PHY 122 Lab Manual

Thomas More College, Algebra-based Introductory Physics

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Preface

This text is intended for a one or two-semester undergraduate course in introductory algebra-based physics.

Download the PDF here

A full PDF version of this document can be found at spring-lab-manual.pdf (719 kB).

Contents

Lab 1

Review the Skills of PHY 121 Lab

In this lab, you will be provided a worksheet of some straightforward exercises that require you to use the following skills that you should have learned in the first term (PHY 121).

- measurement uncertainty
- propagation of uncertainty
- accuracy versus precision
- %-error and %-difference
- Using DataStudio and the Capstone software
- Tabulate data in excel
- Graph data in excel
- Linear Regression
- How to write a Lab Report

The point of this to provide you with an opportunity to ask questions and develop any skills you may have lost track of between then and now.

Lab 2

Archimedes' Principle

Experimental Objectives

- After verifying some properties of the buoyant force using Archimedes' principle, each group will predict the maximum amount of cargo (the number of pennies) that a ship (beaker) will hold without sinking.

Archimedes was a Greek scientist who lived from 287-212 BCE. As the story goes, the king thought that his crown was not pure gold and asked Archimedes to determine if this was true. Archimedes had previously observed that a totally submerged object displaces a volume of fluid which is equal to the volume of the object, and deduced what is now called Archimedes' principle: that the buoyant force on the submerged object is equal to the weight of the displaced fluid. Knowing the weight and density of gold, Archimedes measured the weight of the crown and the weight and volume of the water displaced by the crown, enabling him to determine that the crown was not pure gold.

As any swimmer who has had their head more than about 8 feet deep can tell you, the pressure exerted on the diver by the water increases as the diver swims deeper into the water. We can express this as: the pressure within a fluid is dependent on the depth at which the object sits (h), the gravitational acceleration of the earth (g), and the density of the fluid (ρ_f):

$$P = \rho_f g h. \tag{2.1}$$

Because of this, the bottom surface of any object in a fluid will have more pressure on it than the top surface. This ΔP gives rise to a net upward force acting on the submerged object: the buoyant force (F_B). The magnitude of the upward force depends on the density of the fluid and the size of the object:

$$F_B = \rho_f g V_o, \tag{2.2}$$

where V_o is *the submerged portion* of the volume of the object. A partially submerged object has a smaller buoyant force than a completely submerged object. Interestingly, unless the fluid density depends on the depth of the fluid, the F_B is independent of the depth of the object.

Knowing the buoyant force will help you determine if an object will float or sink. To determine whether an object will sink or float one should use Newton's second law to determine the direction of the net force. Assuming the simplest case of a submerged object feeling only its weight ($F_g = m_o g = \rho_o g V_o$) and the buoyant force ($F_B = \rho_f g V_o$), if the weight of the object is greater than F_B then the net force on the object is down and it will sink. If F_B is larger than the weight then the net force on the object is up and then it will accelerate up. However, when an object is floating, it is in equilibrium and the object's weight is equal to F_B, which depends on the submerged volume. While floating, not all of the object is submerged.

2.1 Pre-Lab Work

Please do the following exercises before coming to lab

Exercise 2.1.1 (Derive F_B)**.** Using the relationship between force and pressure and the relationship between pressure and depth, derive the equations for the buoyant force and for the object's weight.

Hint 1 (force and pressure). $F = PA$

Hint 2 (pressure and depth). Recall Equation (2.1).

Hint 3 (buoyant force). Recall Equation (2.2). Assume the object is completely submerged.

Hint 4 (weight in terms of density). The weight, $F_g = m_o g$, when written in terms of the density of the object and the volume of the object is $F_g = \rho_o g V_o$.

Solution 1 (buoyant force).

$$
\begin{aligned}
F_B &= F_{bottom} - F_{top} \\
F_B &= (P_{bottom}A) - (P_{top}A) \\
F_B &= (\rho_f g h_{bottom}A) - (\rho_f g h_{top}A) \\
F_B &= \rho_f g(h_{bottom} - h_{top})A \\
F_B &= \rho_f g(h_{object})A \\
F_B &= \rho_f g V_{object}
\end{aligned}
$$

Solution 2 (weight). Since $\rho = m/V$,

$$F_g = m_o g = (\rho_o V_o)g = \rho_o g V_o$$

Exercise 2.1.2 (Buoyant Force is depth-independent)**.** Show that although the pressure on an object does depend on depth within the fluid, the $\Delta P = P_{\text{bottom}} - P_{\text{top}}$ (and therefore F_B) is independent of the depth within the fluid.

