?

PROBLEM #2: STANDING WAVE PATTERNS

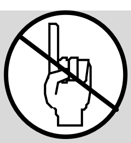
While talking to a friend on the phone you play with the telephone cord. As you shake the cord, you notice the ends of the cord are stationary while the middle of the cord vibrates back and forth; you have a standing wave. As you change the motion of your hand, a new pattern develops in which the middle of the cord is stationary while the rest of the cord vibrates wildly. You decide to investigate these standing wave patterns

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field, Chapter 5, Sections 1- 3

EQUIPMENT

This problem is done using a tightly coiled metal spring approximately 2 meters in length. ***Do not stretch the tightly coiled spring past its elastic limit of 8 meters!*** You also have a meterstick. Hold the stretched spring tightly. Releasing the spring when it is stretched can cause pain and injury to your partner. **Safety goggles must be worn to protect your eyes in the event of an accidental release of one end of a stretched spring. Gloves should be worn to protect your hands.**



WARNING: Never release one end of a spring that is under tension. Doing so might create a snapping motion that could injure somebody. Always release the tension slowly. **Wear** safety goggles while in the vicinity of the springs. **Wear** a glove on the hand holding the spring.

If equipment is missing or broken, submit a problem report by sending 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 experimental set-up. On this sketch label the directly measurable quantities and the unknown quantities.

2. From your sketch, determine the boundary conditions for the standing wave. Can the ends of the spring move?

3. Draw sketches of the three simplest standing wave patterns that are consistent with your boundary conditions. On your sketch, label the wavelength of each standing wave pattern and the length of the spring.

4. Examine your sketch for the simplest standing wave. The frequency of this wave is defined as the first harmonic. From your sketch, find an equation relating the wavelength of the standing wave to the length of the spring.

5. Examine your sketches for the other standing waves. The frequencies of these waves are called the 2^{nd} and 3^{rd} harmonics. Using your sketches, find the equations relating wavelength of the standing wave pattern to the length of the spring for each harmonic.

6. Do you see a pattern in your three equations? For an arbitrary standing wave pattern, or n^{th} harmonic, find an equation expressing the wavelength of the standing wave as a function of n and the length of the spring.

PREDICTION

Find an equation expressing the wavelength of a standing wave in terms of the standing wave pattern, or n^{th} harmonic, and the length of the spring.

EXPLORATION

Do not stretch the tightly coiled spring past its elastic limit of 8 meters!

To create standing waves on the spring, first get a feeling for how traveling waves can become standing waves. Three wave properties are important: (1) how waves travel, (2) how they are reflected at boundaries, (3) how two waves combine. You've already likely spent some time exploring the first two properties of pulses in the previous problem. You should use this experience to determine the length of the stretched spring.

To see how two traveling pulses combine, send a half-round pulse down the spring from each end. Carefully observe what happens when the two pulses meet? Are the observations easier with a slow speed or a fast speed? Draw this interaction in a series of sketches. Can you make this interaction occur so that a coil in the middle of the spring does not move? Try sending a half-round pulse down the spring and as soon as the pulse hits your partner's hand, send another one. What happened when the two pulses met? Record your results and explanations in your lab journal.

Now use your experience with traveling waves to make standing waves. Start by sending half-round pulses down the spring so that the middle of the spring does not move. Start sending more pulses down the spring in increasing rapid succession. Maintain this process until a standing wave develops on the spring.

Make other standing waves with the spring. What is the simplest pattern you can develop? What is the most complex pattern you can develop?

After each of your partners has learned how to set up standing waves, develop a measurement plan for determining the wavelength of each standing wave pattern.

MEASUREMENT

Execute your measurement plan for determining the wavelength of the standing wave for as many different patterns as you can produce with the spring. Make sure to record which harmonic, or pattern, you are examining.

ANALYSIS

For each measurement, how does the wavelength depend on the length of the spring? Use your results to determine a general relationship between the wavelength of a standing wave and the length of a spring for an arbitrary pattern.

CONCLUSION

How does the wavelength of a standing wave depend on the standing wave pattern and the length of the spring? Is this what you predicted?

PROBLEM #3: STANDING WAVE VELOCITY

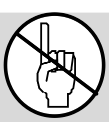
You have been working for a team that is designing the power lines that bring electricity to the city from a wind farm. The specifications require that the power line supports be able to withstand the transverse and longitudinal pulses that might be caused by high winds. Pulses that travel too fast can damage the wire. One concern you have is that standing waves might form in the power lines. Since standing waves can be created by the addition of individual pulses, you are worried that the velocities of these pulses might also add, which could damage the power line. However, your colleague tells you that the velocities of the individual pulses don't add and the velocity of the standing wave is the same as the velocity of the individual pulses. To see who is right, you decide to use a spring to test your ideas.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field, Chapter 5, Sections 1- 3

EQUIPMENT

This problem is done using a tightly coiled metal spring that has an unstretched length of about 2 meters. ***Do not stretch the tightly coiled spring past its elastic limit of 8 meters!*** You also have a meterstick, stopwatch, and a force scale. Hold the stretched spring tightly. Releasing the spring when it is stretched can cause pain and injury to your partner. **Safety goggles must be worn to protect your eyes in the unlikely event of an accidental release of one end of a stretched spring. Gloves should be worn on the hand holding the spring.**



WARNING: Never release one end of a spring that is under tension, because its snapping motion could injure somebody. Always release the tension slowly. **Wear** safety goggles while in the vicinity of the springs. **Wear** a glove on the hand holding the spring.

If equipment is missing or broken, submit a problem report by sending 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 experimental set-up. On this sketch label the directly measurable quantities and the unknown quantities.

2. From your sketch, determine the boundary conditions for the standing wave. Can the ends of the spring move?
3. Draw sketches of the three simplest standing wave patterns that are consistent with your boundary conditions. On your sketch, label the wavelength of each standing wave pattern and the length of the spring.
4. Examine your sketch for the simplest standing wave. The frequency of this wave is defined as the first harmonic. From your sketch, find an equation relating the wavelength of the standing wave to the length of the spring.

PREDICTION

Draw a graph of how the wavelength of a standing wave on the tightly coiled spring depends on the period of oscillation of your hand. What is the slope of this graph?

Using your experience from the earlier problem, **Wave Speed**, write the equation expressing the velocity of a transverse pulse as a function of the tension in a spring.

EXPLORATION

Do not stretch the tightly coiled spring past its elastic limit of 8 meters!

The exploration for this problem is very similar to the earlier problem **Standing Wave Patterns**. For help in creating standing waves on the spring, refer to the Exploration section in that problem.

Measure the tension in the spring. Make sure to keep this tension constant as you are changing the standing wave patterns.

Practice making standing waves on the spring. What is the most and the fewest nodes you can develop on the spring?

After each of your partners has learned how to set up standing waves, develop a measurement plan using the stopwatch to measure the period of oscillation of the standing wave.

Develop a measurement plan for determining the wavelength of each standing wave pattern.

MEASUREMENT

Execute your measurement plan for determining the period of oscillation and the wavelength of the standing wave for each pattern. Make sure to keep the tension in the spring the same for each pattern.

Measure all other quantities necessary to determine the velocity of a transverse pulse.

ANALYSIS

From your measurements, make a graph of how the wavelength of a standing wave on the spring depends on the period of oscillation of your hand. What does the slope of this graph represent? Compare it to your calculated value of the velocity of a transverse pulse.

CONCLUSION

Is the velocity of a standing wave the same as the velocity of a transverse pulse on a spring with a given tension? Since a standing wave doesn't exhibit longitudinal motion, what do we mean when we say "velocity of a standing wave".

PROBLEM #4: STANDING WAVES

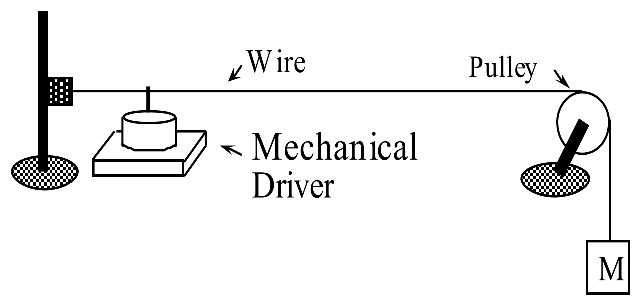
You are part of a quality control team for a factory that manufactures guitar strings. To make sure the strings are all made to the same high standard, you have decided to make a test facility that measures the harmonic frequencies (the frequencies that create standing waves) of the guitar string as a function of the string's tension. Before building the facility, you decide to set up a pattern of standing waves at known tensions for testing.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field, Chapter 5, Sections 1- 3

EQUIPMENT

You have a mechanical driver and a function generator to drive standing waves at designated frequencies on a length of wire. You have a pulley, mass set, two table clamps, rod, a wire clamp and pulley. The mechanical driver should be placed underneath the wire near the end fixed in the wire clamp.



If equipment is missing or broken, submit a problem report by sending 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 experimental set-up. On this sketch label the quantities you can measure and the unknown quantities.
2. Write down the boundary conditions for the standing wave.
3. Sketch a few of the standing wave patterns possible for your boundary conditions and determine the wavelengths of each wave pattern.
4. Use the relationship between a wave's speed, its wavelength, and its frequency. What is the relationship between the wave's frequency and the frequency of the mechanical driver?
5. How will changing the tension affect the wave's speed? How will this change in the wave's speed affect the frequency for various standing wave patterns?

PREDICTION

Calculate the wave velocity as a function of the frequency of the standing wave and other quantities you can measure in the lab using standing waves. How will changing the tension affect wave speed? How will changing tension affect the frequency of a specific standing wave?

EXPLORATION

Begin with the function generator with the power off. Connect it to the mechanical driver using the two banana-plug cables, being careful to use the black GROUND terminal and the red LOW terminal on the function generator. Make sure the mechanical driver's lock mechanism has been released. Turn the generator's amplitude all the way down.

Choose a length of wire, or check with your TA to see if your group will be assigned a particular wire. Determine the most effective way of setting up the equipment for this problem.

Decide on a comfortable range of masses that you will use. You don't want to stretch or damage the wire, but you will want a mass that will give you the sufficient tension to produce standing waves for several frequencies. If the wire is not pulled straight, or if the mass jumps around a lot when the wire is vibrating, you will need more mass to get usefully data.

Determine the range of amplitudes for the driver. Does the amplitude of the mechanical driver affect the wave speed or the standing wave pattern?

Now plan a way to drive the wire using the mechanical driver. Remember that you want the driver to interfere as little as possible with the motion of the wire. Will it be useful to alter its position for different standing wave patterns? Decide on a strategy to find the frequency values that produce standing waves.

How many nodes can you produce on the vibrating wire? How does changing the tension in the wire at a given frequency affect the number of nodes? Pull gently on the pulley end of the wire to find out. (Here you are varying the tension with your fingers.)

How many standing wave measurements will you take to confirm the validity of your prediction? What quantities will you change that affect your measurements? What quantities will you keep the same?

Record your answers to these questions, the explanations behind your answers, and your measurement plan in your journal.

MEASUREMENT

Determine the wire tension and the length of the wire. Arrange the equipment into the configuration you think will minimize the disturbance caused by the driver. Carefully tune to the lowest frequency that produces a standing wave. Raise the frequency and try other standing wave patterns.

Follow your measurement plan to acquire enough data to convincingly determine the wave speed as a function of frequency.

ANALYSIS

Using your measurements, compute the wave speed for standing waves on the wire. Do this for several different frequencies at a given tension. Do all the frequencies give the same wave speed? What is the uncertainty in your analysis and measurements? Repeat the process for enough other tensions to see the functional relationship between the frequency of specific standing waves and tension.

CONCLUSION

Were you able to determine the wave speed using a standing wave? Did wave speed depend on the number of nodes in your standing wave pattern? Did the frequencies of the standing waves depend on the tension in the wire? Did wave speed depend on the amplitude of the standing waves?

What happened to the sounds as you changed the frequency of the driver? What can you deduce about the behavior of guitar strings and the sounds they make?

☑ CHECK YOUR UNDERSTANDING
WAVES

1. A standing wave on a string can be constructed from two traveling waves that move in opposite directions. Can a traveling wave be constructed from the sum of two standing waves?

2. When transverse positive and negative pulses (that have the same symmetric shape and size but travel in opposite directions) meet, is it necessary that there be a moment when the string on which they move is flat? If so, how does the pulse "know" to continue moving on the string?

3. Explain what would happen to the lowest frequency standing wave if the tension in the wire were increased.

☑ CHECK YOUR UNDERSTANDING
WAVES

PHYSICS LAB REPORT RUBRIC

Name: ____ID#: ______________
Course, Lab, Problem: ____
Date Performed: ____
Lab Partners' Names:____
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<table>
<tr><th>Earns No Points</th><th>Earns Full Points</th><th>Possible</th><th>Earned</th></tr>
<tr><td colspan="4">Argument</td></tr>
<tr><td>no or unclear argument
logic does not flow
gaps in content
leaves reader with questions</td><td>complete, cogent, flowing argument
content, execution, analysis, conclusion all present
leaves reader satisfied</td><td></td><td></td></tr>
<tr><td colspan="4">Technical Style</td></tr>
<tr><td>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</td><td>language appropriate for scientific writing
nonverbal media present where appropriate, well-constructed, well incorporated
objective, indicative, logical style
consistent
division into sections is helpful</td><td></td><td></td></tr>
<tr><td colspan="4">Use of Physics</td></tr>
<tr><td>predictions unjustified
experiment physically unjustified
experiment tests wrong phenomenon
theory absent from consideration of premise, predictions, and results</td><td>predictions justified with physical theory
experiment is physically sound and tests phenomenon in question
results interpreted with theory to clear, appropriate conclusion</td><td></td><td></td></tr>
<tr><td colspan="4">Quantitativeness</td></tr>
<tr><td>statements are vague or arbitrary
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equations, numbers with units, uncertainties throughout
prediction confirmed or denied, result found by some form of uncertainty analysis
results, conclusions based on data</td><td></td><td></td></tr>
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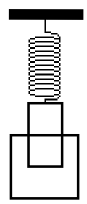
LABORATORY 3
FLUIDS

PROBLEM #1: FORCES AND LIQUIDS

While working with a sports medicine group, you are investigating the use of swimming pools for physical therapy. Being underwater gives a sense of "reduced weight", which can be useful for injured athletes who exercise in the pool as part of their rehabilitation. You know that the gravitational force on a person doesn't change as you stay on the surface of the earth, so the sense of reduced weight must result from a force exerted by the water. One of your co-workers believes that this force depends on the amount of a person's *mass* that is submerged while another claims that only the person's submerged *volume* is important. This is important because you need to know if the effect is the same for different people. To resolve this dispute, you calculate the size of this force as a function of the amount of the person's body that is underwater. Your next step is to test your calculation in the laboratory. You decide to use metal cylindrical objects hanging from a spring and measure the extension of the spring when different fractions of the object(s) are submerged in water. To see if the effect is due to volume or mass, you repeat the measurements using additional metal cylinders of the same size but different mass.

EQUIPMENT



You will have a container of water and small metal cylinders of the same volume with different masses. You will also have a spring, string, meter sticks, rulers, calipers, a balance and rods and clamps to construct a support.

WARM-UP

1. Draw a picture of the object hanging on a spring with no water involved. Indicate all the forces acting on the object. Write down the condition satisfied by the forces acting on the object. Find the relationship between the weight of the object and the extension of the spring in equilibrium.
2. Draw a picture of the object hanging on a spring, with a portion of the object submerged in water. Label all the forces acting on the object.
3. Calculate the force exerted by the water on the partially submerged object. To do so, it may help to imagine replacing the underwater volume of the object with water at equilibrium. What force must the rest of the water exert on this volume of water to maintain equilibrium? How is that related to the force exerted by the water on the submerged object?
4. Write down the conditions satisfied by the forces acting on the object immersed in water. Find the relationship between (a) the volume of the submerged portion of the object and (b) the extension of the spring.

PREDICTION

Beginning with basic physics principles, write an equation that relates the spring extension to the submerged volume and the weight. Make sure that you state any approximations or assumptions that you are making.

EXPLORATION

Decide on a procedure to measure the extension of the spring in a consistent manner. Does a single metal cylinder provide a measureable extension in and out of the water? Try using two cylinders of the same material affixed together with tape to create a longer and heavier object. Does the amount of tape used affect the results?

Decide on a procedure to change the submerged volume of the object in a measurable way.

Decide on how many measurements using different masses and submerged volumes you will need to test your prediction.

Decide how you will measure the spring constant for the spring that you use.

MEASUREMENT

Determine the spring's spring constant.

Make measurements of the masses of the object, the volume of the submerged portion, and the extension in the spring. Repeat for enough volumes (and masses) to convince others of your results.

ANALYSIS

Graph the extension of the spring versus the mass of hanging object with no water involved. For each object, graph the extension of the spring versus volume submerged. Repeat for the extension of the spring versus the submerged mass. If the graphs resemble lines, estimate their slopes and determine their physical significance, using your prediction equation as a guide. Be sure to estimate uncertainty.

CONCLUSION

What do your measurements reveal about the relationship between volume submerged and the extension of the spring? Do your measurements agree with your predictions?

How is the stretch of the spring related to an athlete's "perceived weight"? If you wished to reduce an athlete's "perceived weight" by a particular amount, what would you need to know in order to determine the appropriate depth of the pool for that person? Explain.

PHYSICS LAB REPORT RUBRIC

Name: ______________________________ ID#: ______________

Course, Lab, Problem: ______________________________

Date Performed: ______________________________

Lab Partners' Names: ______________________________

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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			

LAB 4: 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 Knight, Jones and Field Chapter 7.

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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.

LAB 4: WAVE OPTICS

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.

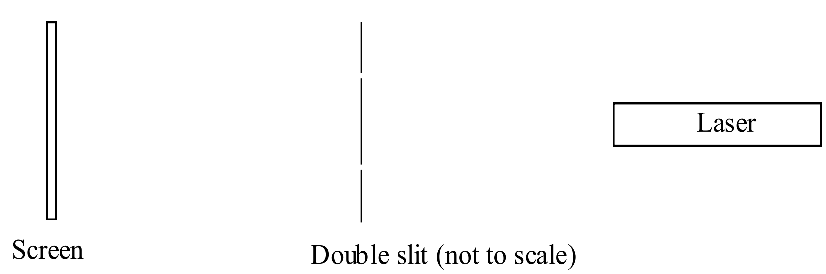
In this problem and the next, **Interference Due To A Single Slit,** you will study light interference in a simplified system to explore how these two issues can be dealt with. In this lab problem, you will investigate the interference pattern due to more than one object. In the single slit problem you 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.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones and Field Chapter 7.

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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

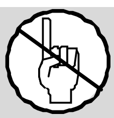
WARM UP

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.

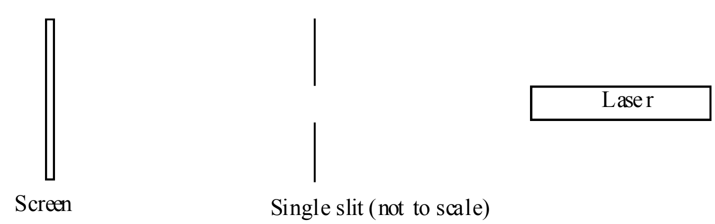
In this problem and the previous problem, **Interference Due To A Double Slit**, you study light interference in a simplified system to explore how these two issues can be dealt with. In the present lab problem, you will develop a technique for determining the size of a single object from its diffraction 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.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones and Field Chapter 7.

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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

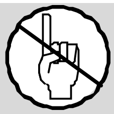
WARM UP

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.

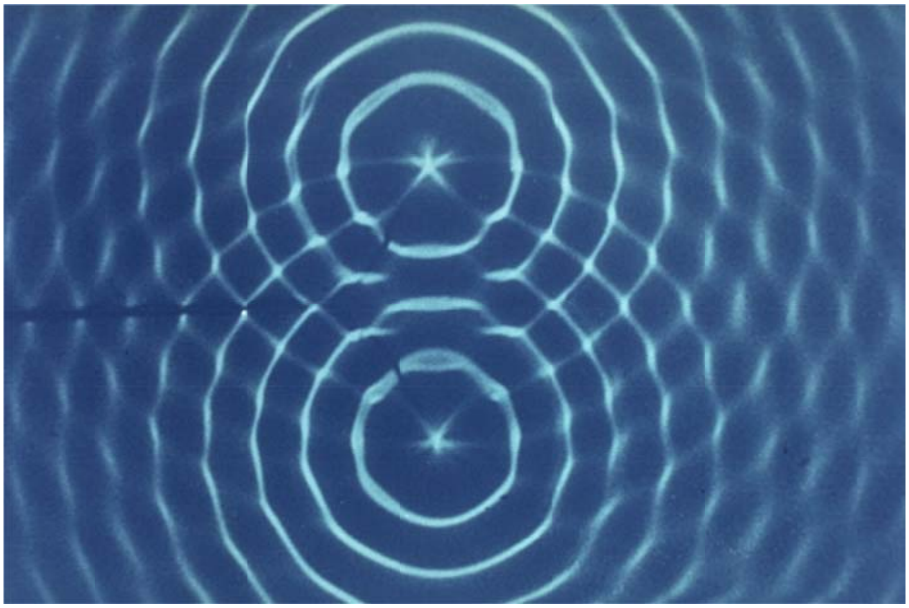
Do your observations provide evidence for the wave nature of light?

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
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?

☑ CHECK YOUR UNDERSTANDING
WAVE OPTICS

PHYSICS LAB REPORT RUBRIC

Name: ____ID#: ____________

Course, Lab, Problem: ____

Date Performed: ____

Lab Partners' Names:____

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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			

LABORATORY 5: 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:

Read Knight, Jones and Field Chapter 8.

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 5: GEOMETRIC OPTICS

PROBLEM #1: 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.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones and Field Chapter 8.

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 equipment is missing or broken, submit a problem report by sending 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 #2: 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.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones and Field Chapter 8.

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.

Read the section *Excel – MAKING GRAPHS* in the **Software** appendix. You will be using the software throughout 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 equipment is missing or broken, submit a problem report by sending 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.

IMAGE POSITION

PROBLEM #3: 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.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones and Field Chapter 8.

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 equipment is missing or broken, submit a problem report by sending 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.)

IMAGE SIZE

☑ CHECK YOUR UNDERSTANDING
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?

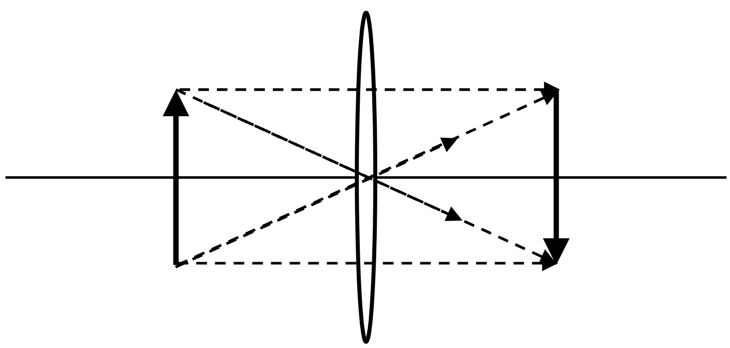
3. What would happen if the same object were located 18 cm from a converging lens with focal length 18 cm?

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

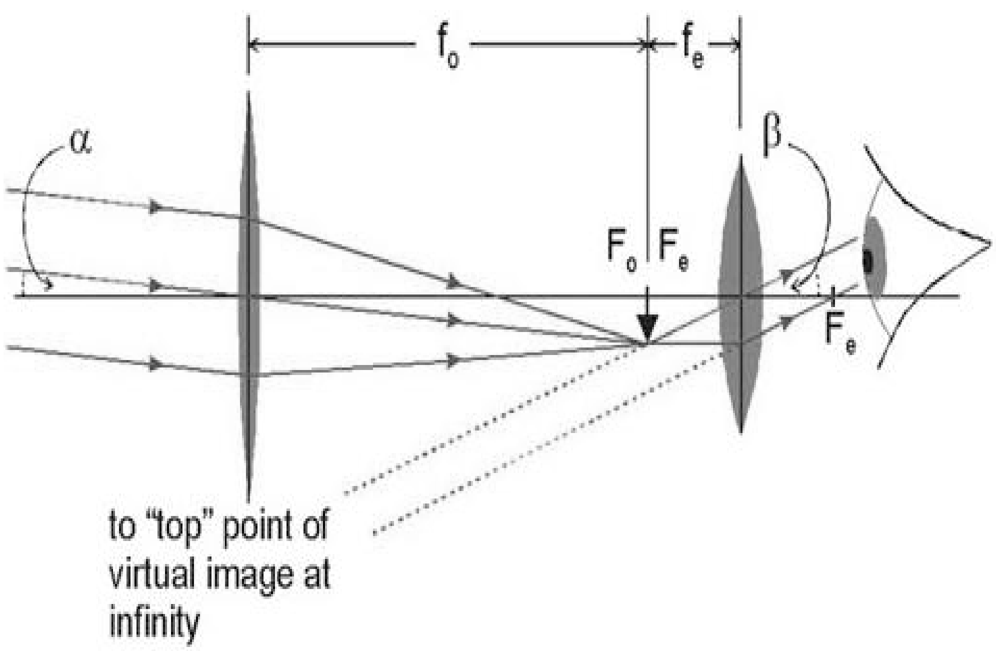
5. In any of the situations above, what would happen if the middle 2/3 of the lens were blocked?

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?



☑ CHECK YOUR UNDERSTANDING
GEOMETRIC OPTICS

Physics Lab Report Rubric

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

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			

LABORATORY 6
ELECTRIC FIELDS AND FORCES

Action-at-a-distance forces (gravitational, electric, and magnetic) make up a common part of your everyday experiences. These forces are difficult to fit into our physical intuition for two reasons. First, it is hard to conceive of objects interacting when they are not in contact. Second, objects that interact by these action-at-a-distance forces create systems that have potential energy. The question naturally arises: Where is this potential energy?

The conceptual difficulties of both the force and the potential energy for an action-at-a-distance interaction are solved through the concept of a field. Under field theory, an object affects the space around it and creates a field. Another object entering this space is affected by that field and may experience a force. The fields interact with each other, not the objects. One object causes a field and the other object's field interacts directly with the first field. When two objects interact in this way we envision the potential energy as residing in the field.

Using fields to study interactions solves the intellectual puzzle of action-at-a-distance. Field theory, however, is a much more abstract way of thinking about the world. The only reason we use field theory is 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 using the field concept to solve problems.

You will first explore electric fields by building different configurations of charged objects and mapping their electric fields in a water tray. In the final problems of this lab, you will measure the behavior of electrons as they travel through an electric field.

OBJECTIVES:

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

- Qualitatively construct the electric field based on the geometry of charged objects;
- Determine the magnitude and direction of the force on a charged particle in a given electric field.

LABORATORY 6
ELECTRIC FIELDS AND FORCES

PREPARATION:

Read Knight, Jones & Field Chapter 10. 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 of the quantities involved.

PROBLEM #1: ELECTRIC FIELD VECTORS

As part of your internship with a local computer printer company, you have been assigned to a team developing a new ink-jet printer. Your team is investigating the use of electric charge configurations to manipulate the ink particles in the printer. To help the design work, the company needs a computer program to simulate the electric field for complicated charge configurations. The lead engineer has assigned you the task of evaluating such a program. To test the program, you use it to qualitatively predict the electric field from simple charge configurations and see if it corresponds to your expectations. You form your expectations from your knowledge of the force that would be exerted on positive charge. To accomplish this task, you start with a single positive charge. You then try a single negative charge. Finally, you add them together to get a dipole configuration.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 1 – 5.

EQUIPMENT

You will use the computer application Electrostatics 3D. This program allows you to take position, potential and electric field data at any point near any given charge distribution in a 2D workspace.

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a positively charged point object.
2. At a point in space some distance from that object, imagine you have another positively charged point object. Draw a vector representing the force on that "imaginary" object.
3. Now move your "imaginary" positively charged object to another point in space and draw the vector representing the force on it. How does the magnitude of the force on the "imaginary" object depend on its distance from the original 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 original positively charged point object.

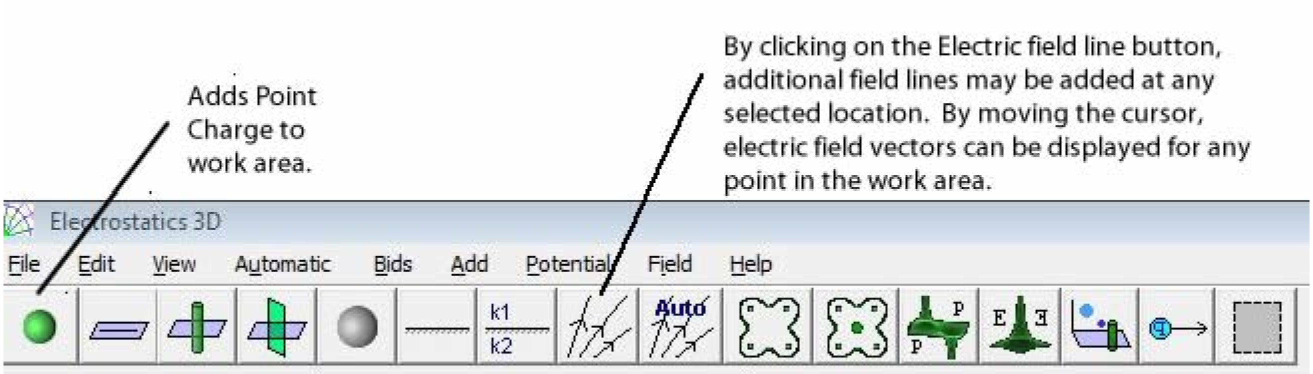
4. Repeat the above steps for a negatively charged point object and a dipole. For the dipole, remember that if two objects exert a force on a third object, the force on that third object is the **vector sum** of the forces exerted by each of the other objects.