Hint. The derivation of F_B in Exercise 2.1.1 will show this.

Solution. See Solution 2.1.1.1.

Consider and compare the following three situations.

Exercise 2.1.3 (Fully submerged, large density)**.** Consider a completely submerged object that has a density that is larger than the density of the fluid.

1. Draw a free-body diagram.
2. Indicate which force is larger in any.
3. Which direction is the net force?
4. Does the object "want" to float or sink?

Exercise 2.1.4 (Fully submerged, small density)**.** Consider a completely submerged object that has a density that is smaller than the density of the fluid.

1. Draw a free-body diagram.
2. Indicate which force is larger in any.
3. Which direction is the net force?
4. Does the object "want" to float or sink?

Exercise 2.1.5 (Partially submerged)**.** Consider an object that has a density that is smaller than the density of the fluid and is allowed to float.

1. Draw a free-body diagram.
2. Indicate which force is larger in any.
3. Which direction is the net force?
4. Using Newton's Second Law show that if an object has a density $\rho_o = .5\rho_f$ that only 0.5 of the object's volume is submerged.

Write a brief paragraph comparing the important differences between those three situations.

Exercise 2.1.6 (density of water)**.** Look up the density of water.

2.2 Procedure

Activity 2.2.1 (Develop Your Understanding)**.** Do the following to prepare for the experiment.

(a) Select an object for which you can easily measure the volume using a caliper.

(b) Measure the dimensions and calculate the volume.

Hint 1. Remember to account for the uncertainty.

Hint 2. You learned about the uncertainty of calipers in http://physics.thomasmore.edu/Labs/121/s-mm-pro.html, from PHY 121L.

(c) Measure the mass using the scale-balance at your table.

Hint 1. Since you will be comparing this to a measurement of the apparent mass, which cannot be measured using the electronic scale, you should use the scale balance at your lab table rather than the electronic scale at the front of the room.

Hint 2. Using the same scale for both of these measurements will help to cancel out any intrinsic calibration errors.

(d) Calculate the density of the object. How does this compare to the density of water?

Hint 1. Remember to include the uncertainty!

Hint 2. Why is it relevant to compare the density of the object to the density of water? (Recall Exercises 2.1.3–2.1.5.)

(e) Predict what buoyant force this object would have if it were completely submerged in water. You will compare calculations based on measurements to this number in Task 2.2.2.h.

Hint. Remember to include the uncertainty!

(f) Predict what a scale would read if this object were completely submerged in water. (This is called the "apparent weight".) You will compare the actual measurement to this number in Task 2.2.2.g.

Hint. Remember to include the uncertainty!

Activity 2.2.2 (Verify Your Understanding)**.** You should ensure that you understand these results *with uncertainty* before continuing. If this doesn't make sense, then check your numbers, check your units, remeasure quantities that you thought you were sure of, and ask your instructor.

(a) Place a balance on top of a support rod so that the side with the string dangling can drop into a container of water.

(b) Place an overflow container under the scale so that the string can dip into the container if the lab jack is raised or lowered.

(c) Find the mass of your catch beaker.

Hint. The catch beaker should be a finely-marked graduated cylinder because you will be using it to measure both the volume and the mass of the fluid that overflows from the overflow container.

(d) Place a catch beaker next to the overflow container and slowly fill the overflow container until it *just starts* dripping. Gently tap the overflow container once. ***Be very careful not to bump your table after this.***

(e) As thoroughly as possible, drain and dry off your catch beaker and put it back in place. If you cannot dry it off completely, you will not be able to accurately complete all of the necessary steps.

(f) Attach your object to the string, measure the mass of the object, m_o, *in air* while the object dangles above the water.

(g) Raise the lab jack until the object is completely submerged. ***Be sure to catch all of the water that overflows from the container!*** The scale should now read a reduced mass, m_s, for the submerged object. Record this value. Does it agree with your prediction in Task 2.2.1.f?

(h) You now have three ways of calculating the buoyant force: (Pay attention to which of these three is the most precise and why.)

(a) The water (via the buoyant force) supports the difference in weights between not submerged and totally submerged. Calculate the buoyant force, with uncertainty, as the difference in these *weights*. Does it agree with your prediction in Task 2.2.1.e?

(b) Measure the volume of the overflow water. This is equal to the volume of the object submerged, $V_f = V_o$. Calculate (with uncertainty) the buoyant force from this volume, $F_B = \rho_f g V_o$. Does this agree with your prediction in Task 2.2.1.e?

(c) Note that $\rho_f V_f = m_f$, so instead of measuring V_f, we can measure the mass of the overflow water. The buoyant force can also be found from: $F_B = m_f g$, the weight of the fluid. Does this agree with your prediction in Task 2.2.1.e?

Activity 2.2.3 (Consider How the Buoyant Force Changes as an Object is Submerged)**.** For this part, you are going to repeat the previous procedure, with three modifications. First, you won't be able to measure the volume with a caliper. Second, based on Task 2.2.2.h, we now know which measurement provides the best estimate (smallest uncertainty) for the buoyant force, so you should only need to use that best technique for measuring the buoyant force. Finally, we will consider an object in air, partially submerged, and fully submerged.

(a) Select a fairly large object for which you cannot easily measure the volume using a caliper. This must fit within the overflow container without touching the sides.

(b) Refill the overflow container, as before, until is just starts to overflow.

(c) As thoroughly as possible, dry off your catch beaker. If you cannot dry it off, you will have to measure its mass with whatever water is in it and you will not be able to use the previous section technique Item 2 because you cannot accurately measure the volume of new water.

(d) Attach the object to the string hanging from the balance and find the mass in air, m_o.

(e) ***You will need to do the rest of this* very *carefully. Go slowly and do not bump the table.*** Raise the lab jack until the object is about half submerged. Catch the overflow water.

(f) Measure the apparent mass of the object and the mass or volume of the overflow water, as appropriate for using the best method

- Calculate the buoyant force with uncertainty.
- Calculate the volume (with uncertainty) of the object that is submerged.

(g) Without removing any of the water from the catch beaker, continue to submerge the object and catch the overflow water until the object is completely submerged.

(h) Measure the new apparent mass of the object and the mass or volume of the overflow water, as appropriate for using the best method

- Calculate the buoyant force with uncertainty.
- Calculate the volume (with uncertainty) of the object that is submerged.
- Calculate the density (with uncertainty) of the object.

Once all of that has gone well and you are comfortable with your understanding of the buoyant force, you are now trained to run a "shipyard". Congratulations!

Activity 2.2.4 (Fill the Cargo-Hold)**.**

(a) You have been provided with a beaker and some pennies. Use the information in the previous sections to predict the maximum number of pennies that can be gently placed into the beaker without allowing it to sink. You should measure the mass of the beaker and the dimensions of the beaker. The volume of a cylinder is $V = \pi r^2 h$. You should also measure about 30 pennies (all at once) to find an average mass for the pennies.

After you have calculated your prediction with uncertainty, prepare the overflow canister with water and dry the catch beaker. Invite the instructor to your table and allow the instructor to test your prediction.

2.3 Questions

1. Why does an object weigh a different amount when in air and when submerged in water?

Hint. The answer to this question might be a useful sentence to include in your theory section.

2. Why is it important to make certain that no air bubbles adhere to the object during the submerged weighing procedures?

Hint. The answer to this question might be useful to include in your theory section. Alternatively, if you mention this as a source of uncertainty (in the analysis), then you should also address (in the procedure) what you did to minimize the chance of this happening.

3. What would the buoyant force be for an object that was immersed in a fluid with the same density as the object?

Hint. The answer to this might make an interesting supplemental statement if you discuss Exercise 2.1.3 and Exercise 2.1.4 in your report.

4. A floating barge filled with coal is in a lock along the Ohio River. If the barge accidentally dumps its load into the water, will the water level in the lock rise or fall?

Hint. Trying to figure out the answer to this question will help you think about the ideas relevant to this chapter in the text. Some instructors might consider asking this question on a quiz or an exam.

5. There are two identical cargo ships. One has a cargo of 5 tons of steel and the other has a cargo of 5 tons of styrofoam. Which ship floats lower in the water?