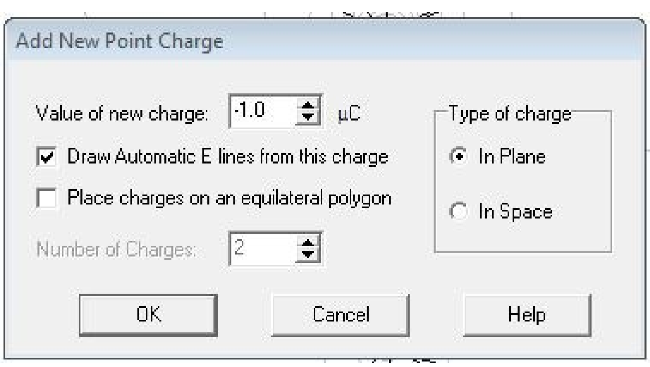
PREDICTION

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?

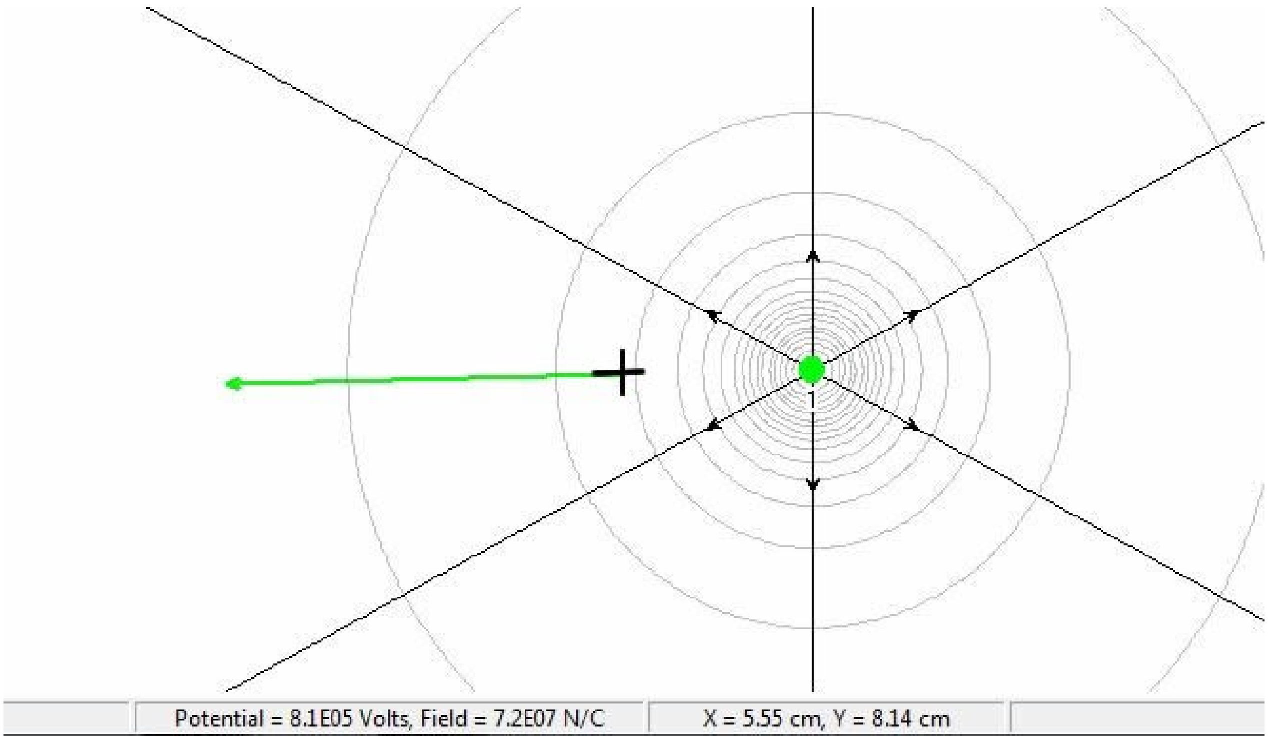
EXPLORATION

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

After you investigate an electric field map of the positively charged point object, one that is negatively charged, and the dipole, draw an electric field vector map for each case

Looking at the electric field map of your dipole, imagine a positively charged point object at the tail position of each vector. Compare the force on that "imaginary" object with the force on it if you moved it to another position. Where is the force on the "imaginary" object the greatest? The least? What would be true of the force if the "imaginary" object was negatively charged?

CONCLUSION

How does each of these maps compare with your prediction? Where is the field the strongest? How is this shown in your map? Where is the field the weakest? How is this shown in your map?

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

PROBLEM #2: THE ELECTRIC FIELD FROM A DIPOLE

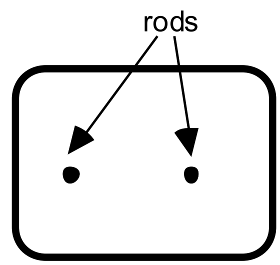
You have a summer job with a company that designs and manufactures measuring instruments for research laboratories. Your boss has asked you to test a new instrument that is designed to measure electric fields underwater. To become familiar with how it works, you decide to first use the instrument to determine the pattern of an electric field that you already know. You create a two-dimensional dipole field by giving two parallel metal points opposite charges with a battery while their ends are placed on electrostatic paper, which conducts electricity similarly to water. You then measure the electric field on the paper.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 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.



Overhead view of setup.

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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a positively charged point object.
2. At a point in space some distance from that object, imagine you have another positively charged point object. Draw a vector representing the force on that "imaginary" object.
3. Now move your "imaginary" positively charged object to another point in space and draw the vector representing the force on it. How does the magnitude of the force on

the "imaginary" object depend on its distance from the original 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 original positively charged point object.

4. Repeat the above steps for a negatively charged point object and a dipole. 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

Draw a sketch of the pattern of the electric field created in a plane perpendicular to two parallel metal rods with opposite charges. Record where you think the electric field will be the strongest, and where you think it will be the weakest.

When you get to lab, check your sketch by making a field map of *2D charged rods* using the **Electrostatics 3D** application, instructions for using it are in the earlier problem, **Electric Field Vectors**.

EXPLORATION

Remember that the purpose of this problem is to become familiar with both (a) the electric field on the electrostatic paper and (b) the electric field probe. Start by setting up the electrostatic paper as instructed in the appendix. With the rods are connected to the battery, set the digital multi-meter (DMM) to the "volts" setting. Place the tips of the probe on the paper midway between the tips of the two rods. Rotate the probe so the center of the probe stays in the same spot. Record the meter readings at various orientations as you rotate. Do the values change? Is there a minimum or maximum value? Are there any symmetries in this data?

The DMM displays the largest value when the electric field on the paper at that position is parallel to the imaginary line that connects the two probe tips. If the value on the display is negative, the electric field is in the opposite direction as when it is positive. Using the data you have already collected, determine the direction of the electric field at the point midway between the two electrodes? Is this the direction you expected? Why?

Now place the field probe near, but not touching, one of the rods and rotate the probe through a range as you did before. Record your data. Determine the direction of the electric field. Compare the value you found at the midway point to that near an electrode when the probe is aligned with the electric field.

The value displayed on the DMM is larger for a stronger electric field. Where is the electric field on the paper the strongest? Is this where you expected it to be? Why?

MEASUREMENT

Select a point in the electrostatic paper where you wish to determine the electric field. Place the probe on the paper at that point and rotate until you have found the direction of the electric field. Record the magnitude and direction of the field at that point by drawing a vector in your lab journal (the length of the vector proportional to the value displayed on the DMM).

Repeat for as many points as you need to accurately map the electric field to check your prediction. When you have taken enough data, your finished product is a map of the electric field.

CONCLUSION

How does your map compare to your prediction? Where is the field the strongest? How is this shown in your map? Where is the field the weakest? How is this shown in your map?

PROBLEM #3: THE ELECTRIC FIELD FROM PARALLEL CHARGED PLATES

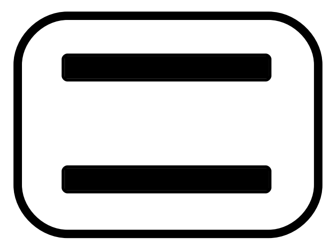
The research laboratory that you are working in is designing an electrostatic deflector for an air purification system. Your supervisor has assumed that the electric field between two charged plates is constant and always perpendicular with the surface of the plates. Every other electric field you know weakens as you move further away from the charged surface. You decide to test this assumption by mapping the electric field between two parallel plates using electrostatic paper.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 1 –5.

EQUIPMENT

You have electrostatic paper, two brass rods (to serve as electrodes), two brass plates, 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.



Overhead view of setup.

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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw a horizontal plate as made up of a line of point charges.

2. Qualitatively determine the electric field at some point above that line of charges by adding together the contributions at that point due to all of the charges' electric fields. One way to do this is to start with one charge and draw the electric field vector at some point above it. Note the direction of the electric field. Now add a charge at an equal distance on each side of the original charge. At the point of interest draw the electric field vector from all three charges. From your drawing get the sum of these vectors and note its direction. Continue by adding two more charges to each end of the line and repeat the vector sum. What do you think will be the direction of the electric field as you add a very large number of charges in this way?

3. If the line of charges is infinite, the procedure in step 2 will give you the direction of the field at every point above the plate. What does this tell you about the direction of the electric field at every point above or below the infinite plate?
4. Now sketch the situation for two parallel plates with opposite charge. At a point between them draw the electric field vector from each plate and add them. Repeat for a selection of points between the two plates.
5. Repeat step 4 for the regions outside the plates.

PREDICTION

Make a sketch of the electric field pattern for the charge configuration on the electrostatic paper. Label areas where you expect the field to be strongest and where it should be weakest. Is there an area where the field is relatively constant?

When you get to lab, use the Electrostatics 3D simulation to check your sketch of the electric field between two parallel plates.

EXPLORATION

Review your journal or read the appendix to familiarize yourself with how to use the electrostatic paper and DMM.

Place the two slender metal plates on the paper and place a brass electrode on each. Then connect one electrode to each terminal of a battery or power supply.

How should you determine how far apart the plates should be? How many data points do you need between the plates? How many do you need outside the plates? Do the plates need to be perfectly parallel?

Outline your measurement plan.

MEASUREMENT

Map the electric field on the paper from two opposite-charged parallel plates. Your map should show both the magnitude and direction of the electric field. Be sure you map the field outside the plates as well as between the plates.

CONCLUSION

How does the map of the electric field compare to your prediction? Why? Is your supervisor's assumption that the electric field between the plates is constant justified? Is there a region in which the assumption is not valid? If you are very close to a charged surface, what is the direction of the electric field relative to that surface?

PROBLEM #4: GRAVITATIONAL FORCE ON THE ELECTRON

You are working in a research laboratory that is attempting to make a better electron microscope. The key to advancing the project is the precise control of a beam of electrons. To study this, you decide to use a cathode ray tube (CRT); cathode ray tubes where the basis of older TV sets and computer screens. In a 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 (you see them glow).

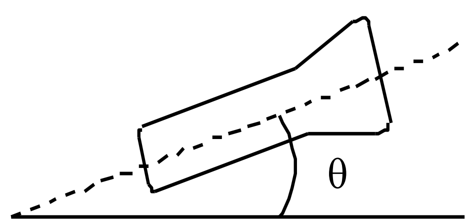
You know that every object in flight near the Earth's surface is subject to the gravitational force. From your physics experience you also know that the acceleration of all objects in free fall is the same, independent of their mass. Even though an electron has a small mass, it has the same gravitational acceleration as a baseball or a bullet. You worry that the gravitational force will deflect the electron from its path giving it the parabolic trajectory that you studied in the first term of physics.

Instructions: <u>Before lab</u>, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. <u>During lab</u>, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 1 – 5 & 7. Review the chapters on Motion in Two Dimensions and refresh your knowledge of projectile motion.

EQUIPMENT

You are using the Cathode Ray Tube. The fluorescent screen has a half centimeter grid in front of it so you can measure the position of the beam spot. Along with the CRT you will need several banana cables and a Cenco CRT power supply.



Read the sections *Cathode Ray Tube (CRT) and Accessories* and *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

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

If equipment is missing or broken, submit a problem report by sending 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 CRT in the horizontal position. Be sure to include all components as shown in the ***Equipment*** appendix in your sketch, except the deflection plates, because you will not use them in this problem. Make sure that you understand the function of all of the parts.
2. Draw the electron's path from the time it leaves the electron gun until it hits the screen. Label all of the important kinematic quantities in the problem. The target quantity for this problem is the electron beam deflection at the screen. The quantities that you can measure in this problem are

   (a) the position of the electron beam spot on the fluorescent screen,

   (b) the initial electron accelerating voltage (V_{acc} in your sketch),

   (c) the distance from the end of the electron gun to the CRT screen, and

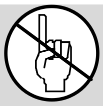
   (d) the angle the CRT makes with the horizontal.
3. In this projectile motion problem, you know the electron's acceleration and you need to find its initial velocity. How much potential energy does an electron have when it first enters the acceleration plates given a voltage across the plates of V_{acc} ? Use conservation of energy to find how much kinetic energy the electron has upon leaving the acceleration plates. Given this kinetic energy, what is the electrons velocity? Assume that the direction of the electron leaving the electron gun region of the CRT is along the central axis of the tube.
4. Using the velocity of the electron and the kinematics of a projectile fired horizontally under the influence of gravity to determine how far the electrons fall as they travel down the length of the horizontal CRT.

PREDICTION

Calculate how far an electron falls during its flight within the CRT when the CRT is *horizontal* ($\theta = 0^o$), as a function of the initial velocity of the electron. Assume that the initial velocity is along the central axis of the CRT.

Based on your knowledge of kinematics, predict if this electron deflection (distance from the center of the CRT at the screen) will increase, decrease or stay the same as the angle is increased from horizontal ($\theta = 0^o$) to vertical ($\theta = 90^o$). Make a graph of the electron deflection-versus-angle of incline of the CRT from the horizontal. 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 one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

Read the ***Equipment*** appendix for connecting the Cenco power-supply to the CRT. *Before* you turn the power supply on, make sure to check that the connections are correct. You should have between 250 and 500 volts of electric potential between the cathode and anode. After a moment, you should see a spot that you can adjust with the knob labeled “focus”. If your connections are correct and the spot still does not appear, inform your lab instructor.

Do you expect the gravitational deflection to vary as a function of the angle of the CRT with the horizontal? Try different orientations to see if you can observe any difference.

For what orientation of the CRT can you find the 'zero deflection' position? This is the location of the beam spot when there is no gravitational effect on the motion of the electrons.

Devise a measuring scheme to record the angle of the CRT and the position of the beam spot and complete your measurement plan.

MEASUREMENT

Measure the position of the beam spot with the change in angle. Try to get as many different measurements as you can as you change the CRT’s angle from 0 to 90˚

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

ANALYSIS

Use your data to graph the position of the electron beam spot versus the angle the CRT makes with the horizontal.

If you observe a deflection, how can you tell if the gravitational force causes it? What else could cause a deflection?

CONCLUSION

Does the Earth's gravitational force affect the motion of the electrons in the CRT in a measurable way? When you deflect the electron beam by an electric field what correction will you need to apply to account for the gravitational field?

Did your data agree with your predictions? Did you observe any deflection of the electron beam? Was it in the direction you expected? Was it bigger or smaller than you expected? What could account for any unusual behavior?

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

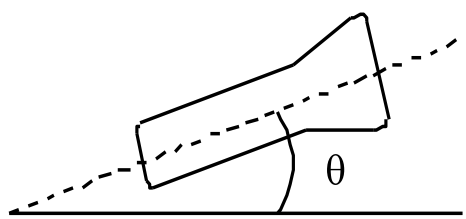
You have been attempting to design a better electron microscope. To precisely control the beam of electrons you will use electric fields in the two directions perpendicular to the original direction of the electrons. For your study of electron control you decide to use a Cathode Ray Tube (CRT) in which the electron passes between one set of parallel plates in the horizontal direction and another set in the vertical direction. 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. The electric fields should be sufficient to sweep the electron beam completely across the screen. Before you can test the sensitivity of the electron microscope design, you will need to determine how an applied electric field affects the position of the beam spot.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 1 – 5 & 7. Review the chapters on Motion in Two Dimensions and refresh your knowledge of projectile motion.

EQUIPMENT

You are using the Cathode Ray Tube. The fluorescent screen has a half centimeter grid in front of it so you can measure the position of the beam spot. Along with the CRT you have several banana cables, a Cenco CRT power supply, an 18volt/ 5amp power supply and a Digital Multimeter (DMM.)



Note: the 18volt/5amp power supply should be used for the deflection plates, many of the Cenco CRT power supplies 0-5 volt outputs are not reliable.

Read the sections *Cathode Ray Tube (CRT) and Accessories* and *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

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

If equipment is missing or broken, submit a problem report by sending 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 pertinent components of the CRT. Only include one set of the deflecting plates shown in Appendix A. Draw a coordinate axis on this picture. Draw the electron trajectory. On the trajectory, draw and label arrows representing the electron's velocity and acceleration in each region of the CRT.
2. Where in your picture will an electron experience an acceleration? What force causes this acceleration? Draw an arrow representing the force on your picture. What forces are you assuming are negligible? In the region of acceleration, make a motion diagram showing the electron's trajectory and showing the electron's velocity and acceleration when the electron enters the region, is in the region, and leaves the region.
3. Write an expression for the velocity of the electrons as they leave the electron gun in the CRT, in terms of the accelerating voltage.
4. Determine how much the electron beam is deflected as it travels perpendicular to the electric field between the deflecting plates (that are set to a voltage V_y).

   Write down a relationship between electric field and the force on the electron. How are force and acceleration related? Is the acceleration constant as the electron travels between the two plates?

   Note: The electric field between two equally charged parallel plates is equal to the voltage between the two plates (V_y, in Volts) divided by the distance between the plates (in meters).

   Write down the equation giving the electron's position as it emerges from the deflecting plates. Write another equation giving the electron's direction.

   Note: If the acceleration is constant, then the electron follows a projectile path even if the acceleration is not from gravity.
5. Draw the electron's trajectory from the time it leaves the deflecting plates until it strikes the screen. In this region, is the electron accelerating? If so, what force(s) cause this acceleration? What forces can you assume are negligible, if any? Use some geometry to write an equation giving the distance from the center the electron strikes the screen. This is the deflection.
6. Write down an equation giving the deflection of an electron from question 5. Determine the quantities that are known and those that are unknown. Write down the equation(s) from question 4 you could use to solve for the unknown(s). If there are any additional unknowns, write down the equation from question 2 that you could use to solve for one of them. If you have an independent equation for each unknown, you can solve the problem. If not review your pictures to see if you can extract any additional information to write down equations for any unknowns not accounted for in the above procedure.
7. Use your equation to sketch a graph of position of the beam spot versus the applied electric field.

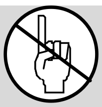
PREDICTION

Calculate how the deflection of the electron spot depends on the electric field between the horizontal deflection plates. Repeat for the vertical deflection plates.

Use this equation to make a graph of deflection versus applied electric field strength for each set of deflection plates.

EXPLORATION

This exploration is similar to that for the earlier problem Gravitational Force on the Electron. If you have already completed that problem, consult your lab journal for the necessary information.



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 one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

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

Before you turn on the electric field between the deflection plates, find the CRT orientation that gives no deflection of the electron beam. In this position the effect of all of the outside forces on the electron is negligible.

Now slowly apply a voltage across one set of deflection plates. Note how the electron beam moves across the screen as the voltage is increased. 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?

Complete your measurement plan.

MEASUREMENT

Measure the position of the beam spot as you change the electric field applied to the deflection plates.

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

ANALYSIS

Draw a graph of your Prediction equation of the deflection of the electron beam as a function of the applied electric field.

Draw a graph using your measurements of the deflection of the electron beam as a function of the applied electric field.

CONCLUSION

How does the graph based on your data compare to the graph based on your prediction? How does the deflection of the electron beam vary with the applied electric field? Did your data agree with your prediction of how the electron beam would deflect due to the applied electric field? If not, why?

PROBLEM #6: DEFLECTION OF AN ELECTRON BEAM AND VELOCITY

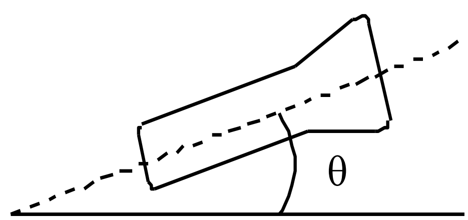
You have been attempting to design a better electron microscope. To precisely control the beam of electrons you will use electric fields in the two directions perpendicular to the original direction of the electrons. For your study of electron control you decide to use a Cathode Ray Tube (CRT) in which the electron passes between one set of parallel plates in the horizontal direction and another set in the vertical direction. 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. The electric fields should be sufficient to sweep the electron beam completely across the screen. Before you can test the sensitivity of the electron microscope design, you will need to determine how the velocity of the electron leaving the electron gun region of the CRT affects the position of the beam spot.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 10, Sections 1 – 5 & 7. Review the chapters on Motion in Two Dimensions and refresh your knowledge of projectile motion.

EQUIPMENT

You are using the Cathode Ray Tube. The fluorescent screen has a half centimeter grid in front of it so you can measure the position of the beam spot. Along with the CRT you have several banana cables, a Cenco CRT power supply, an 18volt/ 5amp power supply and a Digital Multimeter (DMM.)



Note: the 18volt/5amp power supply should be used for the deflection plates, many of the Cenco CRT power supplies 0-5 volt outputs are not reliable.

Read the sections *Cathode Ray Tube (CRT) and Accessories* and *The Digital Multimeter (DMM)* in the ***Equipment*** appendix.

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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

This problem is similar to what you did in the earlier problem, **Deflection of an Electron Beam by an Electric Force**. This time, you can treat the electric field between the deflection plates as a "known" quantity and the velocity of the electron entering the deflection plates as an "unknown". You might use your answers to that problem to help with the following questions:

1. Draw a picture of the pertinent components of the CRT. Only include one set of the deflecting plates shown in Appendix A. Draw a coordinate axis on this picture. Draw the electron trajectory. On the trajectory, draw and label arrows representing the electron's velocity and acceleration in each region of the CRT.

2. Where in your picture will an electron experience acceleration? What force causes this acceleration? Draw an arrow representing the force on your picture. What forces are you assuming are negligible? In the region of acceleration, make a motion diagram showing the electron's trajectory and showing the electron's velocity and acceleration when the electron enters the region, is in the region, and leaves the region.

3. Write an expression for the velocity of the electrons as they leave the electron gun in the CRT in terms of the accelerating voltage.

4. Determine how much the electron beam is deflected as it travels perpendicular to the electric field between the deflecting plates (that are set to a voltage V_y). Write down a relationship between electric field and the force on the electron. How are force and acceleration related? Is the acceleration constant as the electron travels between the two plates?

Note: If the acceleration is constant, then the electron follows a projectile path even if the acceleration is not from gravity.

Write down the equation giving the electron's position as it emerges from the deflecting plates. Write another equation giving the electron's direction. Note: The electric field between two equally charged parallel plates is equal to the voltage between the two plates (V_y, in Volts) divided by the distance between the plates (in meters).

5. Draw the electron's trajectory from the time it leaves the deflecting plates until it strikes the screen. In this region, is the electron accelerating? If so, what force(s) cause this acceleration? What forces can you assume are negligible, if any? Use some geometry to write an equation giving the distance from the center the electron strikes the screen. This is the deflection.

6. Write down an equation giving the deflection of an electron from question 5. Determine the quantities that are known and those that are unknown. Write down the equation(s) from question 4 you could use to solve for the unknown(s). If there are any additional unknowns, write down the equation from question 2 that you could use to solve for one of them. If you have an independent equation for each unknown, you can solve the problem. If not review your pictures to see if you can extract any additional information to write down equations for any unknowns not accounted for in the above procedure.

7. Use your equation to sketch the graph of position of the beam spot versus the initial electron velocity.

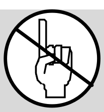
PREDICTION

Determine the change in position of the electron beam as a function of initial electron velocity.

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

EXPLORATION

This exploration is very similar to that of the earlier problem, **Deflection of an Electron Beam by an Electric Force**. If you have already completed that problem, consult your lab journal for most of the necessary information.



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 one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

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

Before you turn on the electric field between the deflection plates, find the CRT orientation that gives no deflection of the electron beam. In this position the effect of all of the outside forces on the electron is negligible.

Now slowly turn apply a voltage across one set of deflection plates. Note how the electron beam moves across the screen as the voltage is increased. Determine a voltage which gives a deflection about half of maximum measurable deflection. Repeat this procedure for the perpendicular set of deflection plates.

The electric field 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).

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

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 electron's velocity entering the deflection plates? What quantities will you hold constant for this measurement? How many measurements do you need? Complete your measurement plan.

MEASUREMENT

Measure the position of the beam spot as you change the initial velocity of the electron entering the deflection plates.

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

ANALYSIS

Draw a graph of your Prediction equation for the deflection of the electron beam as a function of the initial electron velocity.

On the same graph, draw your measurements of the deflection of the electron beam as a function of the initial electron velocity.

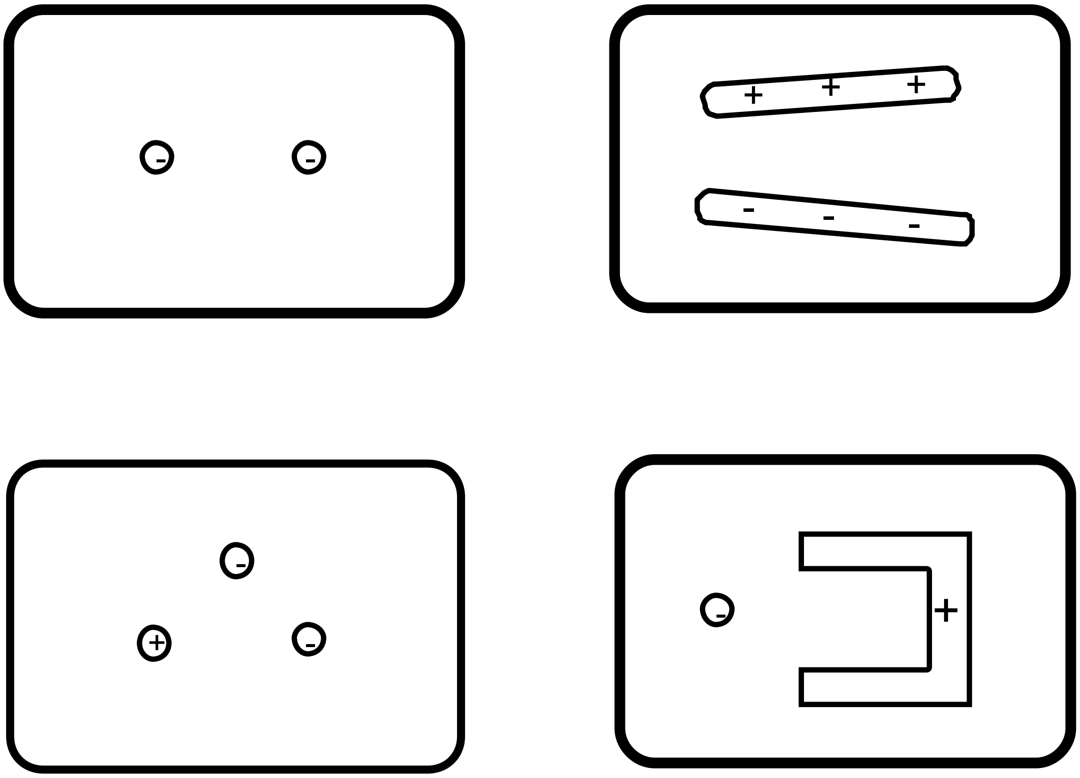
CONCLUSION

How does the graph based on your data compare to the graph based on your prediction? How does the deflection of the electron beam vary with initial electron velocity? State your results in the most general terms supported by your data.

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

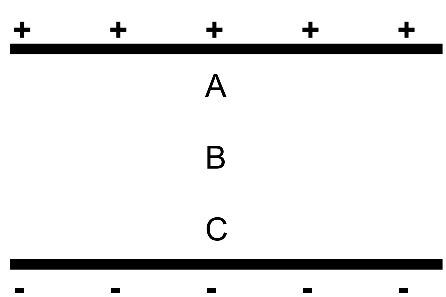
☑CHECK YOUR UNDERSTANDING
ELECTRIC FIELDS AND FORCES

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.



F_A F_B F_C

☑CHECK YOUR UNDERSTANDING
ELECTRIC FIELDS AND FORCES

PHYSICS LAB REPORT RUBRIC

Name: ____ID#: ______________
Course, Lab, Problem: ____
Date Performed: ____
Lab Partners' Names:____
____
____

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			

LABORATORY 7
ELECTRIC CIRCUITS

Electrical devices are the cornerstones of our modern world. We depend on them for almost every aspect of our lives, so it is important to gain a basic understanding of them.

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

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

OBJECTIVES:

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

- apply the concept of circuit to any electrical system;
- apply the concept of conservation of charge to determine the behavior of the electrical current through any part of a circuit;
- apply the concept of conservation of energy to determine the behavior of the energy output of any element in a circuit;
- use the concept of electrical potential to describe the behavior of a circuit;
- relate the electric charge on a circuit element to the potential difference across that element and the capacitance of that element;
- relate the electric current through a circuit element to the resistance of that element and potential difference across that element;
- measure the current through a circuit element with a digital multi-meter (DMM);
- measure the voltage between two points in a circuit with a DMM; and
- measure the resistance of a circuit element with a DMM.

LABORATORY 7
ELECTRIC CIRCUITS

PREPARATION:

Read Knight, Jones & Field Chapters 12 and 13.

- Describe the relationship between charge and current.
- Describe the relationship between potential and potential energy.
- Describe the essential difference between an insulator and a conductor.
- Identify what is an electrical circuit and what is not.
- Apply conservation of energy and conservation of charge to current flowing around a circuit.
- Write down Ohm's law and know when to apply it.
- Describe the difference between a capacitor, a resistor, and a battery.
- Use a DMM to measure potential difference, current, and resistance.

PROBLEM #1: BASIC CIRCUITS

You need more light in your workroom, so you decide to add an additional light fixture to your track lighting. However, you are concerned that adding another light may dim the lights that already are in the track. When you proceed with the addition of another light, you notice that none of the lights are dimmer then before. You wonder what type of circuit your track lighting uses. So, you decide to build a model of circuits using two bulbs and compare the brightness of the bulbs in these circuits to a circuit with a single bulb. You know that the circuit where bulbs are as bright as your reference circuit is equivalent to the circuit that your track lighting uses.