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A PDF version might be found at Archimedes.pdf (141 kB)

Lab 3

Standing Waves on a String

Experimental Objectives

In this experiment, the conditions required for the production of standing waves in a string will be investigated in order to

- empirically verify the relationship between the frequency (f), wavelength (λ), and speed of a standing wave (v), for a series of normal modes of oscillation, and
- use the two relationships of the speed of the wave

$$v = \sqrt{\frac{F_T}{m/L}} \tag{3.1}$$

$$v = \lambda f \tag{3.2}$$

to empirically relate the string tension (F_T) and the wave velocity (v), for one mode of oscillation, specifically the fundamental mode.

A wave is the propagation of a disturbance in a medium. In a transverse wave, the disturbance of the medium is perpendicular to the direction of the propagation of the wave. In this experiment, transverse waves will be propagated along a taut flexible string. The frequency of the waves is determined by the source, the wave generator, which is driving one end of the string. The speed of the waves, v, is determined by the medium itself; namely the linear mass density of the string, (m/L), and the tension in the string which is determined by the static force of a mass suspended from the other end of the string, F_T. This is expressed by Equation (3.1) above.

Upon hitting at the fixed end of the string, the transverse waves will reflect back along the string. If the end of the string is rigidly held then the reflected waves will be inverted 180°. The initial propagated waves and the reflected waves will interfere constructively and destructively. At particular string tensions and/or wave frequencies, this wave superposition will give rise to waves called standing waves or stationary waves. There are many different standing waves patterns (normal modes) possible which have different wavelengths. The different modes are characterized by the number of nodes or antinodes in the wave. At one of the normal modes of oscillation, the amplitude of oscillation can become rather large, much larger than the amplitude of the original propagated wave. This phenomenon is called resonance. In this experiment, each end of the string will be close to a node position. The fundamental frequency (mode n=1) exhibits a wave pattern with one antinode. The second harmonic (mode n=2) exhibits a wave pattern with two antinodes, and so forth.

3.1 Pre-Lab Work

- Define the following terms: **standing wave**, **node**, and **antinode**.

- Draw a set of pictures of a standing wave on a string with two fixed ends showing the fundamental frequency ($n = 1$), and the harmonics $n = 2, 3, 4$, and 5. Label a wavelength, the nodes, and the antinodes on each picture.

- Given Equation (3.1), predict what will happen to the velocity of the wave as the static hanging mass (providing the tension) increases, decreases, or stays the same.

- Given Equation (3.2), how can measurements of λ and f be plotted to determine the wave velocity from the graph? (There is more than one way to do this; one way in particular produces a line.) How should the axes of the graph be labeled? Explain your reasoning.

3.2 Fixed Tension

In order to verify Equation (3.2), you can fix F_T and compare multiple f to the corresponding λ.

3.2.1 Procedure

- If you have not already done so, measure the mass and length of the string in order to calculate the linear mass density (m/L). You might note Question 3.4.3.

- A mechanical vibrator, driven with a (variable frequency) function generator, will be the wave source. Use a string slightly greater than the length of the table. Connect one end of the string to a post such that the vibrator can wiggle the string near that end. Hang the other end over a pulley. Keeping the string horizontal by adjusting the height of the pulley and the location of connection at the other end. The height of the vibrator will determine the height you need the ends to be.

- Set up the system with some particular string tension (like 450 grams). This tension will be kept constant for this entire part.

- Produce 5 different normal modes by changing the frequency of the vibrator. Adjust the standing wave amplitude until it is at its maximum. Record the corresponding frequency for each normal mode.

- Measure the corresponding wavelengths for each normal mode, directly from the string with a meter stick. The vibrator end of the string is not a true node because the string is vibrating a small amount. Take this into account when measuring the wavelengths.

- Try touching the string at a node and at an antinode. What happens to the wave in each case?

- Optional: Try measuring the frequency of the vibrator with a strobe lamp.

3.2.2 Analysis

- Determine the mathematical relation between the wavelength of the standing wave and the frequency of the vibrator that will produce a straight line ($y = mx + b$) when graphed.

- Comment on the significance (and units) of the slope and intercept of this graph. Determine both the precision and the accuracy of the slope and of the intercept; are they consistent with what you expect? (Your expectation should be based on the "other" equation which we are not testing here.)