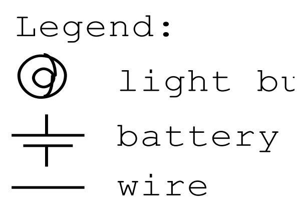
Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

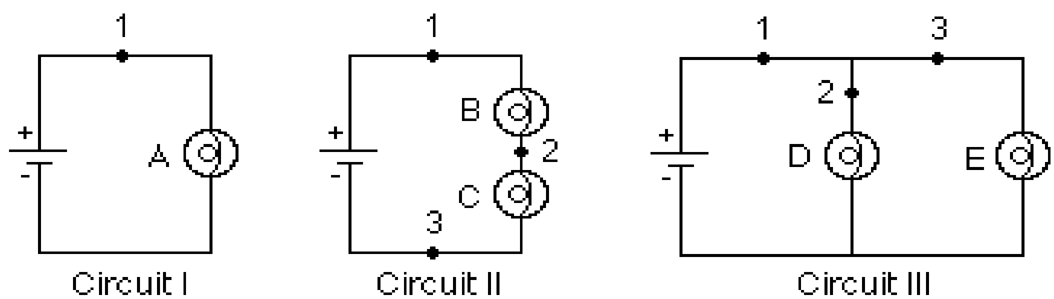
Read Knight, Jones & Field Chapters 12, Section 5 and Chapter 13, Sections 1, 3 & 4

EQUIPMENT

You will build three 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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Consider Circuit I. Assume a constant value for the resistance of A. What is the voltage across A? What is the current through A? Which of these values will determine the brightness of A?
2. Consider Circuit II. Assume that light bulbs B and C have the same resistance as A (this is not entirely true, but it is an approximation that will lead you to the correct answer. Problem 4 will show you more about the resistance of a light bulb). How do resistors in series add up? Find the voltage and current for each bulb. How will the brightness of these bulbs compare with A?
3. Consider Circuit III. Assume that light bulbs D and E have the same resistance as A. How do resistors in parallel add up? Find the voltage and current for each bulb. How will the brightness of these bulbs compare with those in the previous two circuits?

PREDICTION

Rank the order the brightness of 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. Are there any other two bulb circuits that are different then Circuit II or Circuit III? If yes, draw them. If no, explain why.

EXPLORATION

Familiarize yourself with the equipment. If you have trouble setting up the drawn circuits, consult another group or your instructor.

Test all of your batteries and bulbs. Light a single bulb with a single battery using the simplest possible circuit: <u>one</u> battery, <u>one</u> bulb (that is not in its socket), and <u>one</u> wire. How many different configurations can you find that light the bulb? If you find a configuration that works, would it still work if you reversed how the poles of the battery were connected? Try it.

Look closely at the inside of a light bulb. Draw a picture of what you see. Also draw how you think the inside structure of the light bulb is connected to the outside. Write down your reasons. If the bulb does not light, can you tell what is wrong? Is the battery dead, the bulb burned out, or the circuit connected incorrectly?

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

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? Pay attention to large differences you may observe, rather than minor differences that may occur if two "identical" bulbs are not exactly identical. How can you test whether minor differences are due to manufacturing irregularities? Is more current going through the first bulb than going through the second, 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 is this related to conservation of charge?

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 the two circuits?

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 of Circuit II compared to the current at point 1 of Circuit I? What do you think would happen to the brightness of the bulbs B and C if you added another bulb in the same row? Try it and find out. Can you explain your observations?

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 is this related to the conservation of charge?

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 Circuit III compared to the current at point 1 in Circuit I?

Comparing the three circuits, does the amount of current at point 1 appear to depend on the number of bulbs in the circuit and how they are related? What do you think would happen to the brightness of bulbs D and E if you added another bulb in parallel to them? Try it. Can you explain your observations?

CONCLUSION

Rank order brightness of the bulbs. How did this compare to your prediction? What is the circuit that corresponds to your track lighting? Circuit II is called a "series circuit" and Circuit III is called a "parallel circuit". What does a battery do for a circuit? Does the battery supply a constant current to all circuits? Does the battery supply a constant energy to all circuits? Does the battery supply a constant potential difference to all circuits? Use your observations about bulb brightness to explain your answers.

Check your conclusions about current by using a digital multi-meter (DMM) to directly measure the currents through parts of the circuits. Read the ***Equipment*** appendix and become familiar with how to measure current with a digital multi-meter. Try measuring the current at point 1 in Circuit I. Did the bulb remain lit while you were measuring the current? Did the brightness of the bulb change when you began measuring the current. What happens if you choose a different scale on the DMM? (In other words, what happens if you turn the dial? Make sure you stay on the current measuring parts of the dial.)

Measure the current through points 1, 2 and 3 in Circuit II. Do the same measurement for Circuit III. Do these measurements agree with your conclusions based on bulb brightness?

Check your conclusions about potential difference by using a digital multi-meter (DMM) to directly measure the potential difference across parts of the circuits. Read Appendix A and become familiar with how to measure the potential difference across a circuit element using a DMM. Measure the potential difference across the two poles of the battery in Circuit I with the DMM. Did the bulb remain lit while you were measuring the current? Did the brightness of the bulb change when you began measuring the current? Try changing the scale of the DMM by turning the dial. Make sure you stay on the voltage measuring parts of the dial! What happens? Measure the potential difference across the poles of the battery when it is not connected to anything. How does that compare to circuit I?

For Circuit I measure the potential difference across the battery and bulb A. What is the uncertainty in your measurement? In Circuit II and III measure the potential difference across the battery and across each bulb. Do these measurements agree with your conclusions based on bulb brightness?

PROBLEM #2: MORE COMPLEX CIRCUITS

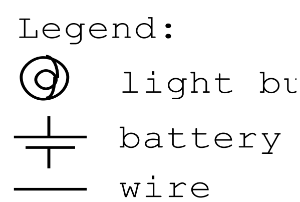
It is the holiday season once again and you decide to put up your decorations. You have three strings of decorative lights. To have enough lights in a row, you will need to connect two of your light strings together end to end. The other set of lights will be enough to light up your doorway. You know that you have a few different ways of connecting the light strings. However, you want to connect them so that they are as bright as possible. Before you begin the long process of decorating, you want to make sure that you are using the right set-up to get the brightest lights. So you build a reference circuit and a model of the possible ways of hooking up the sets of lights in order to determine which gives the most light. In your model one light bulb represents a light string.

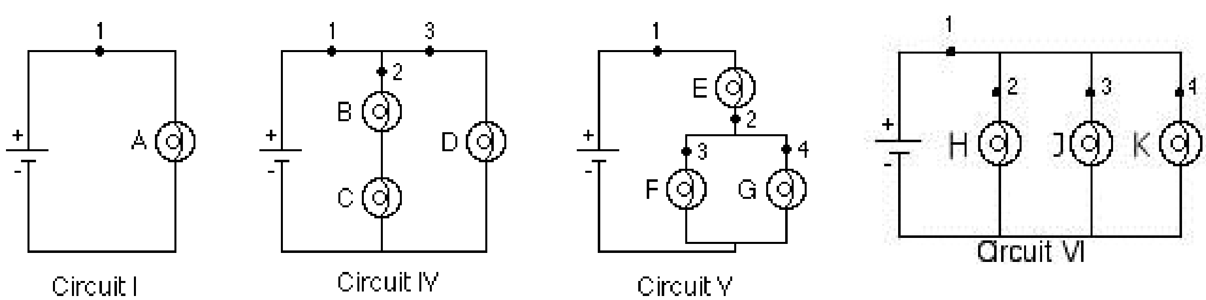
Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapters 12 , Section 5 and Chapter 13, Sections 1-5.

EQUIPMENT

You will build the circuits shown below out of wires, light bulbs, and batteries. Use the accompanying legend to help you 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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Consider Circuit I. Assume a constant value for the resistance of A. What is the voltage across A? What is the current through A? Which of these values will determine the brightness of A?
2. For the rest of the circuits, assume that the resistance of each bulb is the same as that of A (this is not entirely true, but it is an approximation that will lead you to the correct answer. The problem ***Resistors and Light Bulbs*** will explore more about the resistance of a light bulb). In each circuit decide which bulbs are in parallel and which are in series. Using your knowledge of how resistors add up, find the total current flowing through the circuit. Then, using conservation of current and Ohm's law, decide how much current is flowing through each bulb. Compare the current flowing through each bulb to that of A. How does this reflect the bulbs brightness in comparison to A?

PREDICTION

Order the brightness of the bulbs A, B, C, D, E, F, G, H, J, and K from the brightest to the dimmest (use the symbol = for "same brightness as" and the symbol > for "brighter than"). Write down your reasoning.

EXPLORATION

Use a configuration of a single battery, wire and bulb to test your battery and all of your bulbs.

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

Circuit IV: Connect Circuit IV. Compare the brightness of bulbs B and C. Compare the brightness of bulbs B and C to bulb D. What can you conclude from this observation about the amount of current through each bulb? Pay attention to large differences you may observe, rather than minor differences that may occur if two bulbs are not identical. How can you test whether minor differences are due to manufacturing irregularities or different currents through the bulbs?

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

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

Describe the flow of current around the entire circuit. What do your observations suggest about the way the current 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?

Circuit V: Connect Circuit V. Compare the brightness of bulbs F and G. Compare the brightness of bulbs F and G to bulb E. What can you conclude from this observation about the amount of current through each bulb? How does the brightness of bulb E compare to the brightness of bulb A (Circuit I)? What can you infer about the current at point 1 in Circuit V compared to the current at point 1 in Circuit I?

How does the brightness of bulb E compare to that of bulb B (Circuit IV)? If you do not have enough equipment, you may need to team up with another group so that you can build both for comparison. Or, you can switch between Circuit IV and Circuit V quickly by switching the wire connected to the top of bulb G to the top terminal of bulb E. Watch the brightness of bulb E while you do this. What can you infer about the comparison of the current at point 2 in both circuits?

Describe the flow of current around the entire circuit. What do your observations suggest about the way the current divides and recombines at junctions where the circuit splits into two branches? How is this related to the conservation of charge? How does the current through point 2 compare with the currents through points 1, 3 and 4?

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

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

CONCLUSION

Rank the order the actual brightness of the bulbs A, B, C, D, E, F, G, H, J, and K. How did your prediction compare to your results? Can you use the conservation of energy and the conservation of current to explain your results?

How will you connect your three strings of lights?

Check your conclusions about current by using a digital multimeter (DMM) to directly measure the currents through parts of the circuits. Read the ***Equipment*** appendix if you are not familiar with how to measure current with a DMM. Also, review your notes from the earlier problem ***Basic Circuits***.

Measure the current through the numbered points in all the Circuits and compare them. Do these measurements agree with your conclusions based on bulb brightness?

Check your conclusions about potential difference by using a digital Multimeter (DMM) to directly measure the potential difference across parts of the circuits. Read the ***Equipment*** appendix if you are not familiar with how to measure the potential difference across a circuit element using a DMM.

Measure the potential difference across the battery and across each bulb in all the circuits and compare them. Do these measurements agree with your conclusions based on bulb brightness?

PROBLEM #3: SHORT CIRCUITS

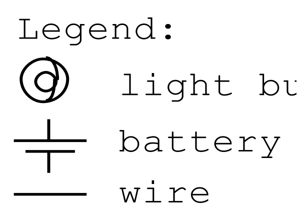
While decorating for the next holiday, you notice that a few of the bulbs on a string of lights do not light up when you turned them on. You take the bulbs out and check them in a different string of lights and observe that the bulbs still work. You wonder why they don't work in the first set of lights. A friend tells you that you must have a short circuit. Your friend explains that you have a short circuit when a wire makes an alternate path for the current to bypass a circuit element. To help understand this idea, you build a few simple circuits to show you the results of a short circuit.

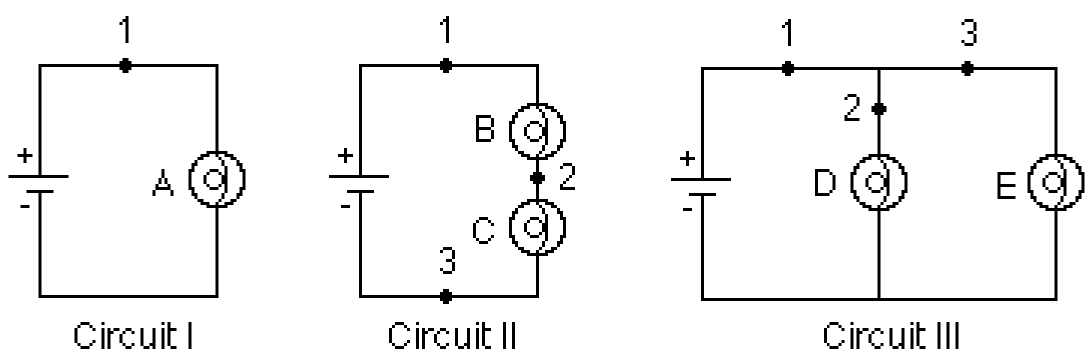
Instructions: <u>Before lab</u>, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. <u>During lab</u>, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapters 12 , Section 5 and Chapter 13, Sections 1-5.

EQUIPMENT

You will build the simple circuits shown below out of wires light bulbs, and batteries. Use the accompanying legend to help you 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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

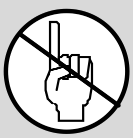
PREDICTIONS

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

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

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

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 voltages, 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 creating large currents. These currents can cause great heat and cause damage to nearby circuit elements or measuring devices. Any short circuits suggested in this manual have been tested, and determined not to significantly damage the equipment.

Build Circuit I. Place a wire across the bulb. What happens to the brightness of the bulb? Hold on to the wire that is across the bulb. Is it getting warmer? How did the current through the bulb change? How did the current coming out of the battery change? Disconnect the battery. Placing the wire across the bulb causes a short circuit and it is called "shorting out" the bulb.

Build Circuit II. What happens to the brightness of bulbs B and C when you place a wire across bulb B? How did the current through C change? How about the current through B? Did the current through point 1 change? In what way? Is the wire across bulb B getting warm? Explain your answers.

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

CONCLUSION

Did your predictions match your observed results? Explain your answers.

PROBLEM # 4: RESISTORS AND LIGHT BULBS

Your research team has built a device for monitoring the ozone content in the atmosphere to determine the extent of the ozone holes over the poles. You have been assigned the job of keeping the equipment at the South Pole running during the winter months when no supplies can get in. When a piece of equipment fails, you need to replace two resistors. Unfortunately you have only one. You do have a light bulb but you are not sure if the bulb acts enough like a resistor to make the circuit work. You decide to make a direct comparison.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapters 12 , Section 5 and Chapter 13, Sections 1-6.

EQUIPMENT

You have banana wires, an 18volt/ 5amp power supply, a digital multimeter (DMM), a light bulb and a resistor.

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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

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

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

   Sketch a graph of voltage versus current for the light bulb.

PREDICTIONS

Draw a sketch of what you expect a graph of voltage versus current to look like for (a) the standard resistor, and (b) the light bulb. Explain your reasoning.

EXPLORATION

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

MEASUREMENT

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

1. Use the chart provided in the **Equipment** appendix to determine the resistance of your resistor based on its color code. What is the uncertainty in this value?
2. Use the DMM set to ohms to measure the resistance of the resistor. What is the uncertainty in this value? Why is this procedure not helpful with a light bulb?
3. Use your power supply, DMM, and resistor to determine the voltage across the resistor and measure the current through the resistor for several different voltages. What is the uncertainty in the value of the resistance obtained by this method?

ANALYSIS

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

CONCLUSION

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

PROBLEM #5: CIRCUIT ANALYSIS

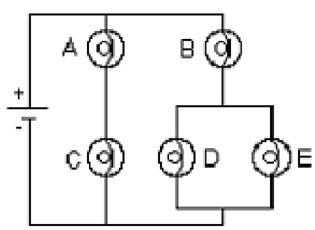
You have a summer job in an electronics company that requires you to make quick judgments about the relative amounts of current through different resistance in complex circuits. You have been calculating the current through each resistor but it takes time. A fellow worker suggests that using a qualitative analysis you can get the same results much faster. You decide to try this technique on several circuits using identical light bulbs so that the brightness of the bulb indicates the relative current through it. You will compare your qualitative results to those you get from a calculation.

Instructions: <u>Before lab</u>, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. <u>During lab</u>, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

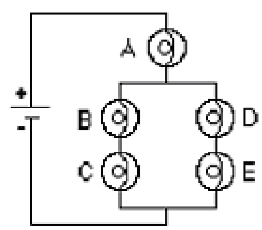
Read Knight, Jones & Field Chapters 12 , Section 5 and Chapter 13, Sections 1-5.

EQUIPMENT

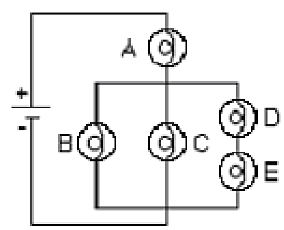
You will have batteries, wires, and five identical bulbs that you can connect to make the three circuits shown.



Circuit IX



Circuit X



Circuit XI

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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

PREDICTIONS

1. Use the qualitative intuition you have developed in the previous problems to complete the following predictions. For each prediction, state which rule(s) you used.

<u>Circuit IX:</u>

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?

<u>Circuit X:</u>

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?

<u>Circuit XI:</u>

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. Check your qualitative predictions by calculating the current through each bulb to predict the relative bulb brightness in the three circuits.

WARM UP

1. If resistors are connected in series how does the current through them compare? Resistors in series add. Does the current through a path **across a fixed potential difference** increase, decrease, or stay the same if the total resistance of the path increases?

2. What happens to currents at a junction? In a parallel circuit, is the potential difference across each path the same or does it depend on the resistance of that path? In a parallel circuit, is the current in each path, always the same, larger if the resistance is larger or smaller if the resistance is larger?

3. If resistors are connected in parallel, is the total current through all the branches more, less, or the same as the current through the branch with the smallest resistance? From that answer, is the total resistance of the entire parallel part of the circuit more, less, or the same as the smallest resistance in the one branch?

4. If parallel branches of a circuit exist, does changing the resistance in one branch change the current in the other branches? Does it change the potential difference across the other branches?

Since the brightness of a bulb depends on the current through it, you can now use these answers to make the qualitative predictions.

The following questions will help you **calculate** the currents in the circuits that are consequences of conservation of charge, conservation of energy, and Ohm's law in electric circuits.

5. Draw and label a circuit diagram showing all voltages, and resistance. Sometimes you may need to redraw the given circuit to help yourself see which resistors are in series and which are in parallel (not necessary in this case). For this problem, the voltages and the resistors (the resistors are all equal) are the known quantities and the current in each resistor is the unknown.

6. Assign a separate current for each leg of the circuit. Indicate your guess for the direction of that current by an arrow on the diagram. If your guess about the current direction is wrong, you will get a minus sign for its value.

7. Apply the conservation of current at each point in the circuit at which wires come together (a junction) to get an equation that relates the currents. Be careful, not all of these equations are independent. You can only use the ones that are.

8. Identify the number of circuit paths (loops) and label them on the diagram. Use conservation of energy to get the sum of the potential differences across all of the elements in each loop. Make sure your signs are correct. Does the potential difference increase or decrease across each circuit element in the direction you have chosen to follow the current? Use Ohm's law to get the potential difference across each resistor. Again be careful, not all of the loop equations are independent. You can only use the ones that are.

9. Check that the number of equations from Warm-Ups 7 and 8 matches the number of unknowns. It is easy to write down more but they add no useful information. If you choose equations that are not independent, your algebra will not result in a solution.

10. Solve your equations for one of the unknown currents and express the other currents in terms of the first current. Simplify your equations as much as possible.

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?

How can you test whether minor differences you observe are due to manufacturing irregularities in the "identical" bulbs?

As a check, use a DMM to measure the current through the bulbs. This is also useful in case you need to check whether a light bulb is unlit or just very dim.

ANALYSIS

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

CONCLUSION

Explain any differences between your qualitative predictions, your calculated predictions, and your observations.

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

PROBLEM #6: SIMPLE CIRCUITS WITH CAPACITORS

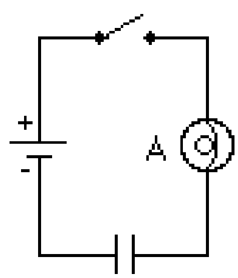
You and your friend are trying to determine if you can use a capacitor to limit the current from a battery in the case of short circuits. You suggest that you try a simple circuit with a capacitor, originally uncharged, connected to a battery through a switch. To monitor the current, you also put a bulb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

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

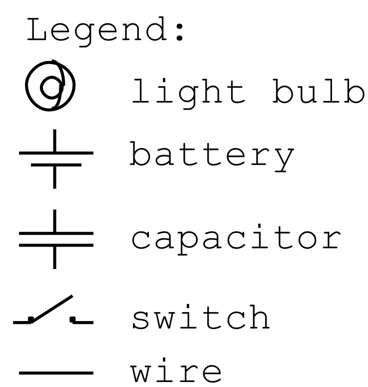
Read Knight, Jones & Field Chapter 13, Section 8.

EQUIPMENT

Build the simple circuit shown out of wires, light bulbs, capacitors and batteries. Use the accompanying legend to help you. You will also have a stopwatch and a Digital Multimeter (DMM).



Circuit XII



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

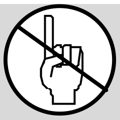
If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

PREDICTION

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

Sketch a graph of brightness versus time assuming the capacitor is initially uncharged.

EXPLORATION



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

Examine each element of the circuit **before** you build it. How do you know if the battery is "good?" Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged. How can you build a “switch” from the materials given?

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

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, connect Circuit XII with the switch in the off (open) position.

Complete the circuit and observe how the brightness of the bulb changes over time. At the instant the circuit is completely connected, how does the brightness of the bulb compare to the brightness of the bulb from Circuit I in the earlier problem, **Basic Circuits**? You may need to build circuit I to compare.

From your observation of the bulb's brightness, how does the current through the bulb change over time? You can check this using the DMM set for current (Amps). See Appendix A for the use of the DMM. Using the picture of the capacitor as two parallel plates that do not touch, how does the current through the capacitor change over the same time? Can you measure this with the DMM? Use the conservation of charge to explain what you observe. What can you infer about the change of the charge in the capacitor?

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.

After a few moments, disconnect a wire from the circuit. Is the capacitor charged or uncharged? To determine if the capacitor is charged, carefully (and safely) remove the battery from Circuit XII and reconnect the circuit without the battery. With only the capacitor, switch, and bulb (no battery) in the circuit, will the bulb light if you close the switch and the capacitor is charged? Uncharged? Try it. Was the capacitor charged before you closed the switch? Was the capacitor still charged a long time after the switch was closed? Use the conservation of charge and the concept of potential difference 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 close the switch on Circuit XII. How does this compare to your prediction?

PROBLEM #7: CAPACITANCE

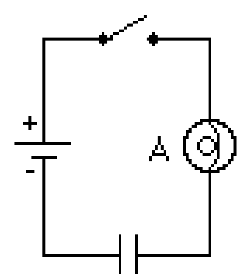
As part of theatrical production, the director of the play wants a light bulb to dim very slowly to heighten the dramatic effect. You have been asked to demonstrate different rates of dimming for the light bulb so the director can select the one necessary for the performance. You decide to design a simple, inexpensive circuit to automatically accomplish this task. You test your design by connecting a battery, a switch, a light bulb, and a capacitor in series. You need to determine how to adjust the rate of dimming of the light bulb by changing capacitors.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

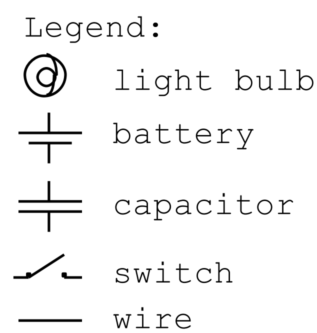
Read Knight, Jones & Field Chapter 13, Section 8.

EQUIPMENT

You can build the simple circuit shown out of wires, light bulbs, capacitors and batteries. Use the accompanying legend to help you build the circuit. You will also have a stopwatch to measure time intervals.



Circuit XII



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

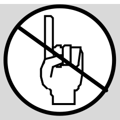
If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

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 producing a painful spark. **Do not** handle the capacitors by their electrical terminals or the bare metal of connected wires. **Always discharge a capacitor when you are finished using it.** To discharge a capacitor, use an insulated wire to connect one of the terminals to the other.

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

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

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, connect Circuit XII with the switch in the off (open) position.

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

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 do 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 Circuit XII.

ANALYSIS

Graph the time it takes for the light bulb to turn off versus capacitance, assuming the capacitor is initially uncharged.

CONCLUSION

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

PROBLEM #8: CIRCUITS WITH TWO CAPACITORS

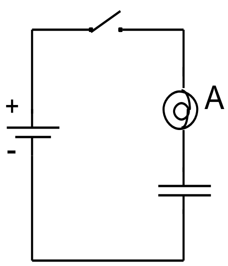
You have been asked to evaluate two circuits that could be used to automatically dim the lights for your theatrical production in a time shorter than a battery, a capacitor, and a bulb. Each circuit uses two capacitors, one battery and one bulb. All of the batteries, capacitors, and bulbs that you have are identical. In one circuit they are connected with a light bulb in series and in the other in parallel. Which one, if either, would you choose?

Instructions: <u>Before lab</u>, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. <u>During lab</u>, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

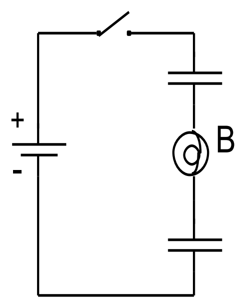
Read Knight, Jones & Field Chapter 13, Sections 7 & 8

EQUIPMENT

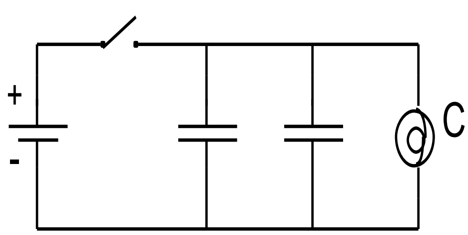
Build the circuits shown out of wires, bulbs, 2 *equal* capacitors, and batteries. Use the accompanying legend to help you build the circuit. You will also have a stopwatch.



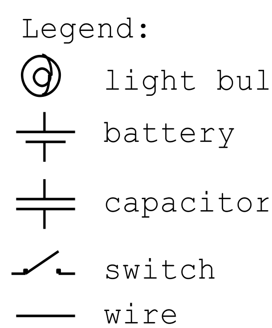
Circuit XII



Circuit XIII



Circuit XIV



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

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

1. Draw the three circuits. Decide which circuit has the capacitors in series and which has the capacitors in parallel.
2. Write down how capacitance combines for both series and parallel circuits. Assuming all the individual capacitors have the same capacitance, rank the three circuits in order of effective capacitance.
3. How does capacitance affect the amount of time a bulb stays lit? Rank the circuits in order of how long the bulb will stay lit. Is there a circuit that will not go out when connected? If so, how long will the bulb stay lit after the battery is disconnected? Relate this length of time to the times that the other circuits stay lit.

PREDICTION

Rank order the total time it takes for each of the bulbs A, B, and C 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 producing a painful spark. **Do not** handle the capacitors by their electrical terminals or the bare metal of connected wires. **Always discharge a capacitor when you are finished using it.** To discharge a capacitor, use an insulated wire to connect one of the terminals to the other.

Make sure all of your capacitors are uncharged before starting the exploration and that they have the same capacitance.

Review your exploration and measurement plan from Problem #7. Connect Circuit XII to use as a reference.

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

Connect Circuit XIII, but do not hook up the battery yet. Do you think bulb B will light when the battery is hooked up? Record your reasoning in your journal. Complete the circuit by hooking up the battery. Record your observations and explain what you saw using the 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.

Connect Circuit XIV, but do not hook up the battery yet. Do you think bulb C will light when the battery is hooked up? Record your reasoning in your journal. Complete the circuit by hooking up the battery. Record your observations and explain what you saw using the conservation of charge and the concept of potential difference.

Develop a plan for measuring the time it takes for bulbs A, B and C 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

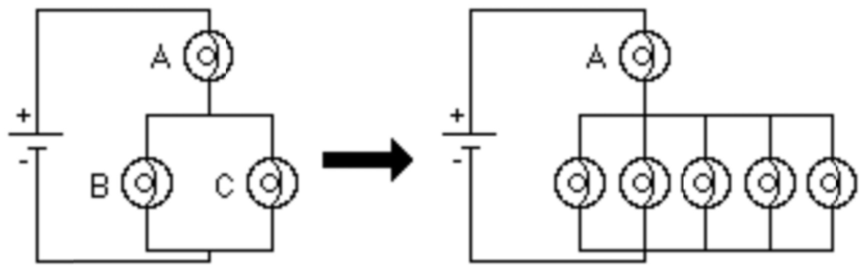
Rank order the actual time it took each bulb to turn off. Do any of the bulbs initially light? Do all the bulbs go off?

CONCLUSION

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

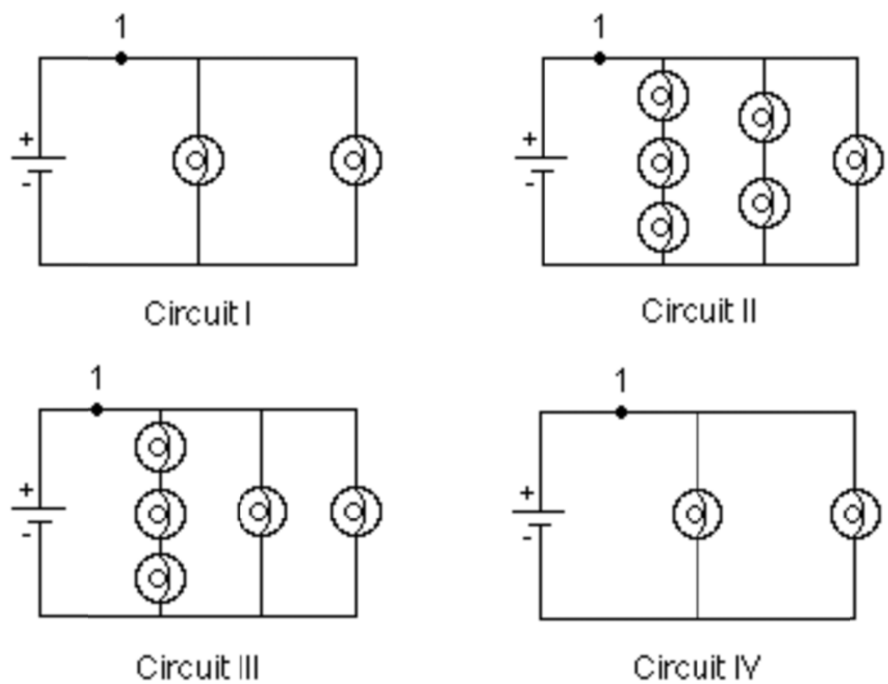
☑CHECK YOUR UNDERSTANDING
ELECTRIC CIRCUITS

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?