- Use one or both of these (slope and intercept) to determine the velocity (with uncertainty) of the standing wave. Relate this (%-error) to the expected value based on the tension you chose for your specific string.

3.3 Fixed Wavelength

In order to verify Equation (3.1), you can fix λ and compare multiple F_T to the corresponding v.

3.3.1 Procedure

- If you have not already done so, measure the mass and length of the string in order to calculate the linear mass density (m/L). You might note Question 3.4.3.
- A mechanical vibrator, driven with a (variable frequency) function generator, will be the wave source. Use a string slightly greater than the length of the table. Connect one end of the string to a post such that the vibrator can wiggle the string near that end. Hang the other end over a pulley. Keeping the string horizontal by adjusting the height of the pulley and the location of connection at the other end. The height of the vibrator will determine the height you need the ends to be.
- Place 150 grams (including the hanger) on the end of the string. (If you start with too little mass, the string stretches different amounts — changing the string's effective density — during the experiment, causing unaccounted for curving in the graph.)
- Adjust the frequency of the generator until the $n = 2$ mode is observed and is at its maximum amplitude. Record the frequency and corresponding wave velocity.
- Repeat the previous step for 6 hanging masses up to about 1200 grams.

3.3.2 Analysis

- Determine the mathematical relation between the hanging mass (F_T) and the wave velocity (v) that will produce a straight line ($y = mx + b$) when graphed.
- Determine which variables the slope and intercept of this graph should be related to. Determine both the precision and the accuracy of the slope and of the intercept; are they consistent with what you expect? (The equation we are testing should imply what to expect.)

3.4 Questions

1. What are the necessary and sufficient conditions for the production of standing waves?

2. Is it valid to consider the tightening of the string to be the same as a change of medium? (Does tightening the string change the way waves move or the way standing waves are produced on the string?) Why or why not?

3. When you measure the length of string, remember that the string will be under tension (pulled on) and may have some "give" to it. It may be possible for it to stretch by nearly 10%. If you don't account for this (if you measure the unstretched length) will your value of density be incorrect too large or incorrect too small? Can you account for this either in the value of the length or in the uncertainty of the length. Will this affect comparison to either of your graphs?

4. Consider the Fixed Tension graph. We noted that the vibrator end of the string should not be considered to be a node. This means that the node might be a little in front of the post or a little behind the post and therefore your wavelength values might be a little wrong, but your error bars should already include the amount the values could be off. Based on the error bars on your Fixed Tension graph, would shifting the wavelength data a little larger or a little smaller have made a difference to the values of slope or intercept that you calculated? If so, would it have increased the value or decreased the value? If not, why not?

5. If the tension and the linear density of the string remain constant, but the pulley is shifted further from the post (so that the region which is vibrating lengthens), how is the resonant wavelength affected? How is the velocity of the wave affected?

6. What was the experimental velocity (and uncertainty) of the waves in part I of the experiment?

7. What will happen to the velocity of the wave if the tension is fixed but the frequency is changed.

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A PDF version might be found at standingwaves.pdf (103 kB)

Lab 4

Speech of Sound in a Cardboard Tube

Experimental Objectives

- The purpose of this experiment is to determine the speed of sound in an air column, both from an open and a closed tube. Data should be taken at a number of different resonant frequencies.

Longitudinal sound waves can be produced by any vibrating source. The frequency of these waves is determined solely by this vibrating source. There must also be a medium (solid, liquid, or gas) in order for the sound wave to be propagated. These waves do not travel through the medium instantaneously. There is a finite wave speed which is determined by the characteristics of the medium. The wave speed is not dependent on the source. If the medium is changed, then the speed of sound also changes. For example, the pressure of a gas, the temperature of a gas, and the gas composition are all factors which affect the speed of sound in the gas.

Sound waves can experience interference just like waves on a string, especially when the waves are inside a tube, like an organ pipe. Traveling waves can reach the end of the tube, then they can be reflected back in the direction in which they came. There are now two sets of waves which can interfere, that is the two sets of amplitudes are added together. At certain frequencies this interference gives rise to a special wave called a standing wave. This is a resonance effect. Standing waves can occur in tubes which have only one end open, or in tubes that have both ends open. The derivation of the equation for these special resonant frequencies will be slightly different for these open or closed tubes. See your text book for the needed pictures and equations.