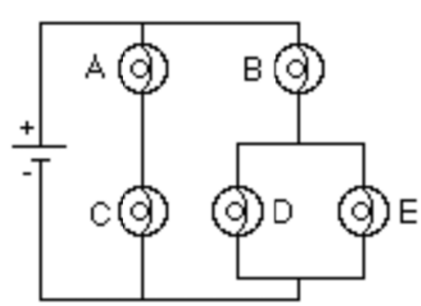


In household circuits, bulb A is in the same position as a fuse or circuit breaker. Why?

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

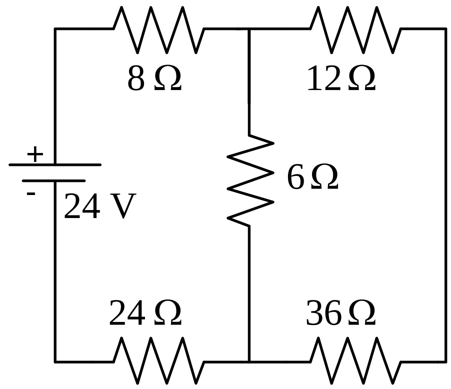


3. Predict what will happen to the brightness of bulbs A, B, C and D if bulb E were removed from its socket. Explain your reasoning.

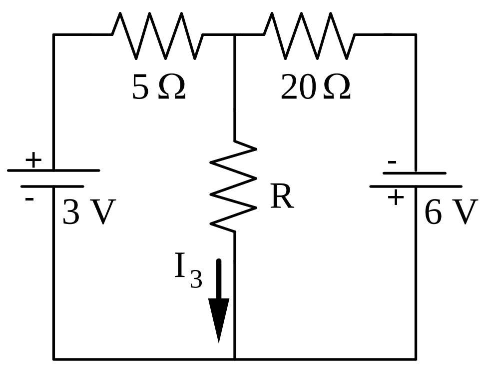


☑CHECK YOUR UNDERSTANDING
ELECTRIC CIRCUITS

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 as what is shown?

Physics Lab Report Rubric

Name: ____ ID#: ______________

Course, Lab, Problem: ____

Date Performed: ____

Lab Partners' Names: ____

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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			

LABORATORY 8
MAGNETIC FIELDS AND FORCES

Magnetism plays a large role in our world's modern technology. Some uses of magnets today are imaging parts of the body, exploring the mysteries of the human brain, and storing information in computers. Magnetism also allows us to explore the structure of the universe, the atomic structure of materials, and the quark structure of elementary particles.

Magnetic interactions can best be described using the concept of a field. For this reason, your experiences exploring the electric field concept in the first lab are also applicable in this lab dealing with magnets. There are similar activities in both labs so you can experience the universality of the field concept. Although the magnetic force is related to the electric force, the two are not the same. 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 will use the magnetic force to deflect electrons.

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 Knight, Jones & Field Chapter 14.

Before coming to lab you should be able to:

- Add fields using vector properties.
- 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.

LABORATORY 8
MAGNETIC FIELDS AND FORCES

PROBLEM #1: PERMANENT MAGNETS

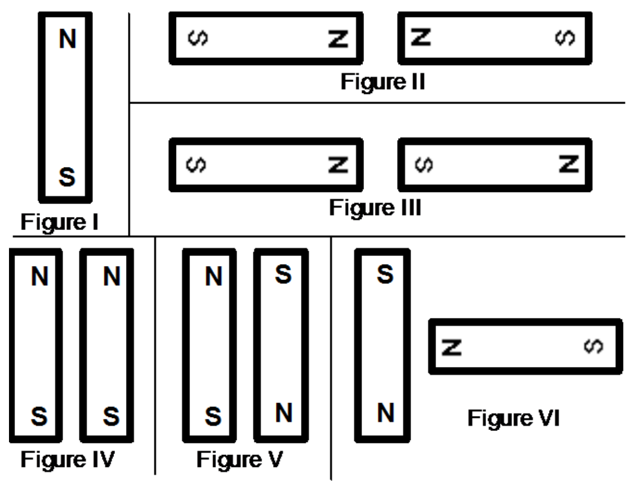
You're working for a company that designs magnetic resonance imaging (MRI) machines. The ability to get a clear image of the inside of the body depends on having precisely the correct magnetic field at each position. In a new model of the machine, the magnetic fields are produced by configurations of permanent magnets. You need to know the pattern of the magnetic field from each magnet and how to combine magnets to change that pattern.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 14, Section 1 & 8.

EQUIPMENT

You have two bar magnets, compass and a taconite plate. When a magnet is placed on top of one of the plate, the taconite pieces align with the magnetic field. A magnetizer is also and should be used to refresh the magnets. 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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

Before you start, you should review the Warm-up questions for the problem, **Electric Field Vectors**, in the Laboratory on Electrical Fields and Forces.

1. Make a sketch of all magnet configurations shown. 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. 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. Remember:

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

   -The direction of the magnetic field is from the north pole to the south pole.

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

PREDICTION

Sketch a map of the magnetic field for each magnet configuration in the figures above. 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 plate is not leaking. Gently shake the plate until the Taconite is distributed uniformly. Properties of magnets can change with handling. Check the poles of the magnet with your compass. Inform your lab instructor if the magnet does not seem to behave as you would expect.

Place a permanent magnet on the plate. How long do you need to wait to see the effect of the magnetic field? Is it what you expected? Try applying small vibrations to the plate. Try different configurations of magnets and determine how to get the clearest pattern in the Taconite.

What influence does the field have on the Taconite pieces? Does the field cause a net force? What did you observe to show that? Does the field cause a net torque? What did you observe that shows that? 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 plate. In your journal, draw the shape of the magnetic field produced. Repeat for each figure in the predictions.

CONCLUSION

How did your predictions of the magnetic field pattern for each configuration of magnets compare with your results?

PROBLEM #2: CURRENT CARRYING WIRE

Your friend's parents live on a dairy farm where high-voltage power lines cross the property. They are concerned about the effect that the magnetic field from the power lines might have on the health of their dairy cows grazing nearby. They bought a device to measure the magnetic field. The instructions for the device state that it must be oriented perpendicular to the magnetic field. To measure the magnetic field correctly, they need to know its shape near a current carrying wire. They know you have taken physics, so they ask you for help. You decide to check your prediction about the pattern of the field with a magnetic compass *before* you make the trip to your friend's farm.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 14, Section 1 – 4

EQUIPMENT

You have a magnetic compass, banana cables, a meterstick, 18volt/ 5amp power supply and the Magnetism 3D computer application.

If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

Draw a picture of a long wire with current running through it. On your drawing choose any place some distance from the wire and away from its ends. Draw all of the other points that have the same size magnetic field as your original point. Explain how you chose these points.

Give a relationship between the current through a wire and the magnetic field at each point in space. Explain all of the quantities in that equation in terms of your drawing. Under what conditions is this equation true? Under what conditions is this equation useful?

PREDICTIONS

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

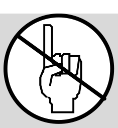
EXPLORATION

To open the Magnetism 3D application, just double click on the icon on the lab computer desktop.

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 Magnetism 3D, 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 several wires together to give a total length of at least a meter. Stretch the wire vertically and move your compass around the wire. Is there any evidence of a magnetic field from a wire with no current? Does the compass always point in the same direction?



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 ENDS!**

Connect the wire to the 18volt/ 5amp power supply and turn the power supply on.

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 large enough to easily move the compass through. Move the compass around the loop. How far away from the loop can you see a deflection? Is this distance larger along the axis of the loop or somewhere else?

MEASUREMENT

Use your measurement plan to create a map of the magnetic field around the stretched wire and the looped wire.

ANALYSIS

The direction of the magnetic field around a current carrying wire can be found by using the "right-hand rule" 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: THE MAGNETIC FIELD FROM A CURRENT CARRYING WIRE

You are working for a car company designing electronics for next year's models. A source of concern is interference from the magnetic fields from the power lines that so often run parallel to roads. You have been assigned to find out the how the size of these magnetic fields vary with the distance the car is from the power lines so they can determine if their new technology will work. You decide to model the situation to test your measurement technique before going out in the field.

Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Read Knight, Jones & Field Chapter 14, Section 1 – 4

EQUIPMENT

You will have a Hall probe and interface, a magnetic compass, banana cables, a meter stick, an 18volt/ 5amp power supply and also 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 equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

WARM UP

Draw a picture of a long wire with current running through it. On your drawing choose any place some distance from the wire and away from its ends. Draw all of the other points that have the same size magnetic field as your original point. Explain how you chose these points.

Give a relationship between the current through a wire and the magnetic field at each point in space. Explain all of the quantities in that equation in terms of your drawing. Under what conditions is this equation true? Under what conditions is this equation useful?

PREDICTIONS

Calculate the size of the magnetic field as it depends on the distance from the center of the wire and the electric current running through the wire

Use this expression to graph the magnetic field strength as a function of position.

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 ENDS!**

To put current through your wire you will need a circuit. Draw this circuit and explain how different parts of the circuit will affect your measurement. How can you minimize this effect so your situation is most like a long straight wire?

Choose a current setting on your power supply so that its maximum current goes through your wire. WARNING; make sure that the maximum current is around 5 amps, if it is significantly higher (by one or more amps) it may damage equipment and increases the risk of shock and injury.

Set up your circuit so that the magnetic field in some region of space most closely approximates that of a long straight wire with current running through it. Put your Hall probe some distance from the wire and measure the magnetic field. **Don't forget to calibrate the probe first!** What orientation does the Hall probe have to be in to measure the size of the magnetic field at that point? Keeping the position the same, change the orientation of the probe and see where the measured magnetic field is largest. When is it the smallest? Do those agree with what you thought? Leave the Hall probe in the same position and lower the current. What happens to the size of the magnetic field? Is that what you expected? Note what happens when you move the probe away from the wire. How far away from the wire can you still measure the magnetic field?

Now move the Hall probe slowly along a path that you have determined has the same size of magnetic field. Does it? How will you orient the probe on the path? Try a path closer to the wire. Try one further away.

Now keep the Hall probe in one place and change the shape of the circuit. How does that affect the magnetic field? Is it what you expected?

Create a measurement plan using information collected above.

MEASUREMENT

Use your measurement plan to measure how the size of the magnetic field depends on the distance from a long current carrying wire. Use the smallest distances possible while still remaining accurate. The more data points you have the more recognizable your graph's pattern will be. If you move the probe away too quickly you will end up with a flat line.

ANALYSIS

Make a graph of your measurements and compare them to your predictions.

CONCLUSION

How did your prediction of the magnitude of the magnetic field caused by a current-carrying wire compare with your measurements? In what situation is the method you used to calculate the magnetic field from a current not useful even though it is still correct?

PROBLEM #4: MAGNETS AND MOVING CHARGE

You are leading a technical team at a company that is redesigning the cathode ray tubes (CRTs) used for computer monitors. To introduce this project to a group of stockholders, you need to demonstrate how an electron beam can be moved across a screen by a magnetic field. You decide to use an ordinary bar magnet held outside of the CRT to deflect the electrons. Before you do the demonstration, you should determine the qualitative effect of bringing a bar magnet up to a CRT.

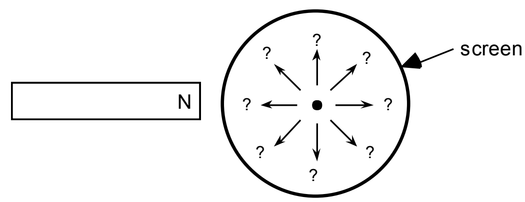
Instructions: Before lab, read the laboratory in its entirety as well as the required reading in the textbook. In your lab notebook, respond to the warm up questions and derive a specific prediction for the outcome of the lab. During lab, compare your warm up responses and prediction in your group. Then, work through the exploration, measurement, analysis, and conclusion sections in sequence, keeping a record of your findings in your lab notebook. It is often useful to use Excel to perform data analysis, rather than doing it by hand.

Review **Deflection of an Electron Beam by an Electric Field**

Read Knight, Jones & Field Chapter 14, Section 1 – 5

EQUIPMENT

You have a cathode ray tube (CRT), banana cables, Cenco CRT power supply, bar magnet, a meterstick, and a compass.



Read the sections *Cathode Ray Tube (CRT) and Accessories* & *Magnetizing a Bar Magnet* in the **Equipment** appendix.

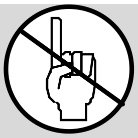
If equipment is missing or broken, submit a problem report by sending an email to labhelp@physics.umn.edu. Include the room number and brief description of the problem.

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? Does the size of the deflection increase or decrease, 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

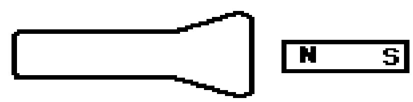


WARNING: You will be working with a power supply that can generate large electric currents. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. NEVER GRASP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

Connect the CRT according to the directions in the appendix, or review previous problems in your lab journal. Select the accelerating voltage that gave the largest deflection for the smallest electric field based on your explorations from Lab I. Record the location of the undeflected beam spot.

Determine which pole on your bar magnet is the north magnetic pole. 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 what direction did the beam deflect?

If you placed the bar magnet perpendicular to the screen of the CRT, should you see a deflection? Try this experiment with both poles of the magnet. Record your results. Were they what you expected?



Can you orient the bar magnet so that it attracts or repels the electron beam?

Place the north pole of your magnet a fixed distance away from the side of the CRT near the screen. Record the deflection. Increase the speed of the electrons by increasing the accelerating voltage as much as possible. Calculate the increase in speed. How does deflection change? Try this with both poles of the magnet. Record your results. Were your results what you 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 adding more magnets. How does deflection change? Try this with both poles of the magnet. Record your results. Were your results what you 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. Do the same for the minimum effect. What is the effect of the Earth's magnetic field on the electron beam relative to the Earth's gravitational field? How did this affect your results from Lab 4, Problem #3?

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

ANALYSIS

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

CONCLUSION

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

☑ CHECK YOUR UNDERSTANDING
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.

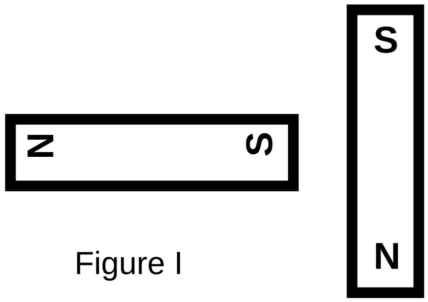


Figure I

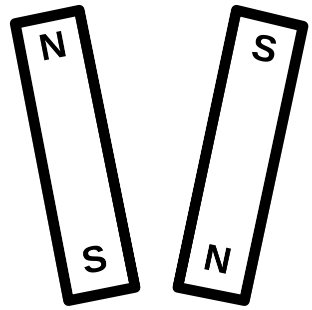


Figure III

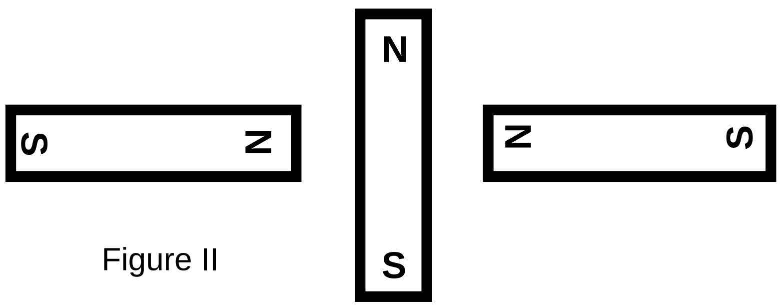


Figure II

2. You and your friends are flipping through the cable channels on the TV when you come across an old Godzilla movie. In one poorly dubbed 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 it to your friends.

3. Two parallel wires have an equal current flowing through them in the same direction. What is the direction of the magnetic field half way between them? How does the size of this field compare to that of a single wire? What would happen to the magnetic field at that point if one of the currents were reversed?

☑ CHECK YOUR UNDERSTANDING
MAGNETIC FIELDS AND FORCES

PHYSICS LAB REPORT RUBRIC

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

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			

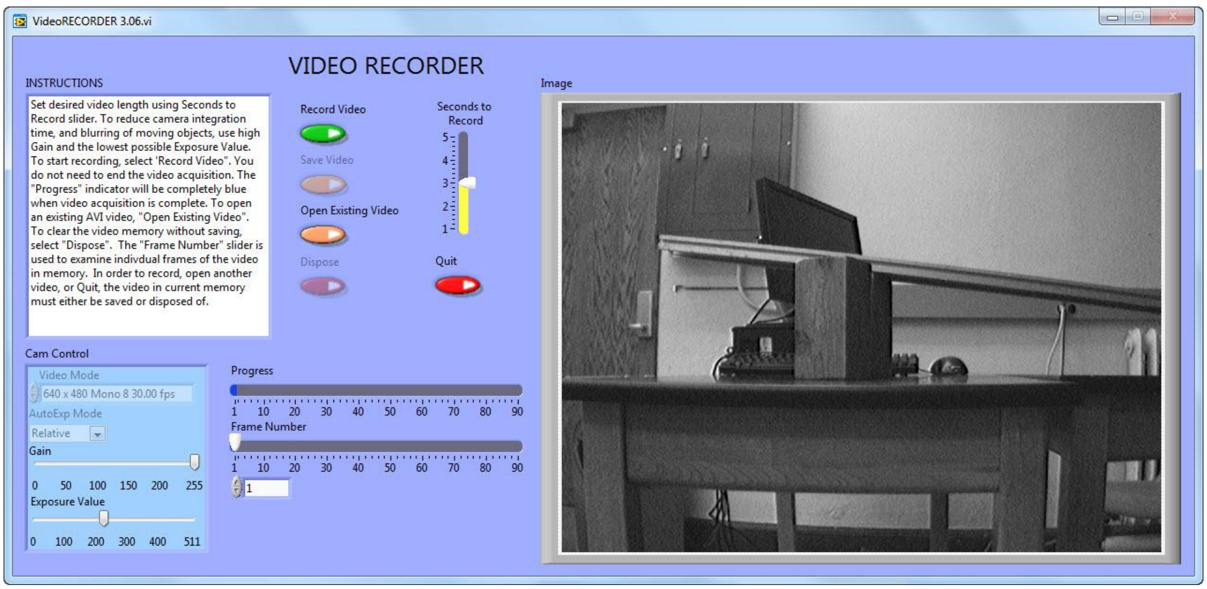
Appendix: **EQUIPMENT**

Video Cameras – Installing and Adjusting

You use Fire-i™ Digital Cameras in conjunction with the VideoRecorder application. The camera is an IEEE-1394a (FireWire) video camera that records 640x480 resolution video at 30 frames per second.

Installing Cameras:

The newest version of VideoRecorder automatically configures and displays the camera image. With a working camera plugged in, launching VideoRecorder results in a live image on the computer screen. The image will not appear if the camera is faulty, or there is an issue with the connection.



If you have a camera that is not working, you should try the following steps:

1. Quit the VideoRecorder application.
2. Hook up a new Fire-i™ camera to the firewire cable.
3. Launch the VideoRecorder application.

If a new camera still does not work, you likely have a bad firewire cable or computer interface card. **Contact labhelp@physics.umn.edu and report a bad video setup - include the room number and host name of the computer.**

Adjusting Cameras:

To get useful data from the video camera, it is helpful to adjust additional camera settings. The VideoRecorder application has camera controls in the lower left corner that allow you to adjust the exposure value and gain of the camera's image sensor. The exposure value sets the duration each frame of video is formed. Generally speaking low exposure values have fast discrete images that are appear dark, high exposure values have slow blurred imaged that are bright. The gain amplifies the brightness of the frame and should be adjusted upwards to make discrete darker images easier to see.

"Good" camera settings - Motionless objects may look grainy; objects in motion have well-defined edges.

- low Exposure value (280 or less)
- high Gain (about 255)

"Bad" camera settings - Motionless objects look nice; motion causes objects to appear blurred without well-defined edges.

- high Exposure value (default is 511)
- low Gain

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

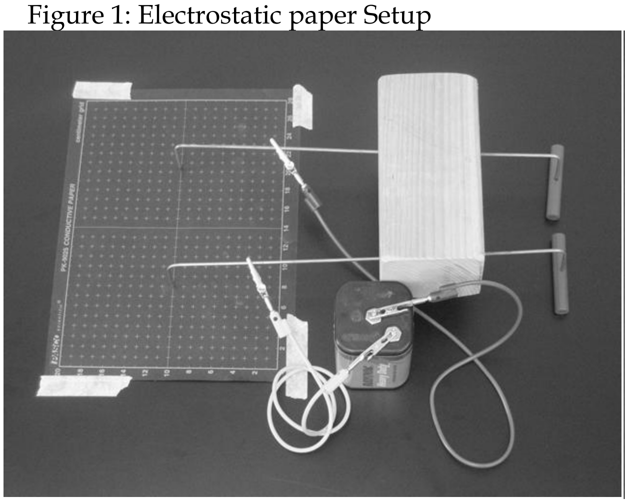
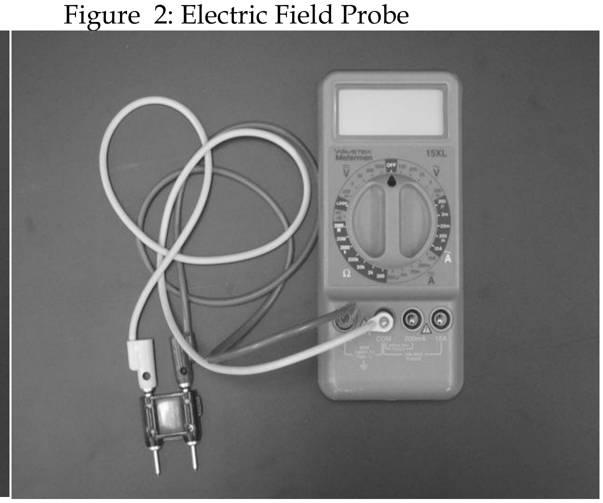


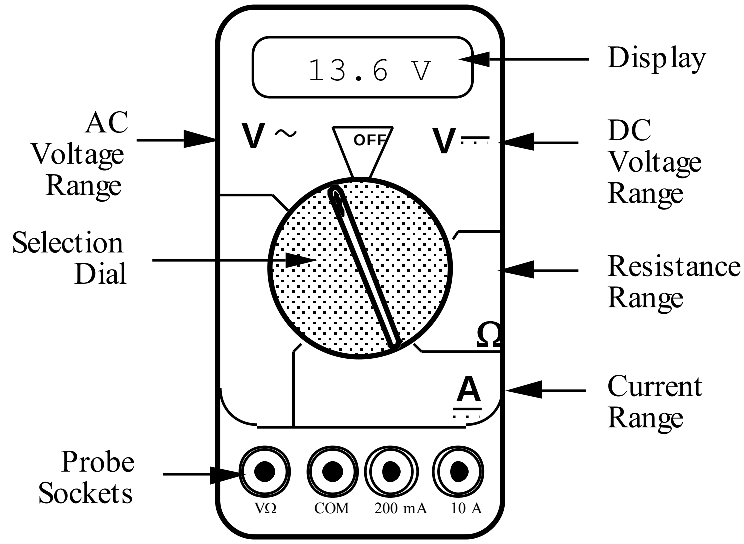
Figure 2: Electric Field Probe



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.

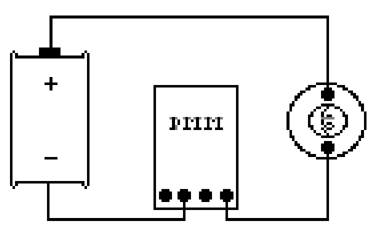


The DMM can measure currents anywhere from 10 amps to a microamp (10^{-6} amps). This versatility makes the DMM fragile, since measuring a large current while the DMM is prepared to measure a small one will certainly harm the DMM. For example, measuring a 1 ampere current while the DMM is on the 2 milliamp 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:



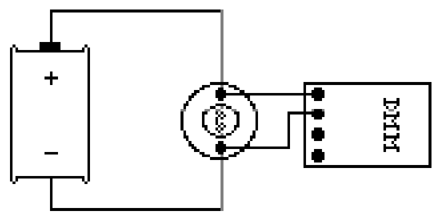
To measure current, the DMM must be placed in the circuit so that all the current you want to measure goes **through** the DMM.

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.

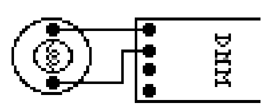
3. If no number appears, try a different measurement scale. Start at the highest voltage scale and work your way down the scales until you get a satisfactory reading.

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:

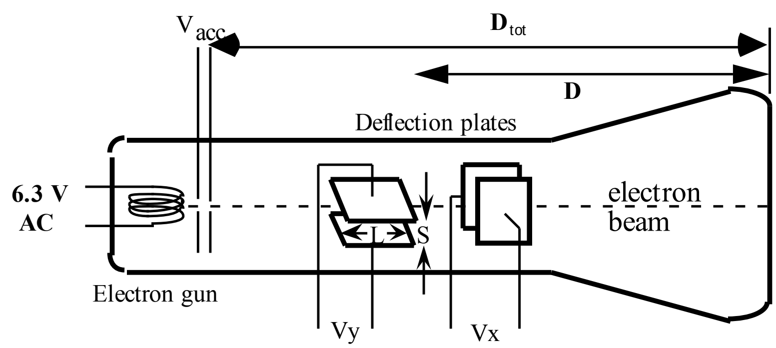
$$\langle I \rangle = \frac{I_0}{2\pi}\int_0^{2\pi} \sin(t)\, dt = 0$$

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:

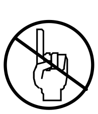
- A thin filament (represented above as a coil of wire), similar to a light-bulb filament, is heated by a current. When the CRT is operating, this filament can be seen as an orange, glowing wire. This hot filament ejects slow-moving electrons.
- Some slow electrons drift toward the high-voltage "acceleration 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.



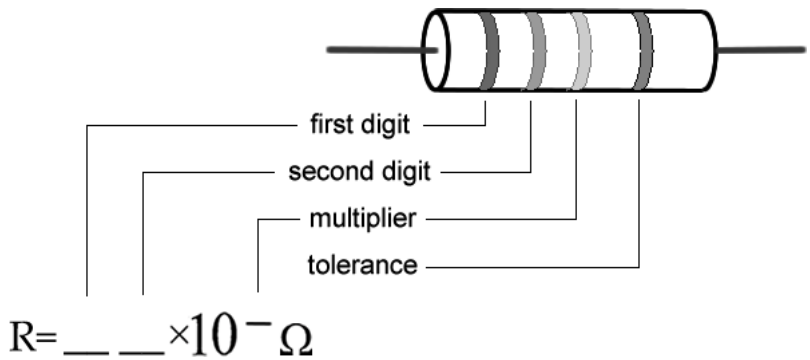
WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply.

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.



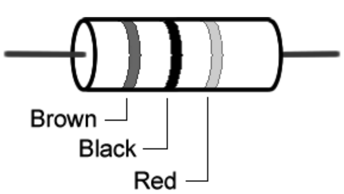
To read the color bands on the resistor, begin by finding the gold or silver band on one end of the resistor; this is the back of the resistor. You begin reading from the other end. Most resistors (including those you will use in lab) are coded to two significant digits. The first two color bands correspond 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.

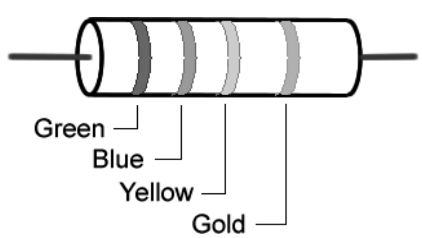
The fourth color band tells you the tolerance, or error bounds for the coded resistance: gold means ±5% tolerance, silver means ±10% tolerance and no fourth band means ±20%.

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
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.

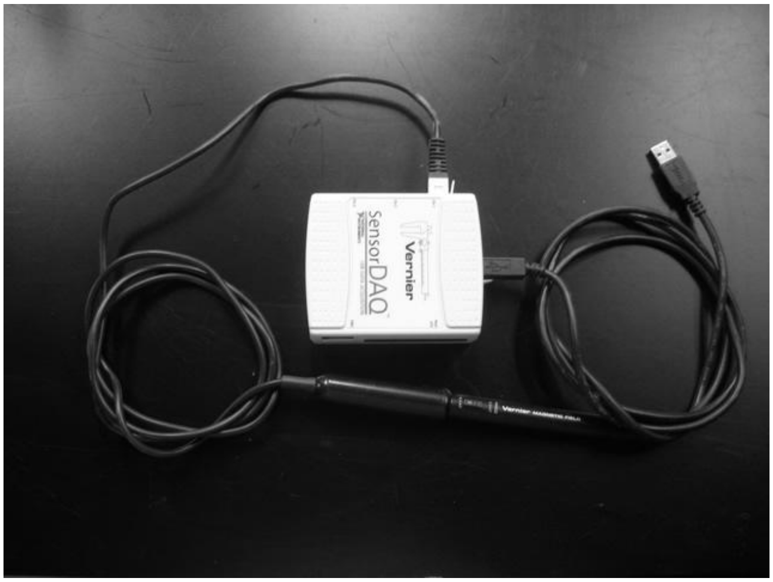
The current and voltage controls are located in the middle. In between the constant current and constant voltage knobs is a switch that allows you to toggle from high currents to low currents. **It is highly recommended that you use only the low current mode.**

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.