4.1 Pre-Lab Work

Show a set of pictures and equations for the first five harmonics, for both an open and for a closed tube. Show and explain what nodes and antinodes are. Show and explain what a standing wave is.

4.2 Experimental Procedure

Initial set-up:

- The source of the waves will be a stereo type speaker, powered by a frequency oscillator. The waves will move through the normal room air inside of a cardboard tube. The speaker will be placed at one end of the pipe.
- A microphone (Pasco) will be placed to receive the waves at the same end of the pipe.
- The Pasco Interface and the software Data Studio in the oscilloscope mode will be used to determine which frequencies give the maximum sound intensity for resonance.
- Measure the length of the tube.

- Calculate the resonant frequency for the n=3 harmonic, using an approximate value for the speed of sound.
- Set the generator frequency near this calculated value.

Doing the experiment:

- Adjust the sound intensity amplitude on the generator (not too loud).
- Adjust the frequency (on the generator) until the amplitude (on the scope) is actually at the maximum. This is called the resonance condition. Record the small range of frequencies which keep the amplitude at a maximum.
- Repeat this procedure to determine 4 additional resonance frequency points.
- Repeat this for both an open tube and for the closed end tube. (Five points for each type of tube.)
- Make a graph of the resonant frequency versus the harmonic number, for each tube type.
- Determine the speed of sound from each graph.
- Calculate a speed of sound value at 20°C.
- Determine the precision and accuracy for this experiment.

4.3 Questions

1. Does the speed of the wave depend on the frequency of the oscillator?

2. How does the speed of sound in air vary with the air temperature? By how much would the results of your experiment change if you conducted the experiment outside today?

3. What is meant by resonant condition?

4. In interference, at least 2 sets of waves are added together. What 2 sets of waves are added together in this experiment?

5. Why does the closed tube only show resonance for the odd harmonics?

6. Demonstrate how sound waves can be reflected by the open end of a tube.

7. What random errors might be in this experiment? And show any evidence of them.

8. What systematic errors might be in this experiment? And show any evidence of them.

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A PDF version might be found at sound-cardboard-tube.pdf (66 kB)

Lab 5

Specific and Latent Heats of Solids

Experimental Objectives

- By measuring properties such as the final temperature of an isolated system that consists of hot and cool materials, you can compute the specific heat of an unknown material and, if this is verifiable, then you will have proven the equations related to the specific heat.
- By measuring properties of an isolated system such as the mass of ice that melts in the presence of other materials, you can compute the latent heat of water and, if this is verifiable, then you will have proven the equations related to the latent heat.

When multiple substances at different temperatures are placed in thermal contact, the hotter substances lose energy (heat) while the colder ones gain energy (heat) until thermal equilibrium is reached. It is assumed that the sum of the heat lost by the warmer objects is equal to the sum of the heat gained by the others:

$$-Q_{\text{lost}} = Q_{\text{gained}} \tag{5.1}$$

Notice that Equation (5.2) says that when you heat the shot, it not only "gets warmer" (increases temperature), but it *also* "heats up" (gains energy). These are *not the same*, but they are very closely related. The relation between the heat content (or internal energy) and the change of temperature is

$$Q = m\,c\,\Delta T \tag{5.2}$$

where m is the mass of the substance, ΔT is the change in the temperature, and c is the specific heat. (The product mc is also known as the "water equivalent.") The specific heat of a substance is a measure of the molecular activity within the material. Measurements of specific heats have played an important role in helping us to understand the nature of matter.

Furthermore, the relation between the heat content and a change of phase is

$$Q = mL \tag{5.3}$$

where L is called the latent heat. There is a latent heat associated with each phase change.

- **Latent heat of fusion,** L_f, refers to the heat associated with the liquid/solid phase change.
- **Latent heat of vaporization,** L_v, refers to the heat associated with the vapor/liquid phase change.