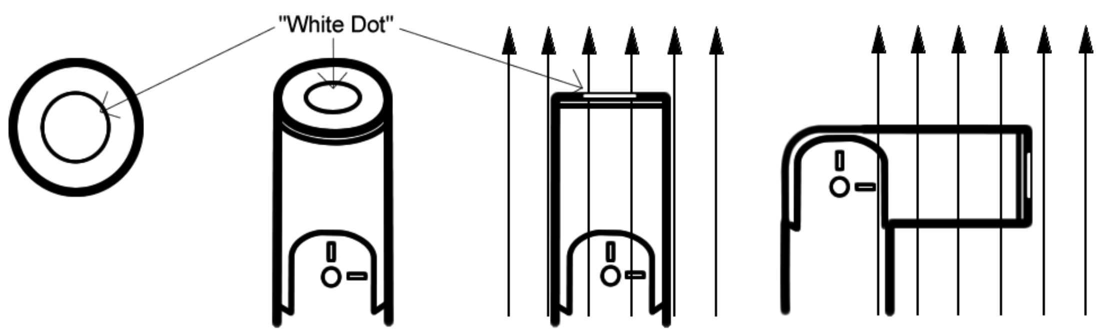
There is a *mater-slave* switch on the back of the power supply. This should always be set to master for the DMM to function properly. If you experience any problems, this is the first place to check.

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.

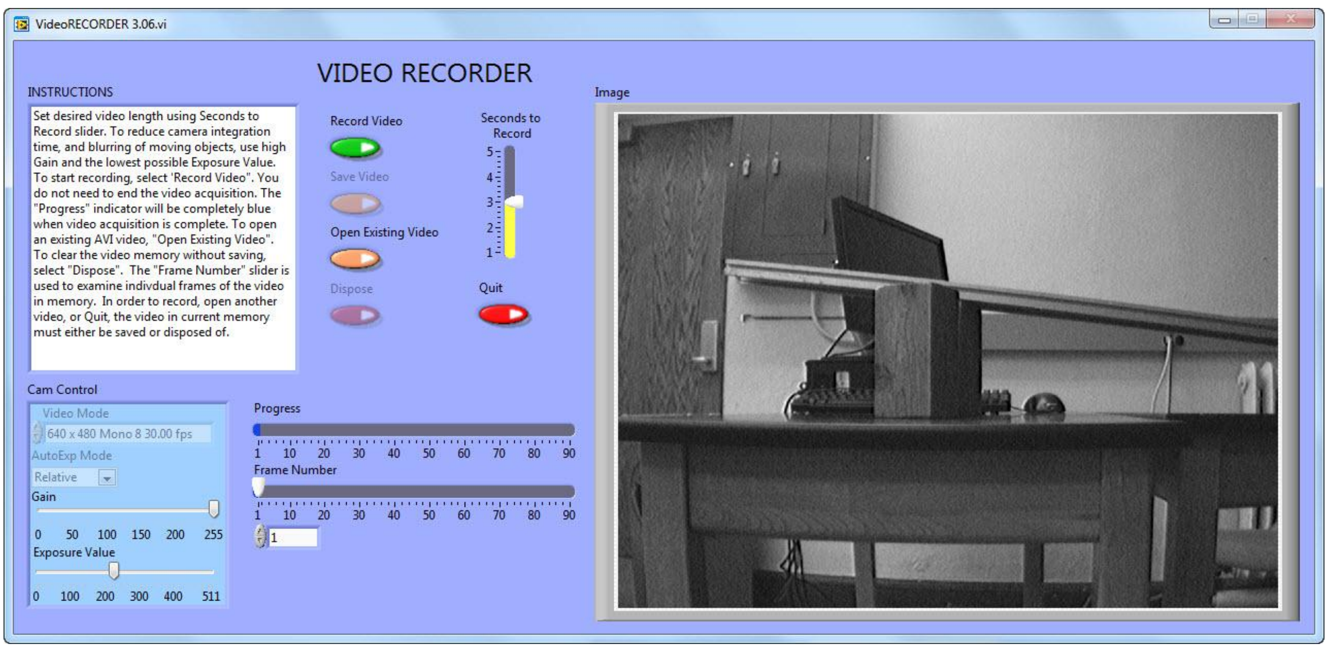
MOTIONLAB & VIDEORECORDER -Video Analysis of Motion

Analyzing pictures (movies or videos) is a powerful tool for understanding how objects move. This appendix will guide a person in the use of VideoRecorder and MotionLab to analyze motion. LabVIEW™ is a general-purpose data acquisition programming system. It is widely used in academic research and industry. Later you will use LabVIEW™ to acquire data from other instruments.

Using video to analyze motion is a two-step process. The first step is recording a video. This process uses the video software to record the images from the camera and compress the file. The second step is to analyze the video to get a kinematic description of the recorded motion.

MAKING VIDEOS – USING VIDEORECORDER

After logging into the computer, open the video recording program by double clicking the icon on the desktop labeled *VideoRECORDER*. A window similar to the picture below should appear.



You should see a "live" video image of whatever is in front of the camera. By adjusting the lens on the camera, you can focus the sharpness of the image as necessary.

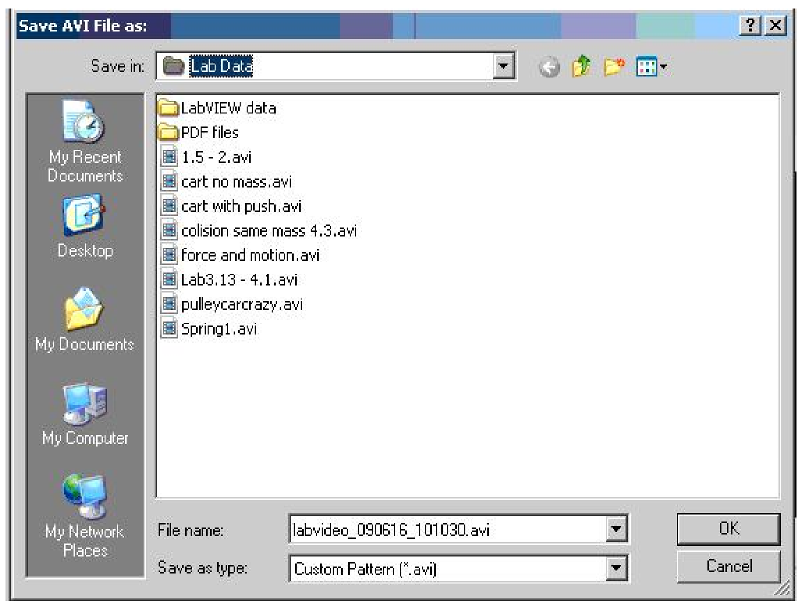
The controls are fairly self-explanatory; pressing the *Record Video* button begins the process of recording a video. While the video is recording, the blue *Progress* bar beneath the video frame shows the fraction of the video recorded. Once you have finished recording, you can move through the video by dragging the *Frame Number* slider control. If you are not pleased with your video recording, delete it by pressing the *Dispose* button.

You might notice that the computer sometimes skips frames. You can identify the dropped frame by playing the video back frame by frame by clicking the arrow above the frame number. If recorded motion does not appear smooth, or if the object skips irregularly, then frames are probably missing. If the computer is skipping frames, speak with your instructor.

While you are recording your video, you should try to estimate the kinematic variables you observe, such as the initial position, velocities, and acceleration. The frame number is shown in the *VideoRECORDER* window, in the box below the *Frame Number* slider. With the frame number and the fact that the video has 30 frames per second, you can use known lengths for objects in the video to estimate kinematic variables. These values prove very useful for your prediction equations. Be sure to record your estimates in your journal.

Once you have recorded a satisfactory video, save it by pressing the *Save Video* button. You will see a *Save* window, as shown here.

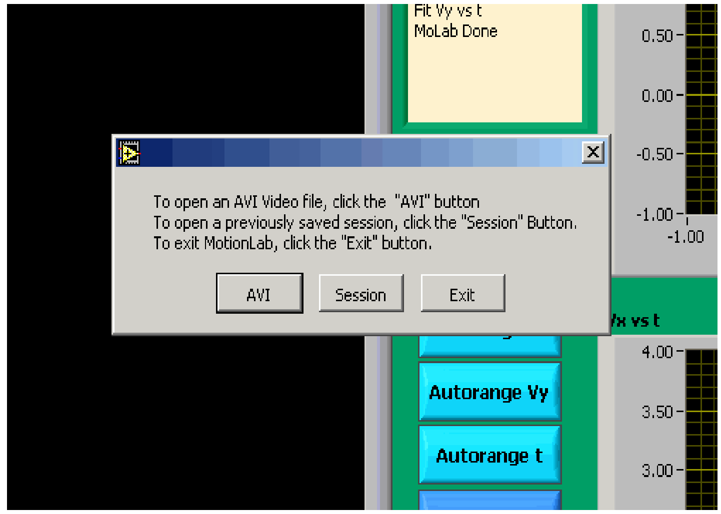
To avoid cluttering the computer, you will only be able to save your video in the *Lab Data* folder located on the desktop. In the *File name* box, you should enter the name that you wish to give to your video. This name should be descriptive enough to be useful to you later.



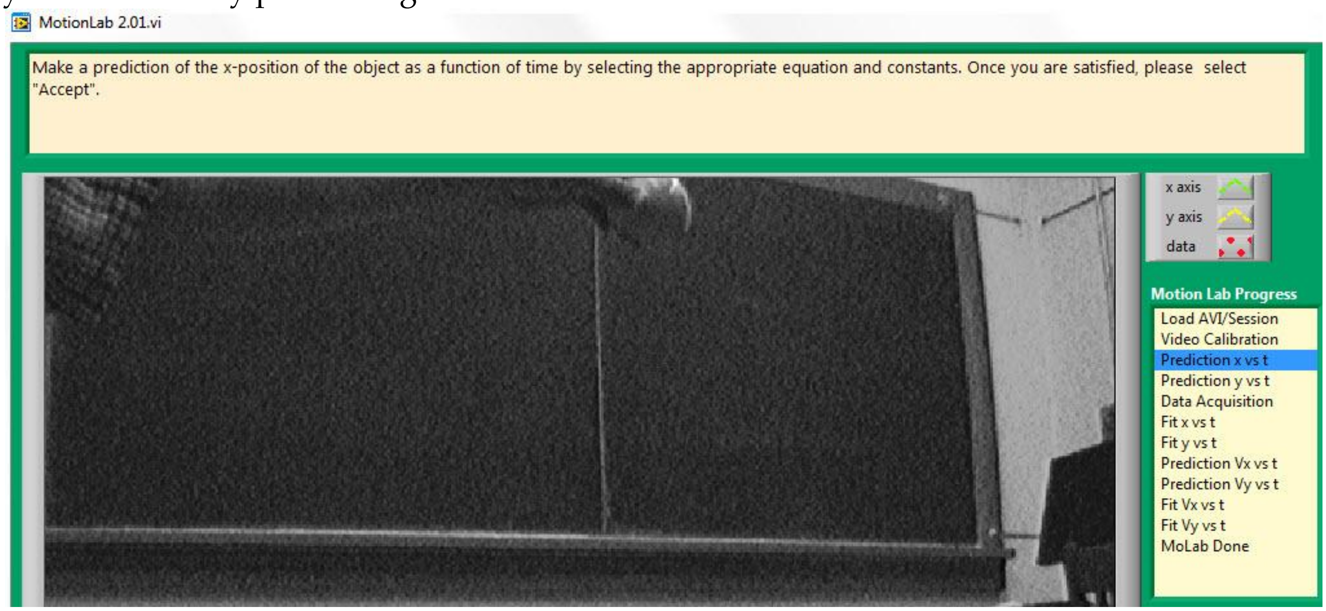
ANALYSIS BASICS – USING MOTIONLAB

Open the video analysis application by clicking the icon labeled *MotionLAB* located in the PhysLab folder on the desktop. You should take a moment to identify several elements of the program. As a whole the application looks complex, once it is broken down it is easy to use.

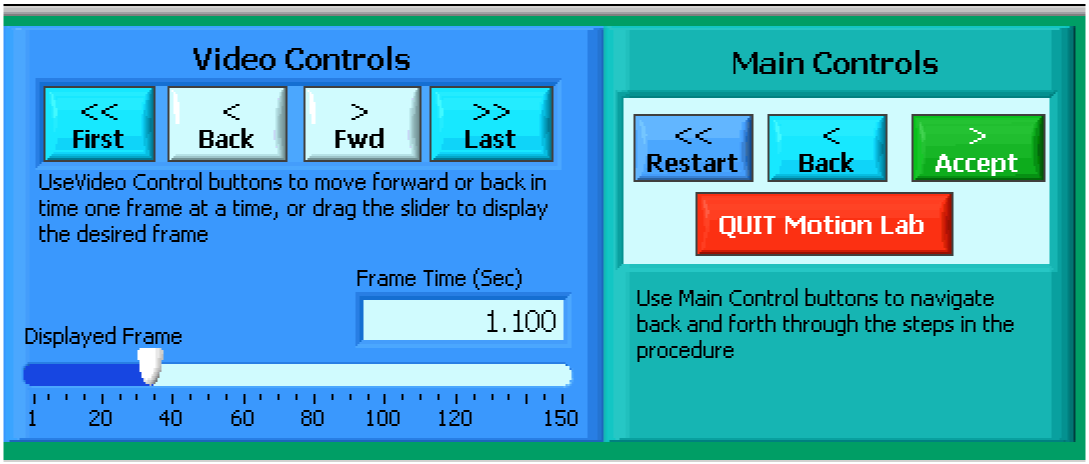
The application will prompt you to open a movie (or previously saved session) as shown here.



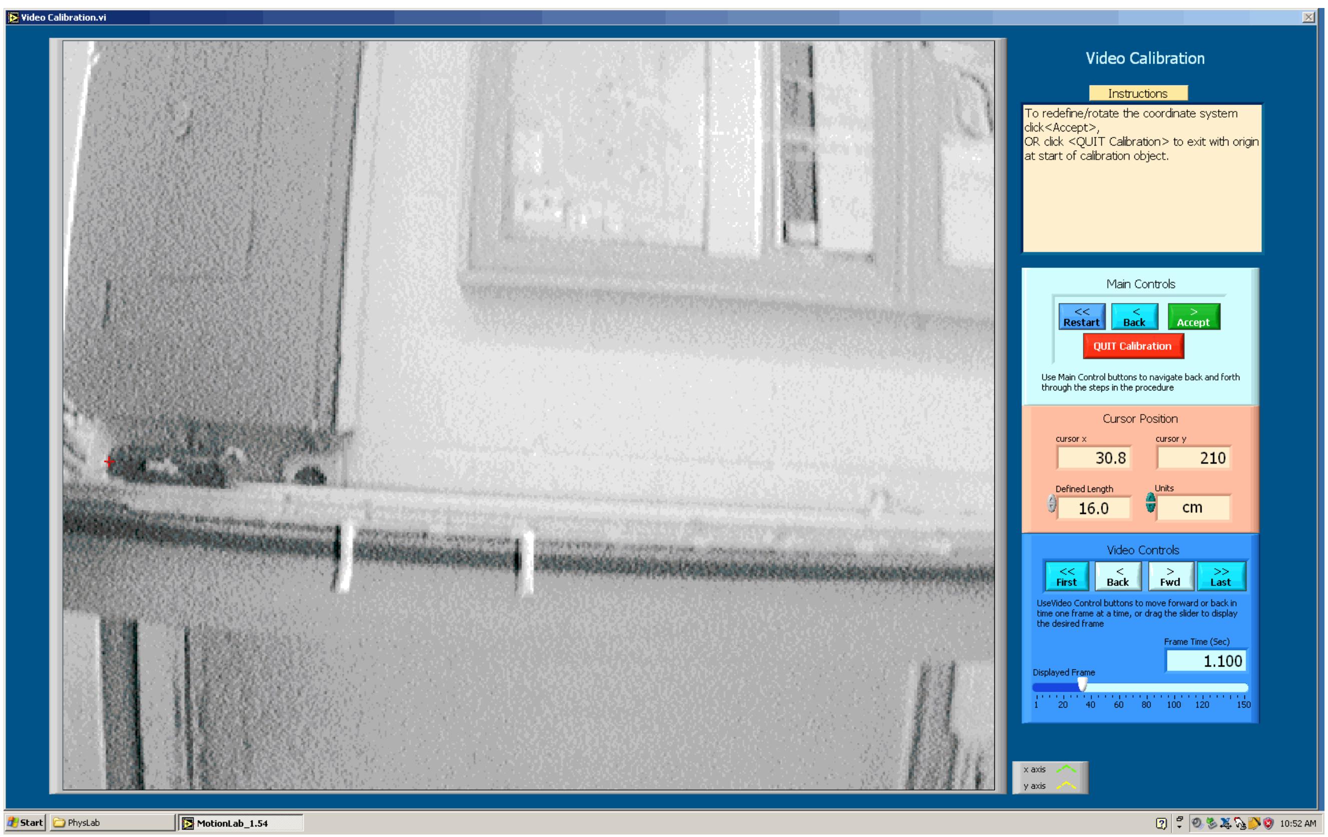
The upper left corner displays a dialog box with instructions for each step during your movie analysis. To the right of the video screen is the progress indicator. It will highlight the step you are currently performing.



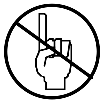
Below the video display is the Video Controls for moving within your AVI movie. The slider bar indicating the displayed frame can also be used to move within the movie. Directly to the right of the Video Controls is the Main Controls. The Main Control box is your primary session control. Use the Main Control buttons to navigate back and forth through the steps shown in the progress box. The red Quit Motion Lab button closes the program.



During the course of using MotionLAB, larger resolution screens pop up to allow you to calibrate your movie and take data as accurately as possible. The calibration screen has an instructions box to the right of the video with Main Controls and Video Controls directly below. The calibration screen automatically opens once an AVI movie has been loaded.

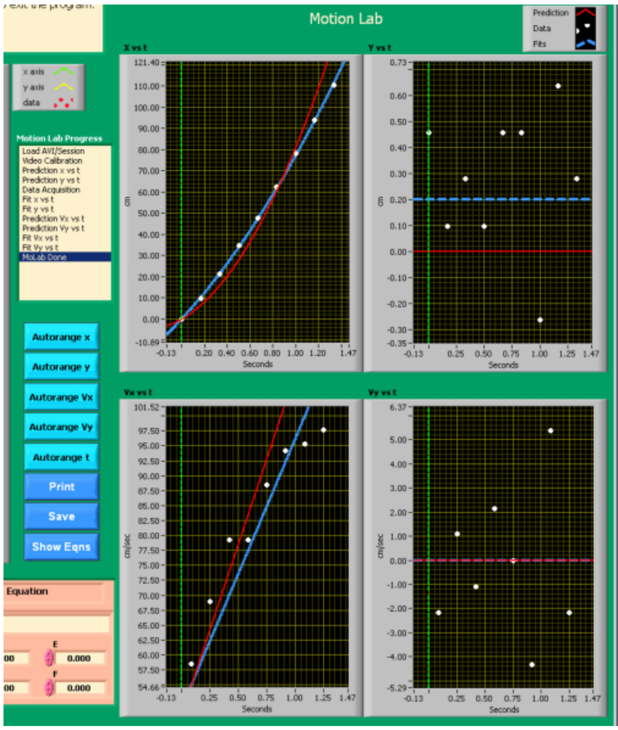


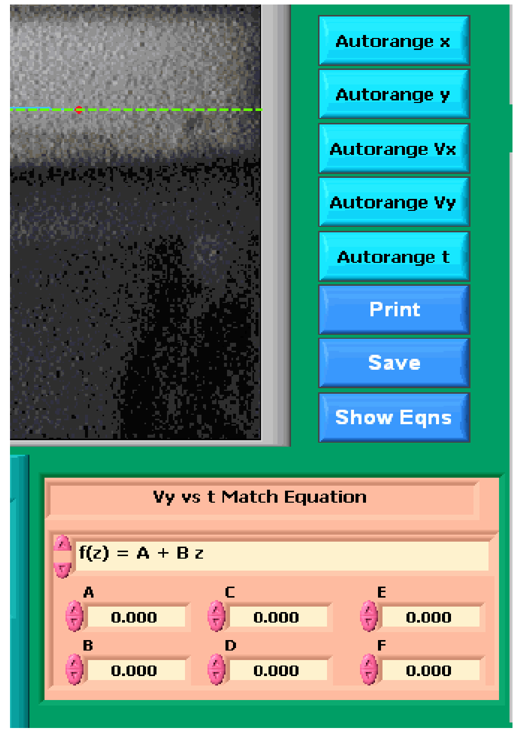
The data acquisition screen appears onlyafter you enter predictions (the progress indicator will display which step you are at.) More will be said about predictions in a bit. The data acquisition screen has the same instructions box and Video Controls, along with a Data Acquisition Control box. The Data Acquisition controls allow you to take and remove data points. The red Quit Data Acq button exits the data collection subroutine and returns to the main screen once your data has been collected. The red cursor will be moved around to take position data from each frame using your mouse.



Be careful not to quit without printing and saving your data! You will have to go back and analyze the data again if you fail to select *Print Results* before selecting *Quit*.

There are just a few more items to point out before getting into calibration, making predictions, taking data and matching your data in more detail. To the right the picture shows the equation box for entering predictions and matching data. Directly above this and below the progress indicator you have controls for setting the range of the graph data and controls for printing and saving. The graphs that display your collected data are shown on the next page. Your predictions are displayed with red lines; fits are displayed with blue lines.





CALIBRATION

While the computer is a very handy tool, it is not smart enough to identify objects or the sizes of those objects in the videos that you take and analyze. For this reason, you will need to enter this information into the computer. If you are not careful in the calibration process, your analysis will not make any sense.

After you open the video that you wish to analyze the calibration screen will open automatically. Advance the video to a frame where the first data point will be taken. To advance the video to where you want time t=0 to be, you need to use the video control buttons. This action is equivalent to starting a stopwatch.

When you are ready to continue with the calibration, locate the object you wish to use to calibrate the size of the video. You must do your best to use an object that is in the plane of motion of your object being analyzed. At times the object under motion can be used, but often placing an additional object in the plane of motion is required.

Follow the direction in the *Instructions* box and define the length of an object that you have measured for the computer. Once this is completed, input the scale length with proper units. Read the directions in the *Instructions* box carefully.

Lastly, decide if you want to rotate your coordinate axes. If you choose not to rotate the axes, the computer will use the first calibration point as the origin with positive x to the right and positive y up. If you choose to rotate your axis, follow the directions in the *Instructions* box very carefully. Your chosen axes will appear on the screen once the process is complete. This option may also be used to reposition the origin of the coordinate system, should you require it, however it might be best to start completely over.

Once you have completed this process, select Quit Calibration.

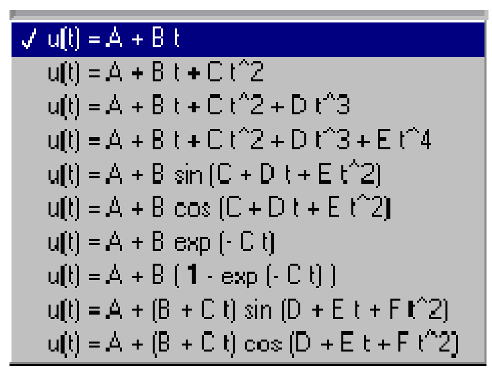
ANALYSIS PREDICTIONS

This video analysis relies on your graphical skills to interpret the data from the videos. Before doing your analysis, you should be familiar with the **Review of Graphs** and **Accuracy, Precision and Uncertainties** appendices..

Before analyzing the data, enter your prediction of how you expect the data to behave. This pattern of making predictions before obtaining results is the only reliable way to take data. How else can you know if something has gone wrong? This happens so often that it is given a name (Murphy's Law). It is 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 into the computer, you first need to decide on your coordinate axes, origin, and scale (units) for your motion. Record these in your lab journal.

Next you will need to select the generic equation, u(t), which describes the graph you expect for the motion along your x-axis seen in your video. You must choose the appropriate function that matches the predicted curve. The analysis program is equipped with several equations, which are accessible using the pull-down menu on the equation line. The available equations are shown to the right.



You can change the equation to one you would like to use by clicking on the arrows to the left of the equation

After selecting your generic equation, you next need to enter your best approximation for the parameters A and B and C and D where you need them. If you took good notes of these values during the filming of your video, inputting these values should be straightforward. You will also need to decide on the units for these constants at this time.

Once you are satisfied that the equation you selected for your motion and the values of the constants are correct, click "*Accept*" in the *Main Controls*. Your prediction equation will then show up on the graph on the computer screen. If you wish to change your prediction simply repeat the above procedure. Repeat this procedure for the Y direction.

DATA COLLECTION

To collect data, you first need to identify a very specific point on the object whose motion you are analyzing. Next move the cursor over this point and click the green *ADD Data Point* button in Data Acquisition control box. The computer records this position and time. The computer will automatically advance the video to the next frame leaving a mark on the point you have just selected. Then move the cursor back to the same place on the object and click *ADD Data Point* button again. So long as you always use the same point on the object, you will get reliable data from your analysis. This process is not always so easy especially if the object is moving rapidly. The data will automatically appear on the graph on your computer screen each time you accept a data point. If you don't see the data on the graph, you will need to change the scale of the axes. If you are satisfied with your data, choose *Quit Data Acq* from the *controls*

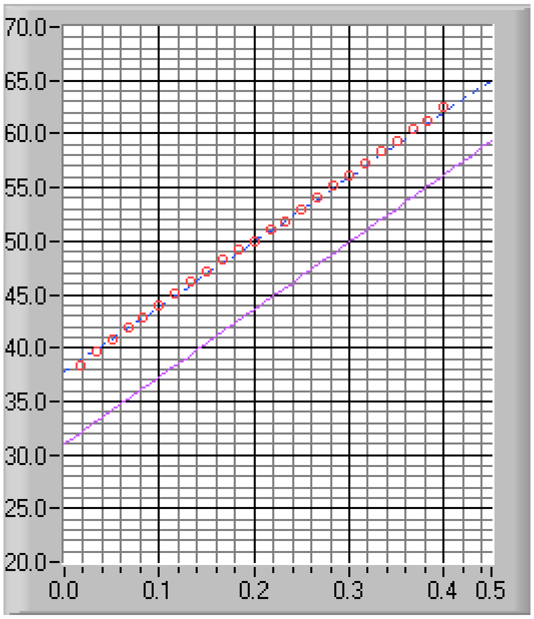
FITTING YOUR DATA

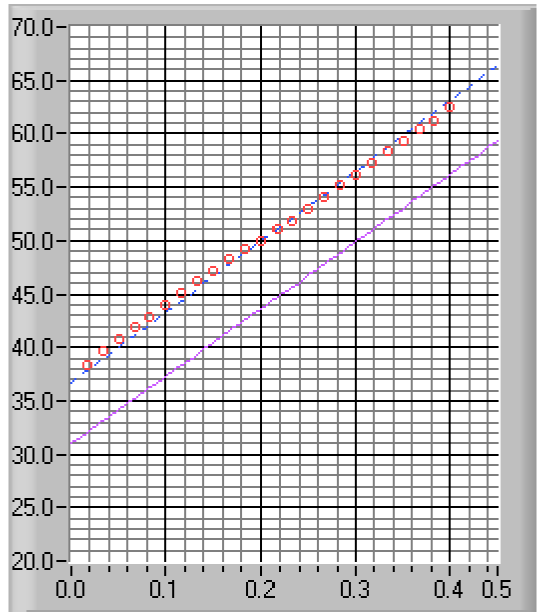
Deciding which equation best represents your data is the most important part of your data analysis. The actual mechanics of choosing the equation and constants is similar to what you did for your predictions.

First you must find your data on your graphs. Usually, you can find your full data set by using the Autorange buttons to the left of the graphs.

Secondly, after you find your data, you need to determine the best possible equation 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.

Lastly, 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. For example, the X-motion plots below show both the predicted line (down) and two other lines that also fit the data (near the circles).





After you have found the uncertainties in your constants, return to your best-fit line and use it as your fit by selecting *Accept x- (or y-) fit* in the *Program Controls* panel.

LAST WORDS

These directions are not meant to be exhaustive. You will discover more features of the video analysis program as you use it. Be sure to record these features in your lab journal.

MAGNETLAB - MEASURING CONSTANT MAGNETIC FIELD

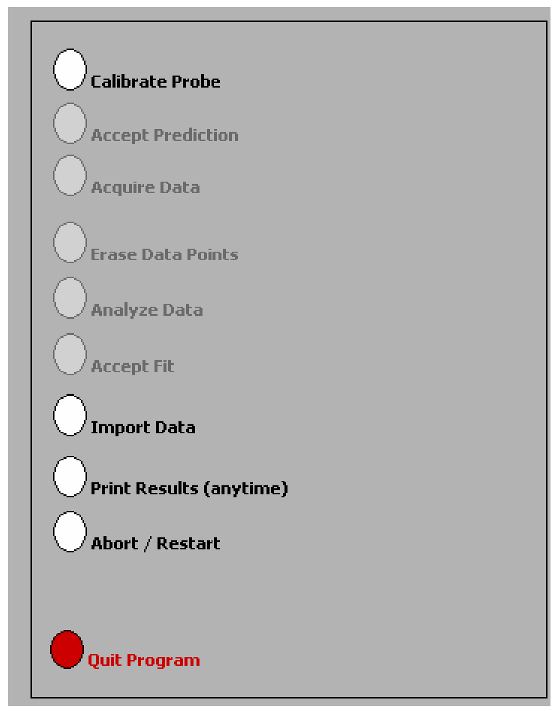
Application Basics

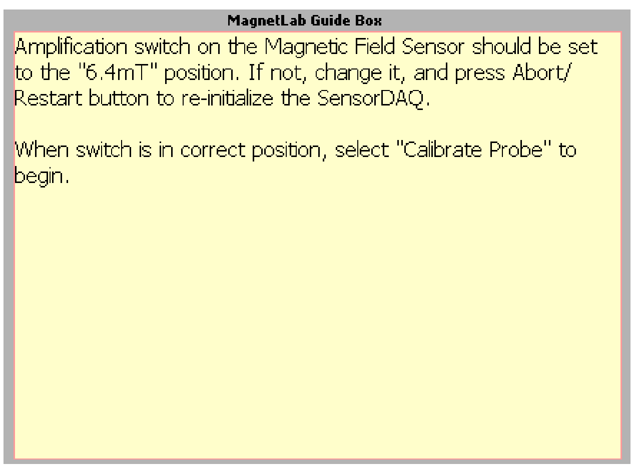
Before you begin, you should ensure that you have read the relevant sections of Appendix A to familiarize yourself with the equipment.

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.

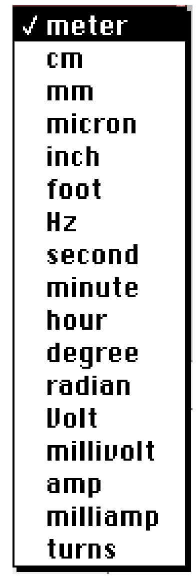
You can also print and/or quit from the Command Panel or abort your analysis and try again.

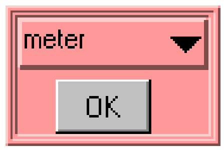
The primary data output you get is by generating pdf files of your results, so be careful not to quit without printing pdf files or exporting your data to be emailed amongst your lab group.

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.

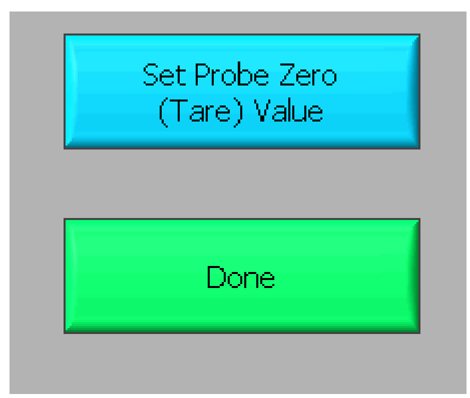
After selecting the "Calibrate Probe" command, you will be asked to do *two* tasks. First, you will need to choose the quantity on the x-axis of your data graph. This is accomplished by moving the cursor over to the word "meter" in the red-colored area (shown below) and then pressing the mouse button.





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.

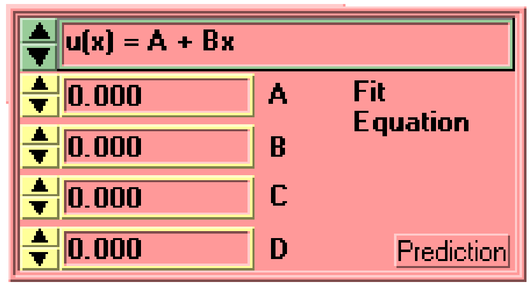


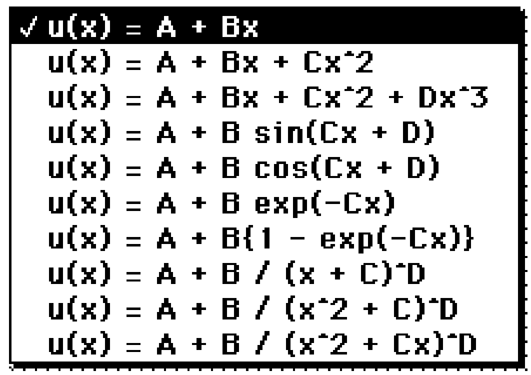
Predictions

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.

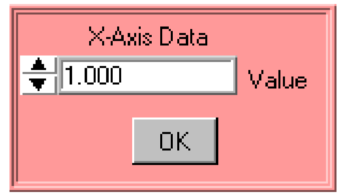
Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes or use the *AutoScale* feature (see Finding Data below). 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.

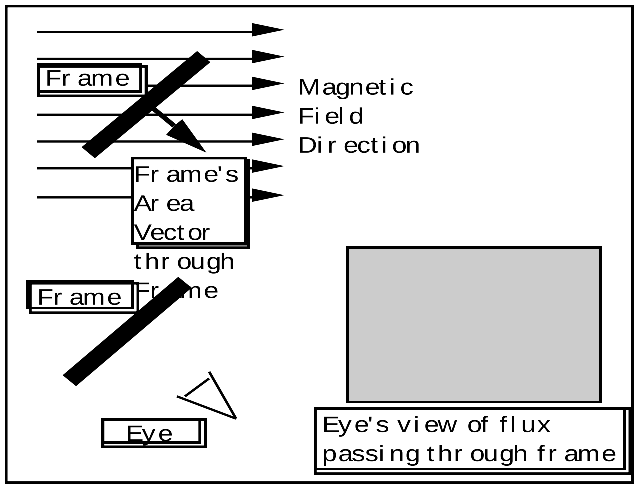
To save your data, simply select *Export Data* and follow the instructions in the windows. Your file should be saved in the **LabData** folder. To retrieve this file, restart *MagnetLab* from the desktop and select *Import Data.*

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.

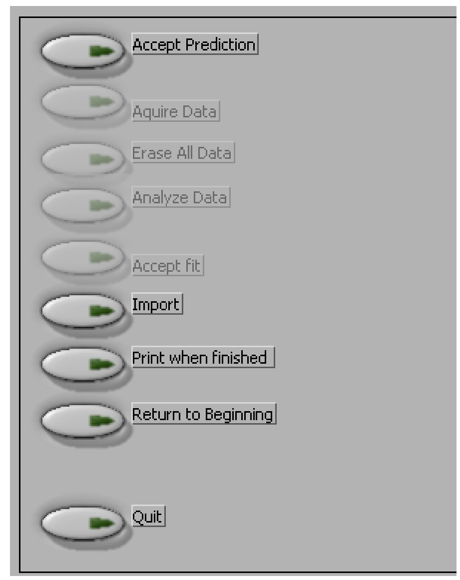
VoltageTimeLAB - MEASURING TIME-VARYING VOLTAGES

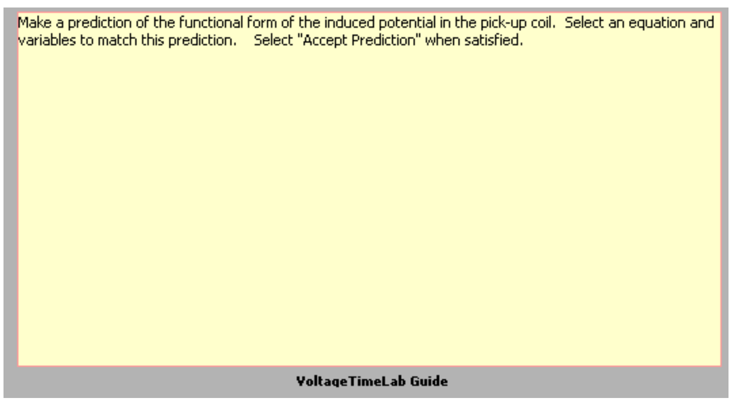
The Basics:

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.

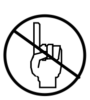
Before you start using the program, you should take a moment to identify several key elements. The two most important of these are the Command Panel, shown to the right, and the Guide Box, shown below.





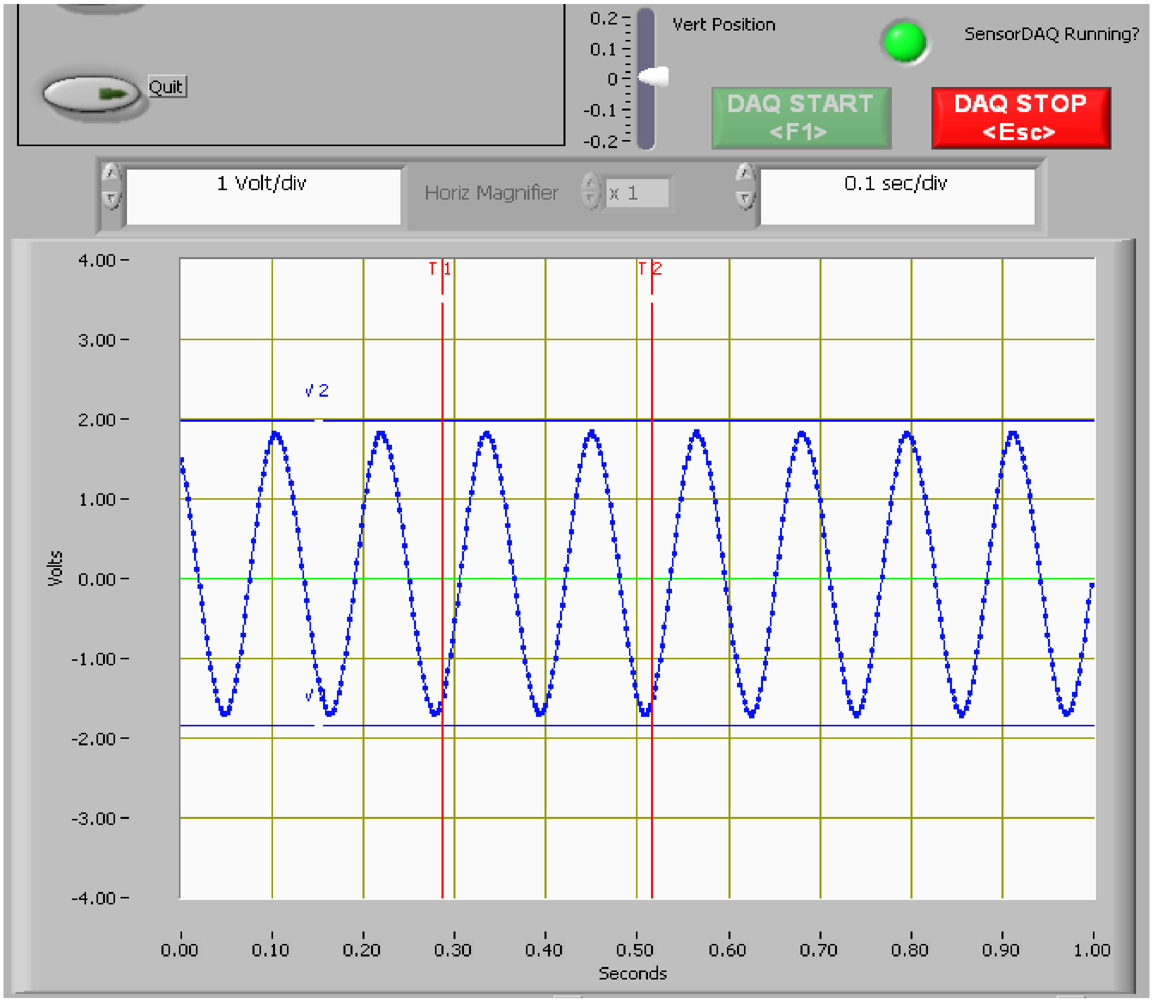
The Guide Box will give you directions and tasks to perform. It will also tell you when to select a command in the Command Panel.

You can also print and/or quit from the Command Panel or abort your analysis and try again.

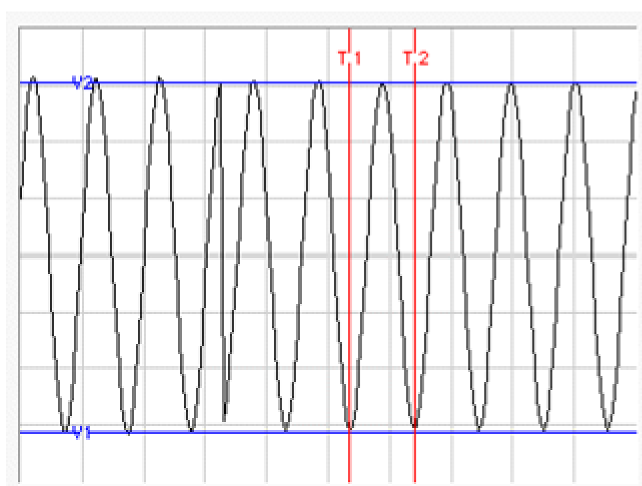


The primary data output you get is by generating pdf files of your results, so be careful not to quit without printing pdf files or exporting your data.

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.

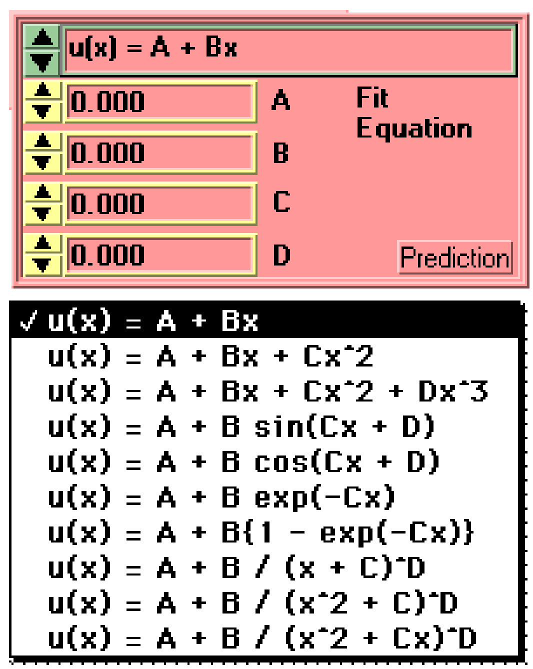
Predictions

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.



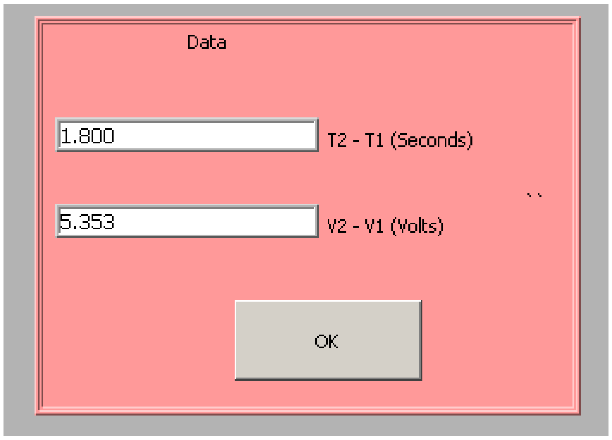
Once you have selected an equation and the values of the constants are entered, your prediction equation is shown on the graph on the computer screen. If you do not see the curve representing your prediction, change the scale of the graph axes (see Finding Data below). When you are satisfied, select 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

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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.*

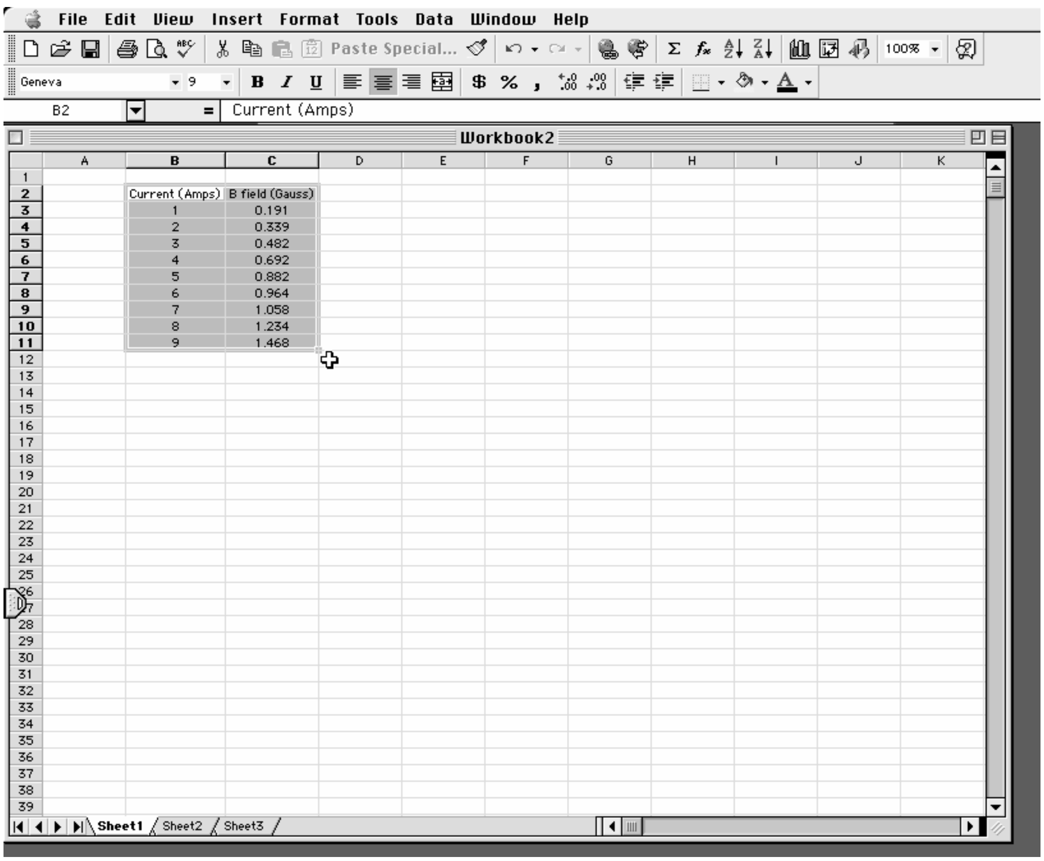
Now you need to estimate the uncertainty in your fit by deciding the range of other lines that *could* also fit your data. This method of estimating your uncertainty is described in the appendix Accuracy, Precision and Uncertainty. Slightly changing the values for each constant in turn will allow you 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.

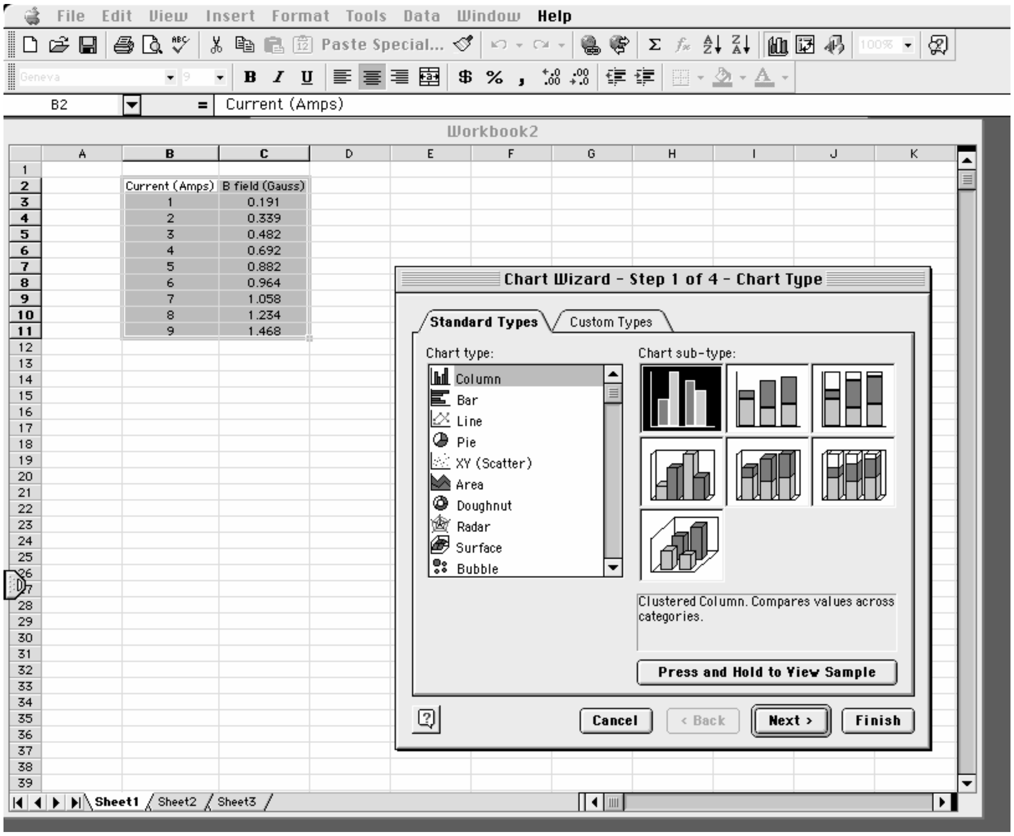
Excel - MAKING GRAPHS

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.

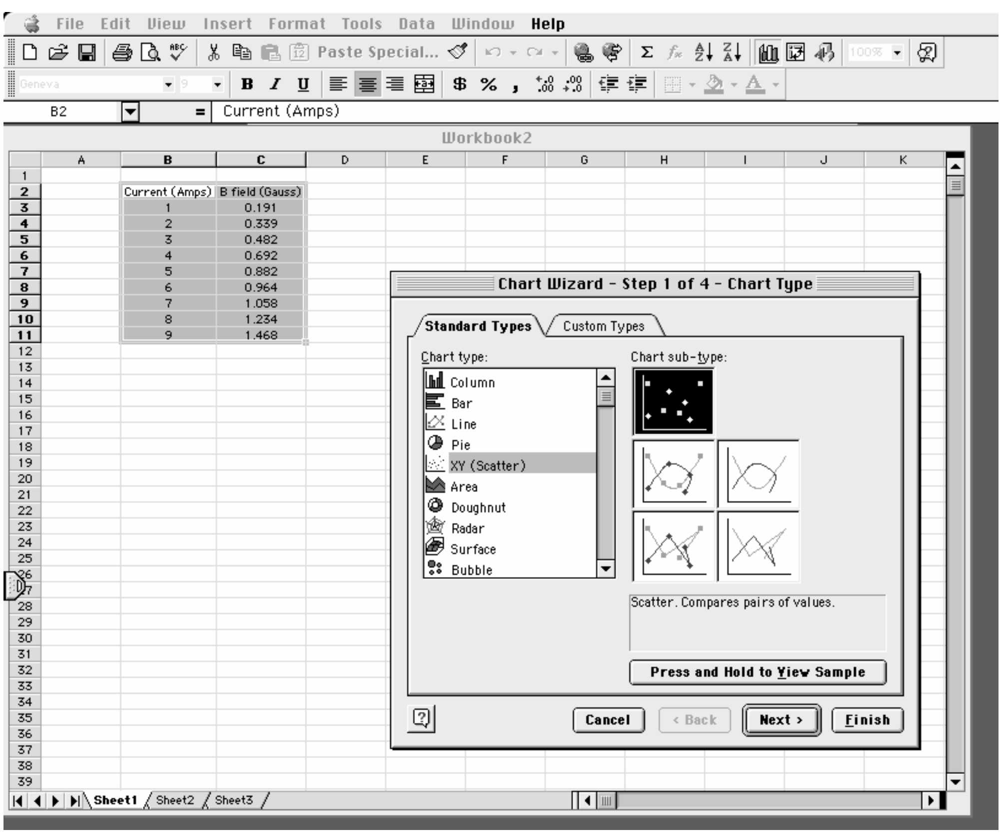
Step 1. Input your measurements and highlight the data using your cursor.



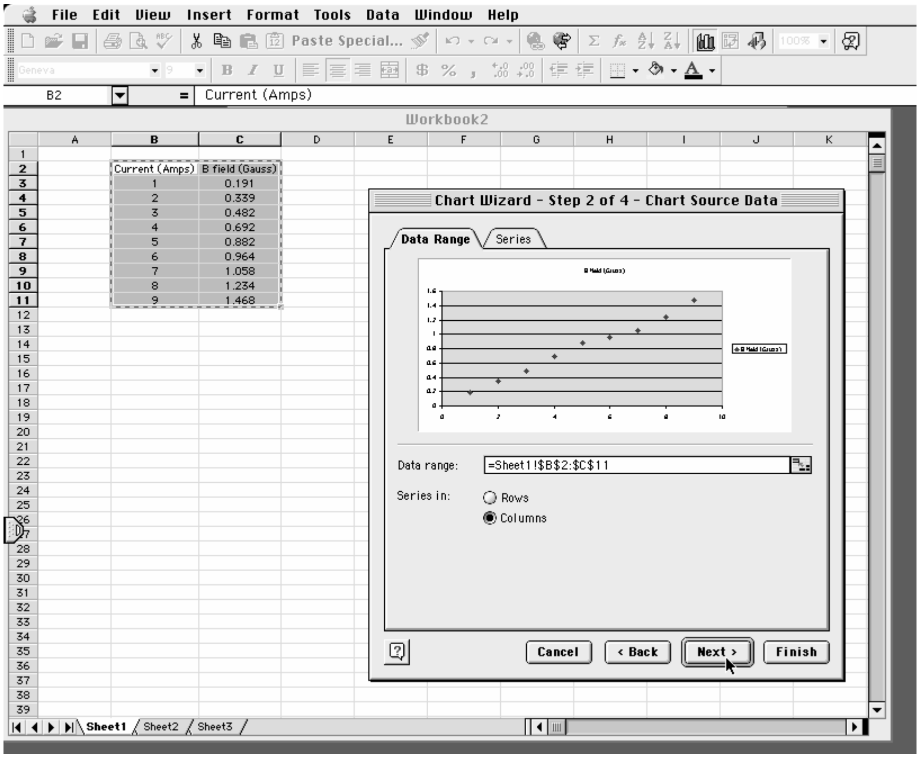
Step 2. Click on the "Chart Wizard" on the toolbar.



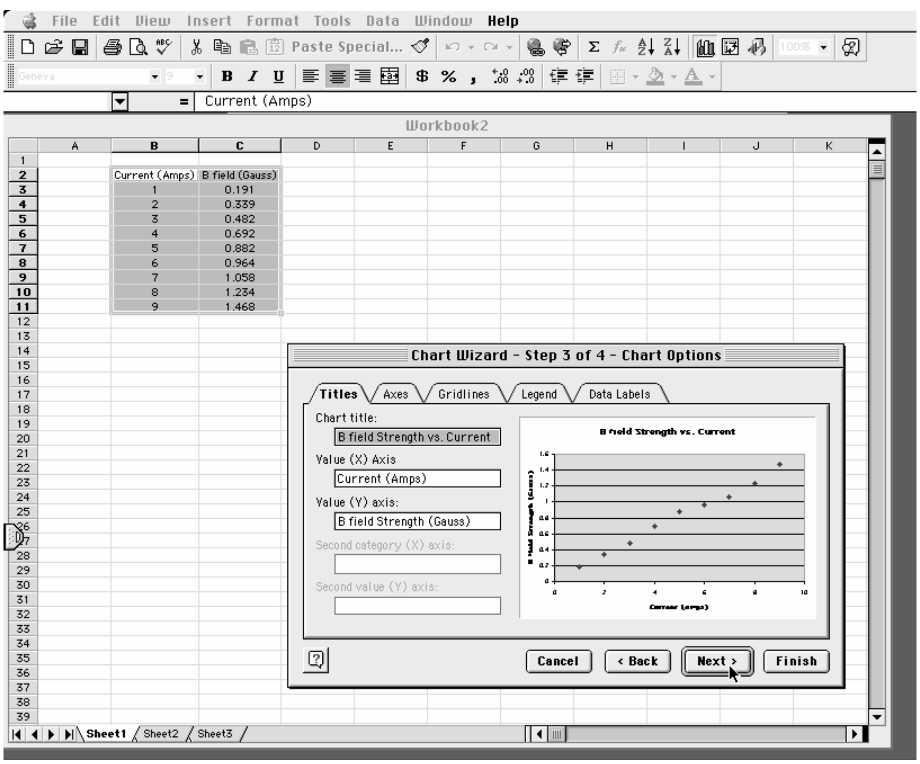
Step 3. Choose XY Scatter, not Line, from the list and click the "Next" button.



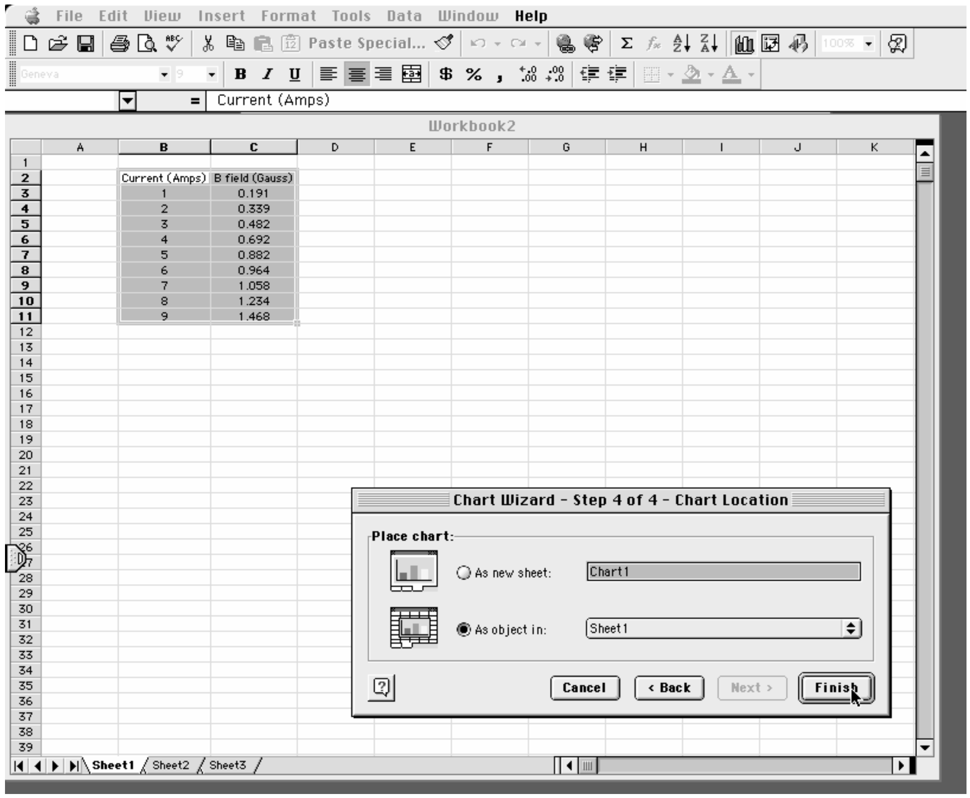
Step 4. Select the "Series in: Columns" option and click the "Next" button.



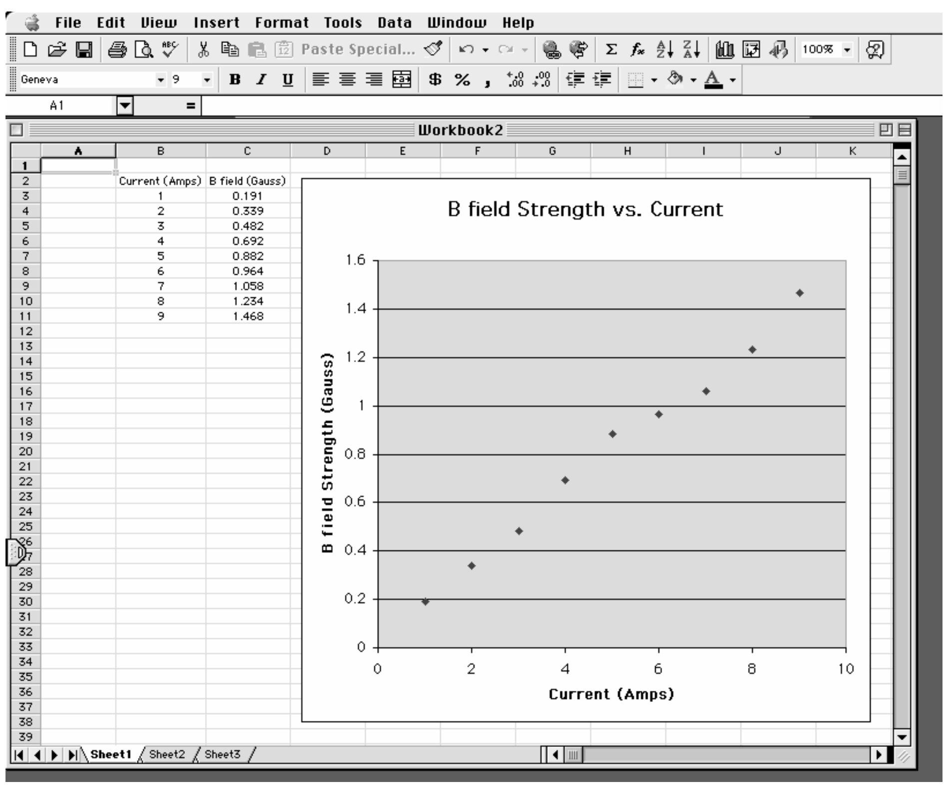
Step 5. Fill in the chart title and axis labels, and click the "Next" button.



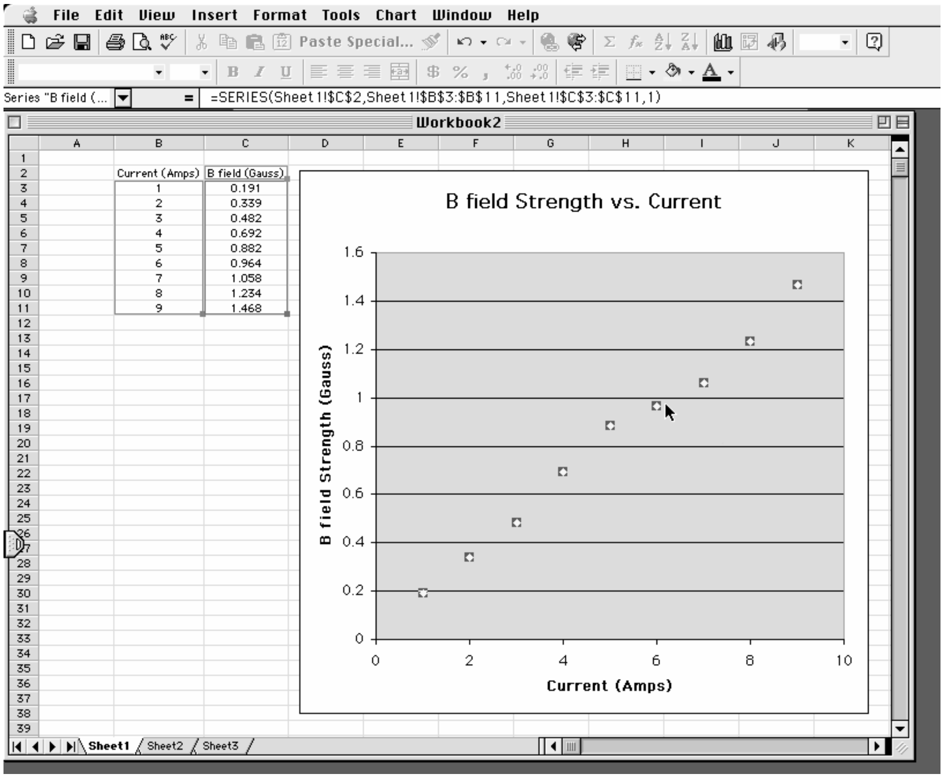
Step 6. Click the "Finish" button.



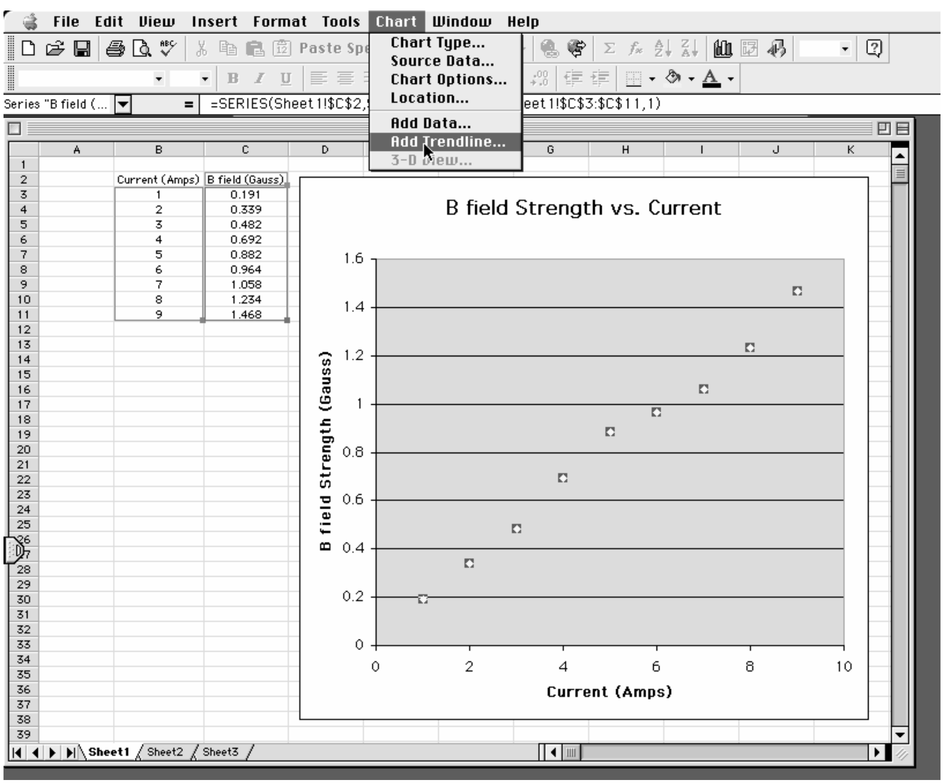
Step 7. Your graph will appear on the worksheet.



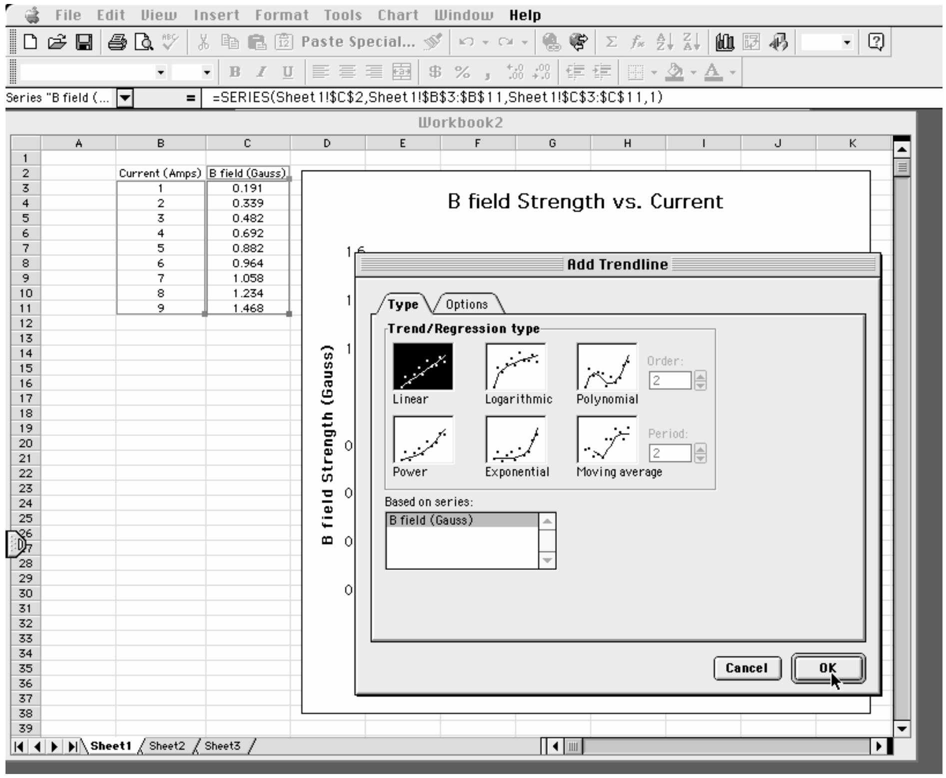
Step 8. Click on the data points to highlight them.



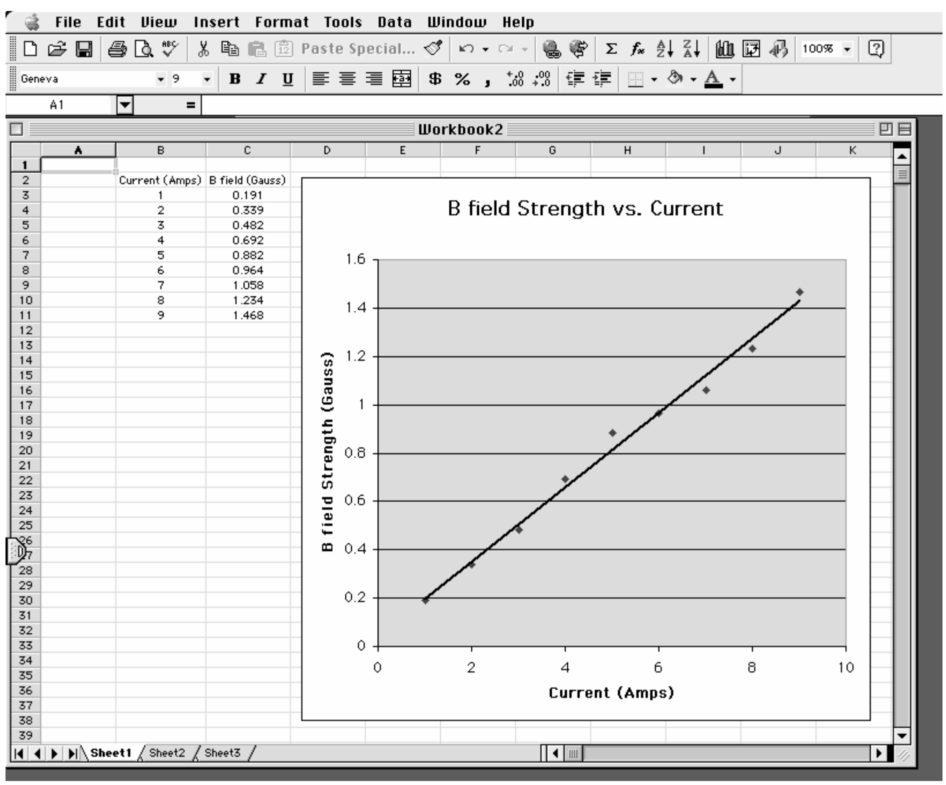
Step 9. Select "Add a Trendline" from the "Chart" menu.



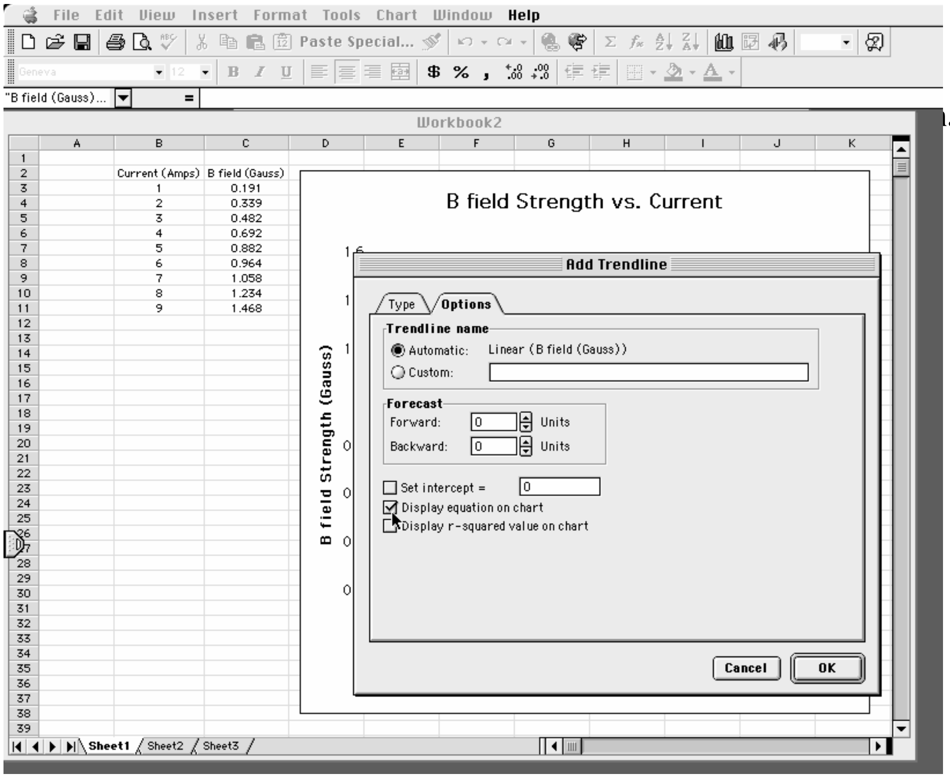
Step 10. Choose the best type of trend line for your data.

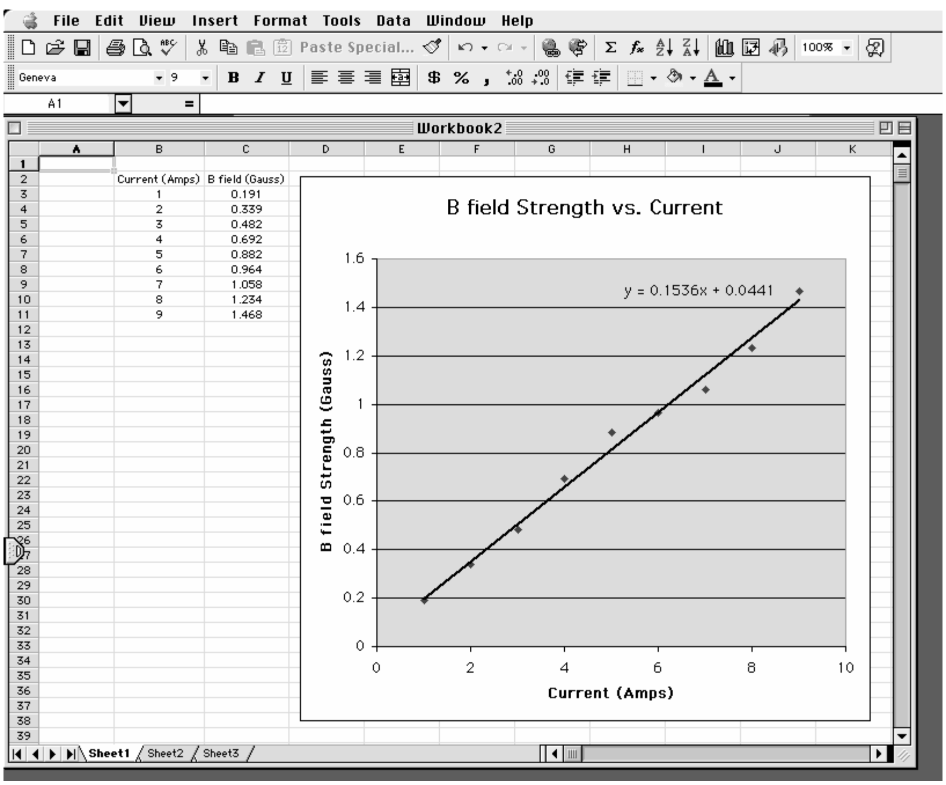


Step 11. The trend line will appear – is it a good fit to your data?



Step 12. If the equation of the line is needed, choose "Display equation on chart."

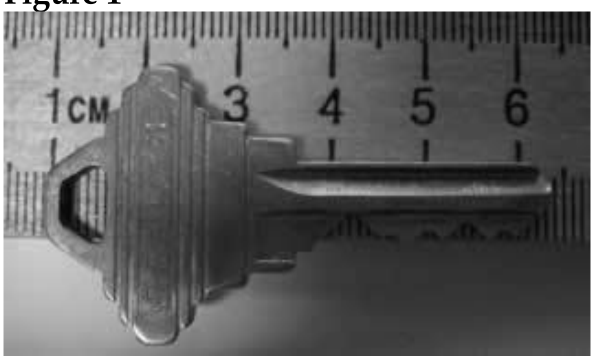




Appendix: **Significant Figures**

Calculators make it possible to get an answer with a huge number of figures. Unfortunately, many of them are meaningless. For instance, if you needed to split $1.00 among three people, you could never give them each exactly $0.333333⋯ The same is true for measurements. If you use a meter stick with millimeter markings to measure the length of a key, as in Figure 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**	17.27
x 2.**5**	x 4.**0**
7920	69.**080**
316**8**	
3**9.600**	
40	69

Division

1**17**	25
2**3**)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}:

[Answer: $121.3 + 6.7 \times 10^{2} = 7.9 \times 10^{2}$]

3. Multiply: 34.2 and 1.5×10^{4}

[Answer: $34.2 \times 1.5 \times 10^{4} = 5.1 \times 10^{5}$]

Appendix: 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?

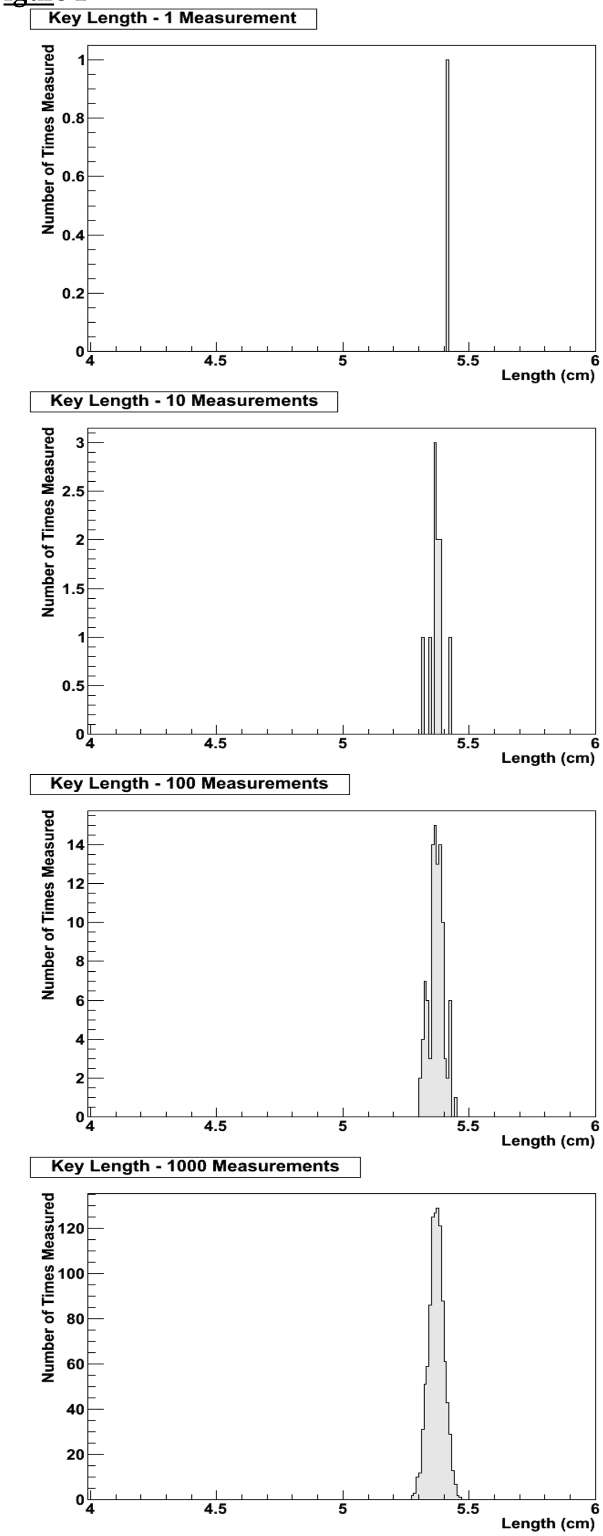
Whenever you measure something, there is always some uncertainty. There are two categories of uncertainty: **systematic** and **random**.

(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

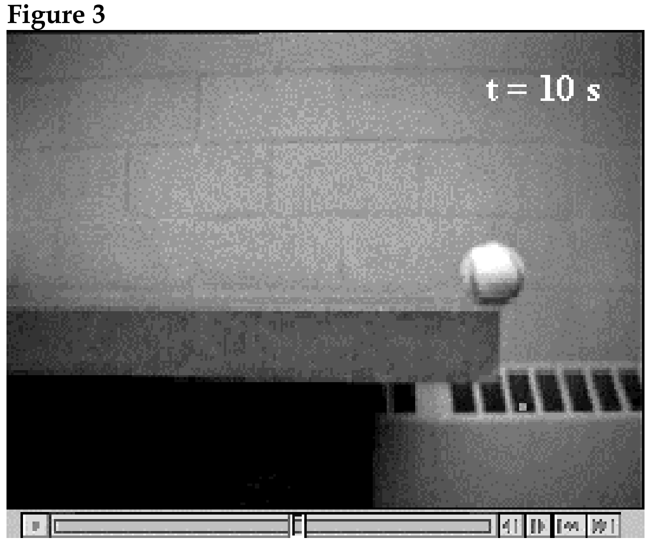
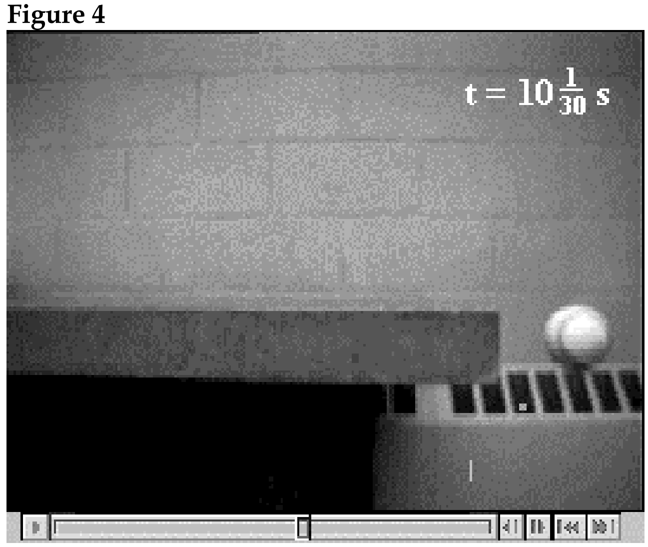


Figure 4



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

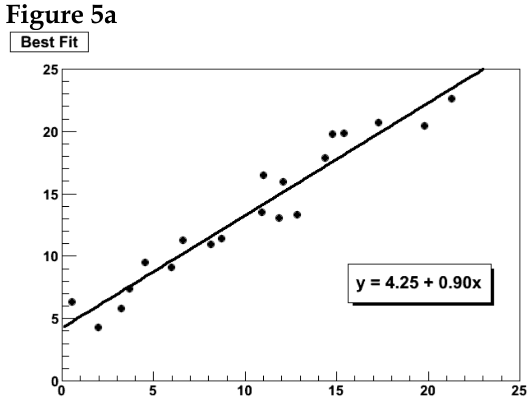


Figure 5b

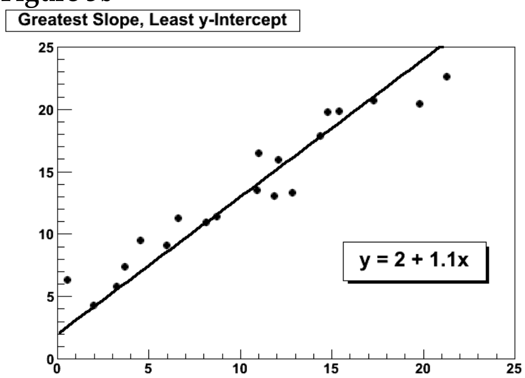
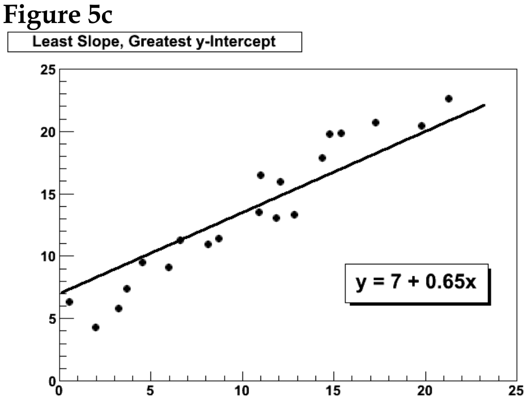


Figure 5c

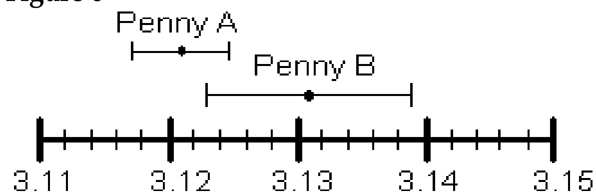


However you choose to determine the uncertainty, you should always state your method clearly in your report.

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:

<table>
<tr>
<td>

Addition:

(3.131 ± 0.008 g) + (3.121 ± 0.004 g) = ?

First, find the sum of the values:

3.131 g + 3.121 g = 6.252 g

Next, find the largest possible value:

3.139 g + 3.125 g = 6.264 g

The uncertainty is the difference between the two:

6.264 g – 6.252 g = 0.012 g

Answer: 6.252 ± 0.012 g.

Note: This <u>uncertainty</u> can be found by simply adding the <u>individual</u> <u>uncertainties</u>:

0.004 g + 0.008 g = 0.012 g

</td>
<td>

Multiplication:

(3.131 ± 0.013 g) x (6.1 ± 0.2 cm) = ?

First, find the product of the values:

3.131 g x 6.1 cm = 19.1 g-cm

Next, find the largest possible value:

3.144 g x 6.3 cm = 19.8 g-cm

The uncertainty is the difference between the two:

19.8 g-cm - 19.1 g-cm = 0.7 g-cm

Answer: 19.1 ± 0.7g-cm.

Note: The <u>percentage</u> <u>uncertainty</u> in the answer is the sum of the <u>individual</u> <u>percentage</u> <u>uncertainties</u>:

$$\frac{0.013}{3.131} \times 100\% + \frac{0.2}{6.1} \times 100\% = \frac{0.7}{19.1} \times 100\%$$

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

Subtraction:	***Division:***
(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.*	(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

Answers: a) Yes, 11%; b) No, 7%; c) Yes, 3.3%

B-2. The area of a rectangular metal plate was found by measuring its length and its width. The length was found to be 5.37 ± 0.05 cm. The width was found to be 3.42 ± 0.02 cm. What is the area and the average deviation?

Answer: 18.4 ± 0.3 cm^2

B-3. Each member of your lab group weighs the cart and two mass sets twice. The following table shows this data. Calculate the total mass of the cart with each set of masses and for the two sets of masses combined.

Cart (grams)	**Mass set 1** (grams)	**Mass set 2** (grams)
201.3	98.7	95.6
201.5	98.8	95.3
202.3	96.9	96.4
202.1	97.1	96.2
199.8	98.4	95.8
200.0	98.6	95.6

Answers:

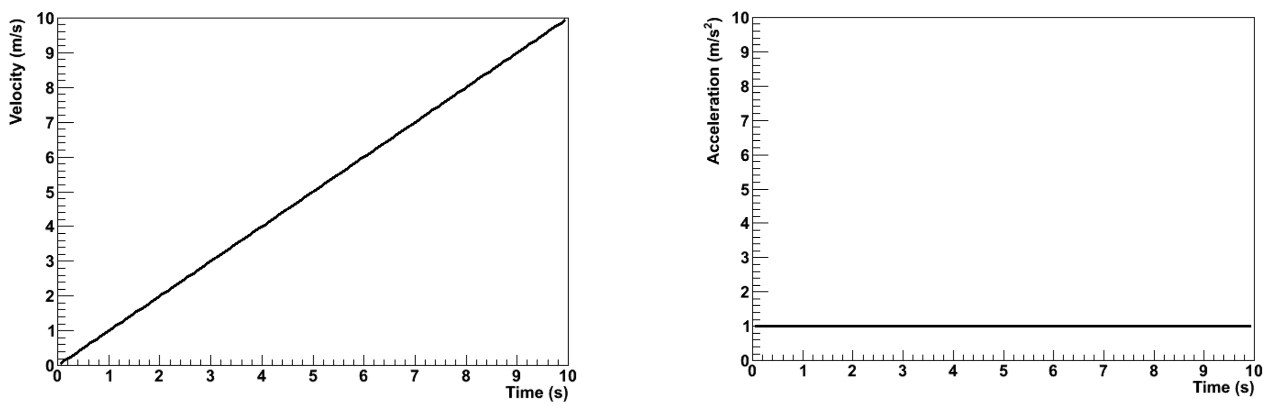
Cart and set 1: 299.3±1.6 g.
Cart and set 2: 297.0±1.2 g.
Cart and both sets: 395.1±1.9 g.

Appendix: **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

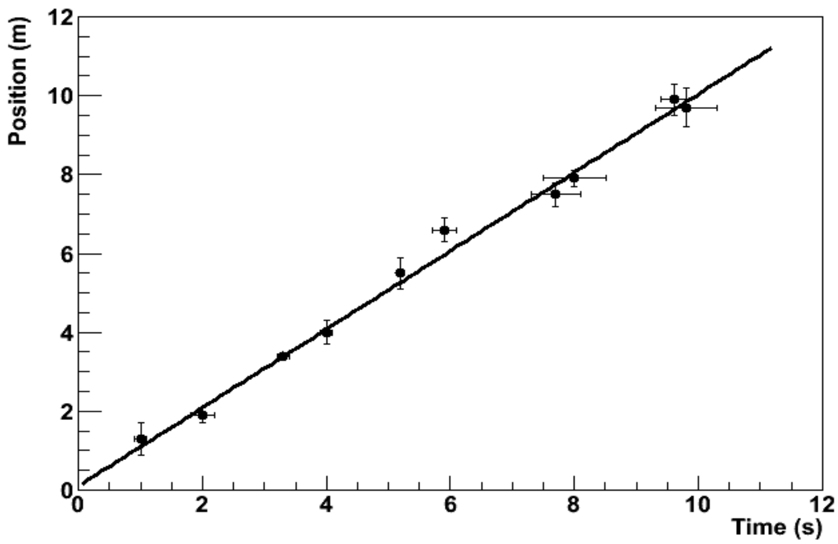


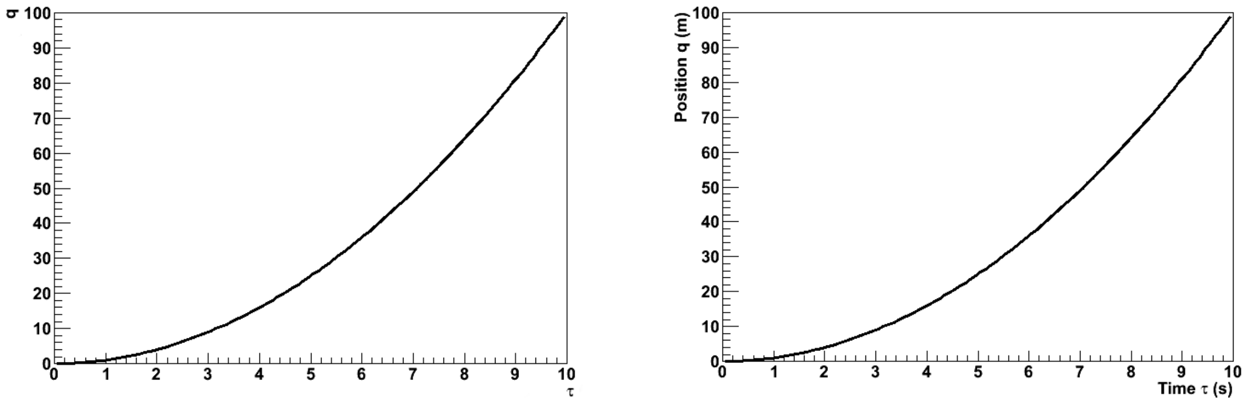
Figure 2: An empirical data set with associated uncertainties and a best-fit line.

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.



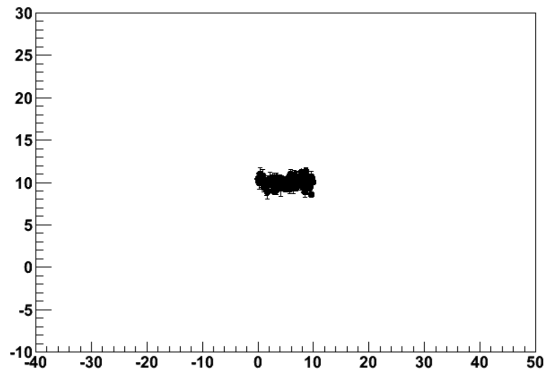
(a)

(b) Position q with respect to time τ for a mass of 3kg. The acceleration is constant.

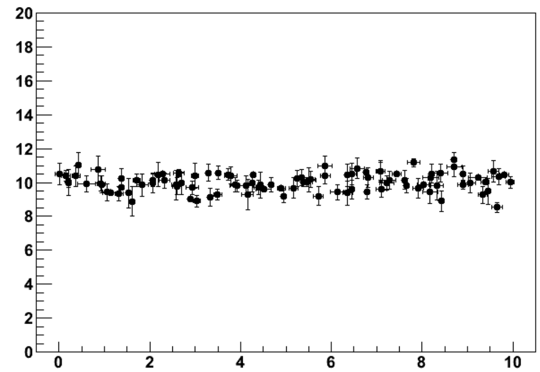
Figure 4: Poorly- versus well-labeled and -captioned graphs. The labels and caption make the second graph much easier to interpret.

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."

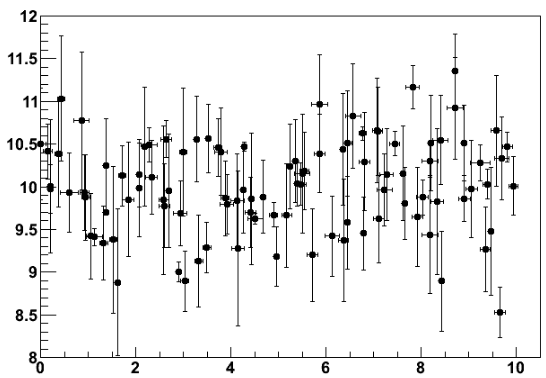
Lastly, we should choose the ranges of our axes so that our meaning is clear. Our axes do not always need to include the origin; this may just make the graph more difficult to interpret. Our data should typically occupy most of the graph to make it easier to interpret; see Figure 5. However, if we are 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.

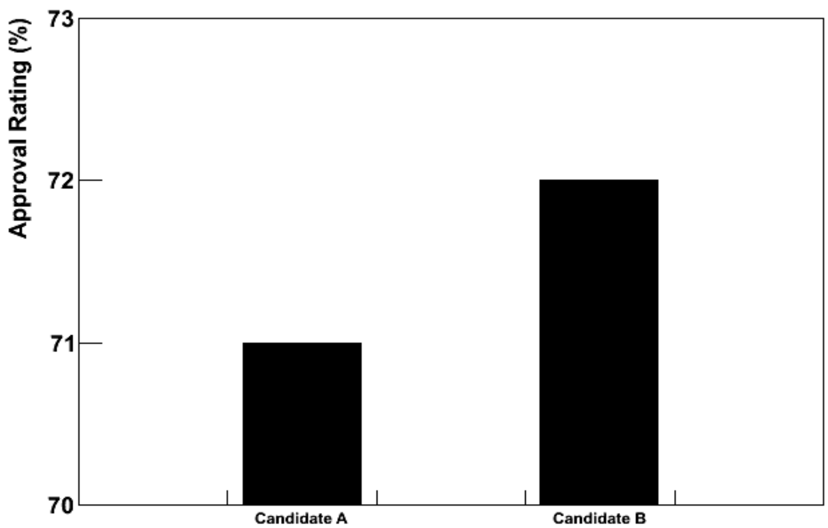


Figure 6: Approval ratings for two candidates in a mayoral race. This graph is designed to mislead the reader into believing that Candidate B has a much higher approval rating than Candidate A.

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.

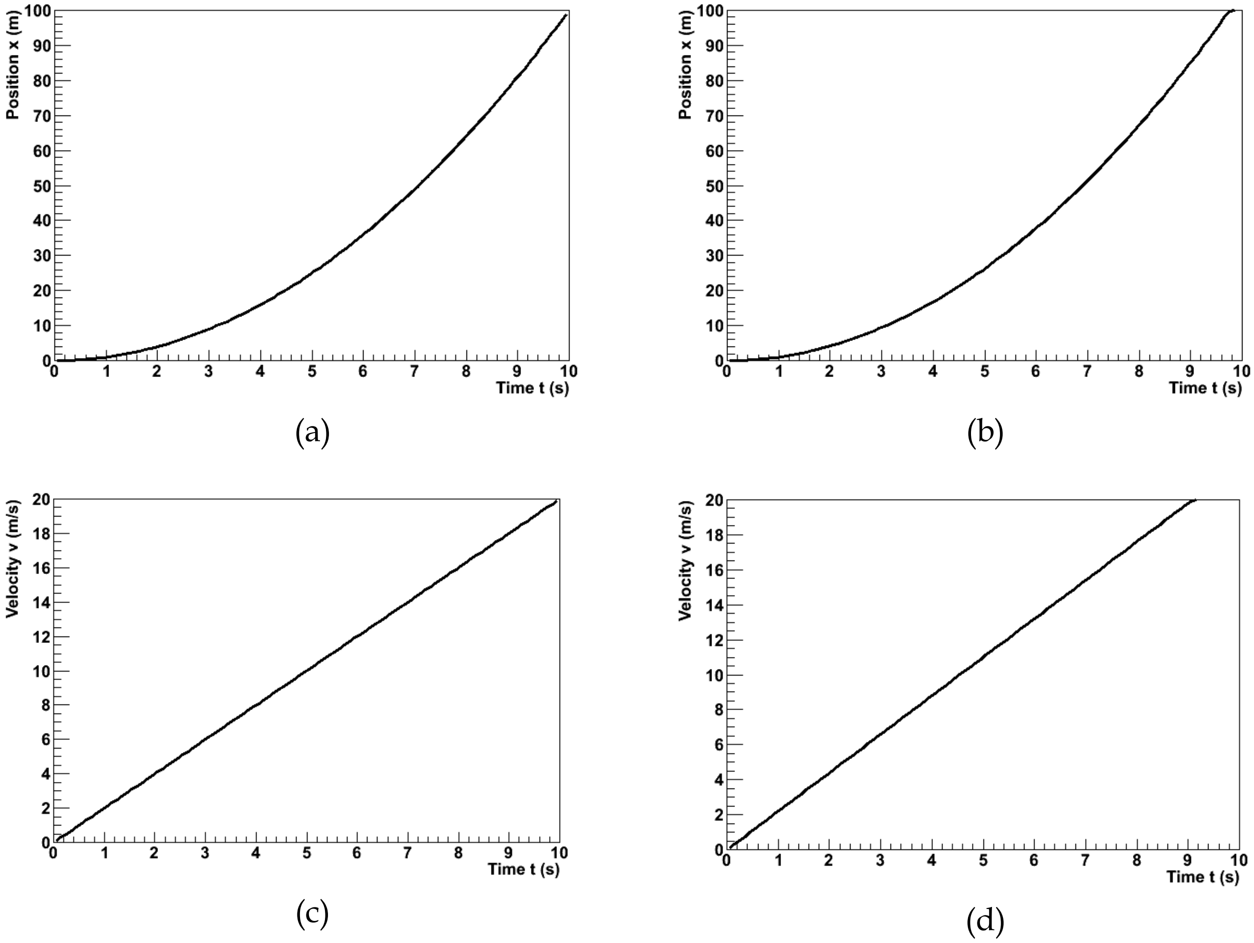


Figure 7: Position and velocity with respect to time for an objects with slightly different accelerations. The difference is easier to see in the velocity graphs.

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.

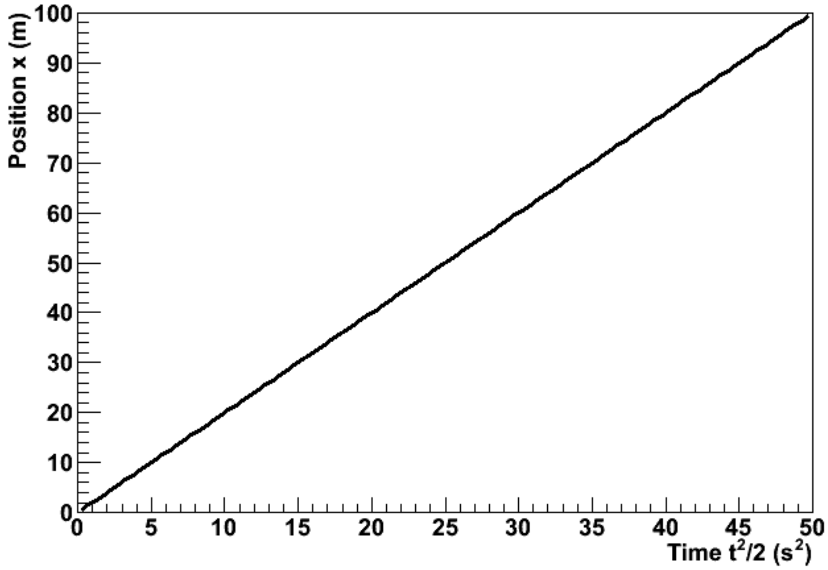


Figure 8: The position of the first object from Figure 7 plotted with respect to $t^2/2$. The relationship has been linearized.

Appendix: **Guide to Writing Lab Reports**

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 answerthat 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 scientifically 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 of the 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. Yourprediction 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 (=Δ) in the vertical component of its velocity (=v_y) during a particular change (=Δ) in time (=t)" would become

$$a_y = \frac{\Delta v_y}{\Delta t}$$

One way you could find this value is as the slope of Vy versus z in your MotionLab data.

What Should I Put in My Lab Report?

Structure your report like this.

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 the Conclusion 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 4: Projectile Motion and Mass

Athos
July 12, 2011
Physics 1101W, Professor: Porthos, TA: Aramis

Introduction

A group of medieval warfare enthusiasts is planning a reenactment and intends to build a trebuchet. If the reenactment is to be safe and realistic, the motion of the projectiles it launches must be well understood. The acceleration of the projectile is constant in time, as confirmed by a previous experiment. This experiment sought to understand the mass dependence of that constant acceleration. To do so, the projectiles were modeled using balls; the trebuchet, using an experimenter's arm. The hypothesis that the acceleration is mass-independent was confirmed.

Prediction

It is hypothesized that the acceleration of an object in projectile motion is mass-independent; this is depicted graphically in Figure 1.

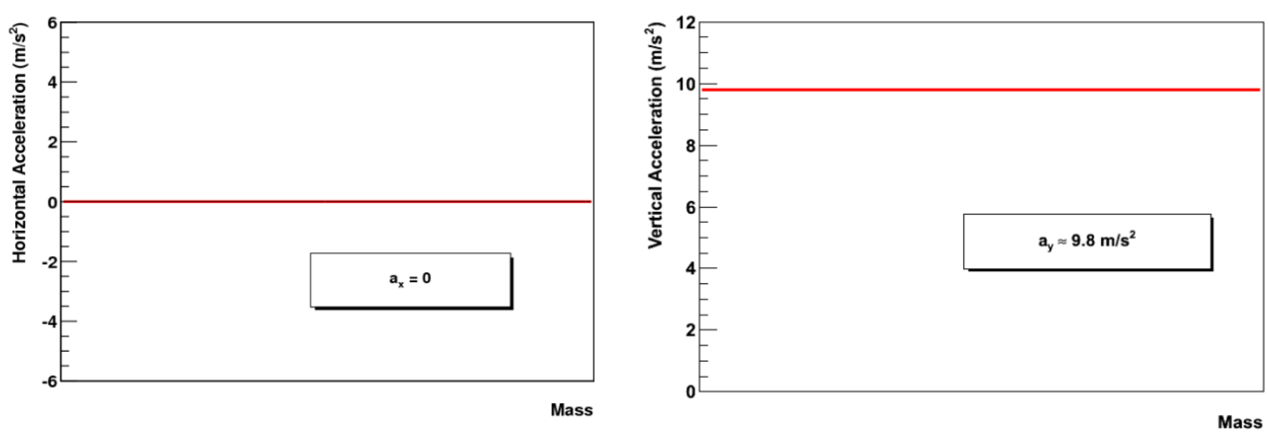


Figure *1*: Horizontal and vertical components of acceleration of a projectile near Earth's surface.

The acceleration of all objects moving ballistically near the surface of Earth is downward and of a magnitude given by local g, approximately 9.8m/s , i.e. is constant with respect to mass. Mathematically,

$$\frac{\Delta\vec{a}}{\Delta m} = \vec{0}$$

This is an assumption of our theory of kinematics.

Procedure

Spherical balls, all of approximately the same size (in order to make approximately constant the effects of air resistance) but of varying masses, were used to model the projectiles. The force of the trebuchet was modeled by throwing by the experimenters. The resulting projectile motion was recorded with a video camera; MotionLab analysis software was used to generate (horizontal position, vertical position, time) triplets at each frame in the trajectories and, by linear interpolation, (horizontal velocity, vertical velocity, time) triplets between each pair of consecutive frames in the trajectories. A meter stick was placed less than 5cm behind the projectiles' plane of motion for calibration of this software. The position and velocity of each projectile as functions of time were fit
by eye as parabolas and lines, respectively. The acceleration of each projectile was then taken to be the slope of the velocity fit because this was deemed more reliable than the position fit and because it was easier to quantify the error in the velocity fit.

Two trajectories were analyzed in this fashion. Due to time constraints, the results of all the lab groups were combined to yield enough data for the analysis. The other groups' procedures were similar, but the details are unknown.

Data

M(g)	a_y(m/s^2) (low)	a_y(m/s^2) (best fit)	a_y(m/s^2) (high)
48.8	9.7	10.0	10.7
51.4	9.3	9.5	11.1
57.3	9.0	10.0	10.6
75.0	9.0	9.7	10.0
141.2	9.1	9.8	10.5
148.6	9.3	9.9	10.8
165.5	9.4	10.0	10.5

Table *1*: The vertical accelerations as measured by MotionLab fits of velocity and the associated masses. The uncertainty in all of the masses is 0.3g

Analysis

The accelerations in the vertical (y) direction as measured by the fits are given in Table 1 in the Data section. The accelerations in the horizontal (x) direction are not given because they are all 0. Errors were assigned to the fits by finding the maximal and minimal values of the parameters which yield apparently valid fits. A constant, the average of the "best fit" accelerations listed in Table 1, was then taken as the single parameter in a 0-degree polynomial fit to the data. The error was taken to be the standard deviation from this parameter. The fit is depicted in Figure 2.

As Figure 2 illustrates, the fit falls within the error of all the data points, so it is valid to say that this has confirmed the prediction that the vertical acceleration is constant with respect to mass.

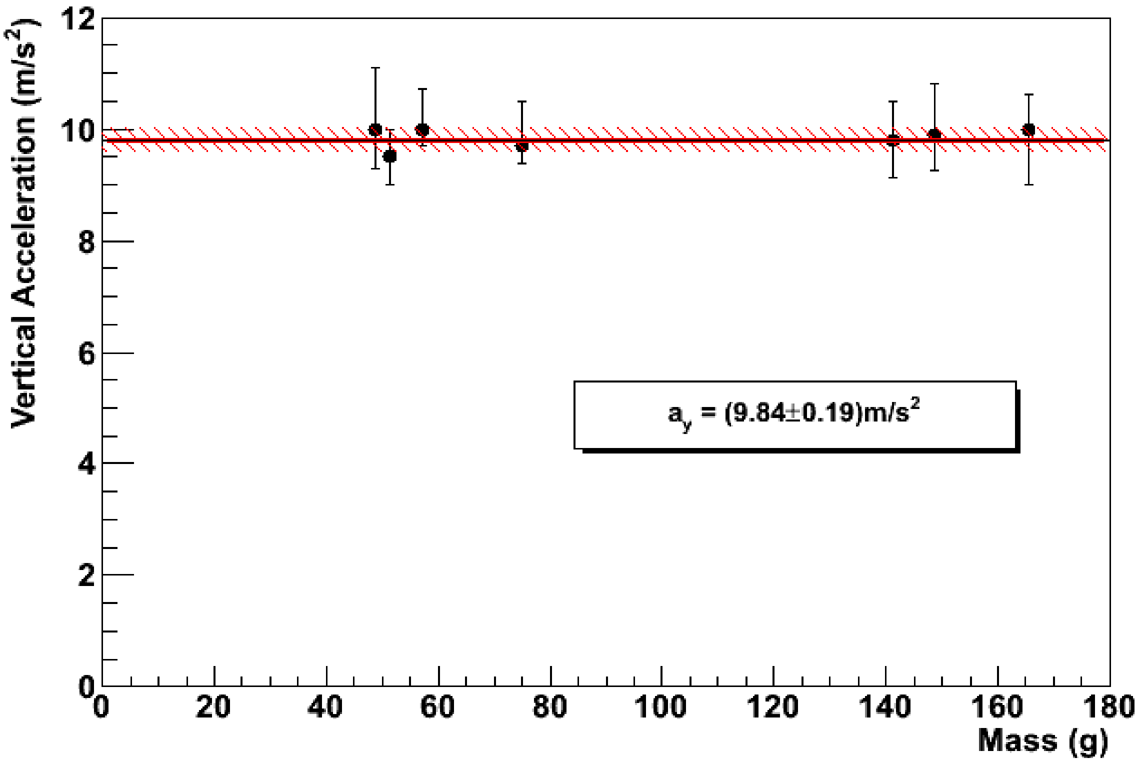


Figure *2*: The measured vertical accelerations versus the respective projectile masses and the constant fit thereto. The errors in the masses are smaller than the markers.

Because all of the horizontal accelerations $a_x = 0$, the hypothesis that the horizontal acceleration of the projectiles is constant with respect to mass has been confirmed; although there exists a nonzero uncertainty in all of these measurements, 0 lies within all possible error intervals.

Possible sources of systematic error include air resistance, distortion due to the camera's optics, error in calibration due to the offset depth of the trajectories versus the meter stick, and the constraint that the first frame of the ball's motion was at time 0, which is accurate only to 0.016s. These, and any other systematics, are believed to be insignificant because the average and expected accelerations in both the horizontal and vertical directions are consistent with the individual measurements to within experimental error.

Conclusion

The motion of projectiles launched by trebuchets was modeled by thrown balls. The hypothesis that the horizontal accelerations thereof are mass-independent was confirmed in that all were measured to be 0. The hypothesis that the vertical accelerations thereof are mass-independent was confirmed in that a single, constant acceleration of $9.84 m/s^2$ lay within the error intervals of all of the measured data points.

BAD SAMPLE LAB

Lab II, Problem 4

Comte de Rochefort

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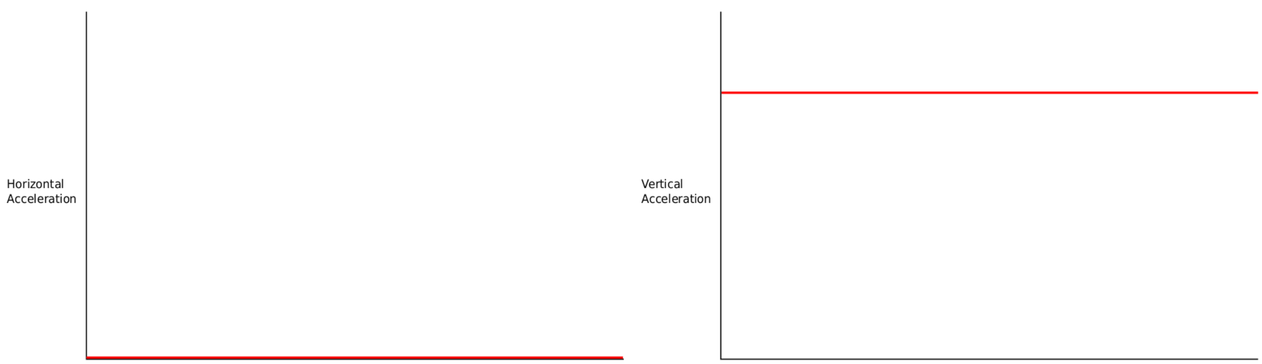
Introduction

We want to figure out how the trebuchet's projectiles will move if their mass is changed. A trebuchet is a kind of medieval catapult that uses gravity to launch rocks. First, we threw balls to simulate the rocks. We recorded them with a camera. Then, we analyzed the videos using MotionLab. Then, we decided that the acceleration does not change when the mass changes.

Prediction



Procedure

The procedure in this experiment began with setup. We collected the following materials:

- meter stick
- tennis ball
- baseball
- video camera on tripod
- computer with MotionLab software
- stopwatch

We then positioned the camera facing the wall. We taped the meter stick to the wall.

We next recorded the videos. We threw the tennis ball in a parabolic trajectory parallel to the wall and recorded a video of it with the camera and computer. We did the same for the baseball.

We then analyzed the videos with MotionLab. We began by setting t=0 to the time when the ball left General Veers's hand. We then used the meter stick to calibrate the length in the video. We defined our coordinate system. It had the origin where the ball was at t=0, x was horizontal, and y was vertical. We then had to make predictions about the position graphs. Since there is no acceleration in the x direction, we predicted it would be a straight, linear line. Since there is acceleration in the y direction, we predicted it would be quadratic. We derived the coefficients for the predictions by measuring how high and how far the ball went with the meter stick and how long it flew with the stopwatch. The first ball flew 88+/-0.05cm in the x direction and 90+/-0.05cm in the y direction, and took 0.85+/-0.005s to complete it’s trajectory. The second ball flew 110+/- 0.05cm in the x direction and 60+/-0.05cm in the y direction. It took 0.86+/- 0.005s to complete it’s trajectory. The predicted equations were x=0+1.054t and y=0+4.185t-4.9tˆ2 for the first ball and x=0+0.694t and y=0+4.185t-4.9tˆ2 for the second ball. We then added a data point at each frame in the ball’s flight. We omitted some frames near the end of the video when the ball was in the distorted region. We took 24 data points for the first ball and 29 data points for the second ball. We fit graphs to the resulting data points. The fits were x=0+1.05t and y=0+3.47t-5tˆ2 for the first ball and x=0+0.71t and y=0+4.37t-5tˆ2 for the second ball. We then had to predict the velocity graphs of the balls. We did this by making the t coefficient in the position function the constant in the velocity function and the tˆ2 coefficient in the position function the t coefficient in the velocity function. This made the xv graph a constant line and the yv graph a linear line. The predictions were xv=1.05+0t and yv=3.47-10t for the first ball and xv=0.71+0t and yv=4.37-10t for the second ball. After this, we had to fit the velocity graphs to the data points. The fits were xv-1.05+0t and yv=3.47-10t for the first ball and xv=0.71+0t and yv=4.37-10t for the second ball. The fits were the same as the predictions, so there were no errors in the predictions. We then got the accelerations from the coefficients of the fits. This was 0.5 of the tˆ2 coefficient in the position fit and the same as the t coefficient in the velocity fit.

After analyzing the videos, we exchanged data with the other groups, left the lab, and analyzed the data.

Data

Ball 1
mass: 57.3+/-0.05g
x distance: 88+/-0.05cm
y distance: 90+/-0.05cm
time: 0.85+/-0.005s
x prediction: x=0+1.054t
x fit: x=0+1.05t
y prediction: y=0+4.185t-4.9tˆ2
y fit: y=0+3.47t-5tˆ2
xv prediction: xv=1.05+0t
xv fit: xv=1.05+0t
yv prediction: yv=3.47-10t
yv fit: yv=3.47-10t

Ball 2
mass: 48.8+/-0.05g
x distance: 110+/-0.05cm
y distance: 60+/-0.05cm
time: 0.86+/-0.005s
x prediction: x=0+0694t
x fit: x=0+071t
y prediction: y=0+4.185t-4.9tˆ2
y fit: y=0+4.37t-5tˆ2
xv prediction: xv=0.71+0t
xv fit: xv=0.71+0t
yv prediction: yv=4.37-10t
yv fit: yv=4.37-10t

Ball 3
mass: 165.5+/-0.05g
x prediction: x=0+1.126t
x fit: x=0+1.13t
y prediction: y=0+3.915t-4.9tˆ2
y fit: y=0+3.37t-4.9tˆ2
xv prediction: xv=1.13+0t
xv fit: xv=1.13+0t
yv prediction: yv=3.37-9.8t
yv fit: yv=3.37-10t

Ball 4
mass: 51.4+/-0.05g
x prediction: x=0+0.877t
x fit: x=0+0.82t
y prediction: y=0+4.469t-4.9tˆ2
y fit: y=0+3.8t-4.7tˆ2
xv prediction: xv=0.82+0t
xv fit: xv=0.82+0t
yv prediction: yv=3.8-9.4t
yv fit: yv=3.8-9.5t

Ball 5
mass: 141.2+/-0.05g
x prediction: x=0+1.203t
x fit: x=0+1.21t
y prediction: y=0+3.258t-4.9tˆ2
y fit: y=0+3.1t-4.9tˆ2
xv prediction: xv=1.21+0t
xv fit: xv=1.21+0t
yv prediction: yv=3.1-9.8t
yv fit: yv=3.1-9.8t

Ball 6
mass: 148.6+/-0.05g
x prediction: x=0+1.281t
x fit: x=0+1.4t
y prediction: y=0+3.258t-4.9tˆ2
y fit: y=0+4.1t-4.95tˆ2
xv prediction: xv=1.4+0t
xv fit: xv=1.4+0t
yv prediction: yv=4.1-9.9t
yv fit: yv=4.1-9.9t

Ball 7
mass: 75.0+/-0.05g
x prediction: x=0+0.943t
x fit: x=0+1.07t
y prediction: y=0+3.895t-4.9tˆ2
y fit: y=0+3.3t-4.85tˆ2
xv prediction: xv=1.07+0t
xv fit: xv=1.07+0t
yv prediction: yv=3.3-9.7t
yv fit: yv=3.3-9.7t

Analysis

We calculate the accelerations from the fits because we know x = x0 + v0*t + 1/2*a*tˆ2. All the accelerations in the x direction are therefore 0. The accelerations in the y direction are -10m/sˆ2, -10m/sˆ2, -9.8m/sˆ2, -9.4m/sˆ2, -9.8m/sˆ2, -9.9m/sˆ2, -9.7m/sˆ2.

We know that the x accelerations should be 0 because we are ignoring air resistance. We know that the y accelerations should be -9.8m/sˆ2. All of the y accelerations are close to this. They differ by 0.2m/sˆ2, 0.2m/sˆ2, 0m/sˆ2, 4m/sˆ2, 0m/sˆ2, 0.1m/sˆ2, and 0.1m/sˆ2; these are all small.

There are several important sources of error in this lab. One is the fisheye effect of the camera lens. Another is the finite accuracy of the measuring devices. The stopwatch can only measure to 0.01s, and the meter stick can only measure to 0.001m, so these measurements are only accurate to half of those values. There is error in MotionLab, too, as can be seen in the differences between some of the position and velocity fits. There was error in that we couldn't throw the balls exactly the same every time. Finally, there could have been human error. We know that all of these errors were not significant, though, because all of the measurements of acceleration were so close to the known right values.

Conclusion

We measured the acceleration of seven balls in projectile motion and got things very close to the right values every time. We can therefore say that the mass dependence of the accelerations in the x and y directions are both constant. In the x direction, it is 0m/sˆ2, and in the y direction, it is -9.8m/sˆ2. This was true for all the masses. This is the same as our original prediction. We can therefore say that this experiment was a success.