For example, given one ice cube (5 g) at -10° C, which is to be warmed to 30° C, we must ***warm*** the ice to the melting point, ***melt*** it, and then ***warm*** the *melted ice* some more. (There are three separate terms.) The heat required to do so is

$$\begin{aligned} Q &= mc_{\text{ice}}\,\Delta T + mL_f + mc_{\text{water}}\,\Delta T \\ Q &= (5\,\text{g})(c_{\text{ice}})[(0^\circ\,\text{C}) - (-10^\circ\,\text{C})] + (5\,\text{g})L_f \\ &\quad + (5\,\text{g})(c_{\text{water}})[(30^\circ\,\text{C}) - (0^\circ\,\text{C})] \end{aligned}$$

This expression gives the amount of heat required (Q_{gained}) regardless of how the ice is warmed. It does address the heat lost (Q_{lost}) by whatever warmed the ice.

5.1 Specific Heat Pre-Lab Exercise

A few days before doing this lab, you should download the pre-lab worksheet and do the math to remind yourself how the propagation of uncertainty works. If you did not learn this last semester, then this is your opportunity! A PDF version of the pre-lab worksheet alone can be downloaded from SHprelab.pdf (29 kB). A PDF version of the pre-lab with room for *your data* can be downloaded from SHprelab-data.pdf (37 kB).

The point of this worksheet is to walk you through the measurements and calculations for the Specific Heat lab in order to help you decide how to analyze the data and develop a thoughtful report. When you calculate the specific heat based on measurements from the lab, you will use Equation (5.1):

$$-Q_{\text{brass}} = Q_{\text{Alcup}} + Q_{\text{water}}$$
$$-m_b c_b \Delta T_b = m_a c_a \Delta T_a + m_w c_w \Delta T_w$$

solving this for c_b, we get:

$$c_b = \frac{m_a c_a (T_f - T_{ia}) + m_w c_w (T_f - T_{iw})}{-m_b (T_f - T_{ib})}$$

The "error analysis" for this lab is somewhat more involved than most of the previous labs. In order to ensure your familiarity with the process, there is a Pre-Lab worksheet appended to the end of the lab manual. It is the last page so that you can tear it off without ruining the rest of the manual. Please use the formula above and the worksheet as a guide to calculate the specific heat, c of brass based on the measurements provided on the worksheet.
After you have completed the calculations, you should answer the pre-lab questions below in your lab notebook. These are written specifically to point out the comparisons that you will need to make when you write up your analysis of the data.

5.1.1 Pre-Lab Questions

1. When calculating Q_w, does one of the terms, ΔT_w, m_w, or c_w, have a significantly larger relative uncertainty? If so, what is it about that measurement that made that uncertainty large while the others were small? Is this uncertainty improvable?

2. When calculating Q_a, does one of the terms, ΔT_a, m_a, or c_a, have a significantly larger relative uncertainty? If so, what is it about that measurement that made that uncertainty large while the others were small? Is this uncertainty improvable?

3. When calculating the numerator, does one of the terms, Q_w or Q_a, have a significantly larger uncertainty? If so, which measurement caused that uncertainty to be large? (See questions 1 and 2.)

4. When calculating the denominator, does one of the terms, ΔT_b or m_b, have a significantly larger relative uncertainty? If so, which measurement caused that uncertainty to be large? Is this uncertainty improvable?

5. Which term, $(Q_w + Q_a)$ or $m_b \Delta T_b$, had the largest relative uncertainty? What is it about that measurement that made that uncertainty large while the others were small? Is this uncertainty improvable?

6. Which measurement ultimately caused the size of δc to be as large as it was? Is there a way to reduce the relative uncertainty by planning the experiment differently? For example, should you use a different mass of water or of metal? Should you start at a different temperature? Should the final temperature be higher or lower? How might one accomplish this?

7. When you do any experiment, a significant component of the analysis should be devoted to the question: For each measurement, if you measured the value to be higher than the true value, then how does this affect the final result? To that end, for this case, answer the following:

(a) If all masses are skewed high by the scale, then is c affected?

(b) If all temperatures are skewed high by the thermometer, then is c affected?

(c) If some heat escaped into the atmosphere, lost to the experiment, then how does this affect the final temperature of the mixture and how does this affect the final value of c?

5.2 The Specific Heat Capacity of an Unknown Metal

The following considerations should allow you to experimentally determine (with uncertainty) the specific heat of the metal and, from that, the composition of the metal. Use these questions to determine your procedure, with notes about where to be careful. Verify the procedure with the professor before beginning the experiment.

1. We would like the metal to be at some warm, stable, and uniform temperature. Can you imagine what convenient temperature we can warm the metal to which satisfies these three conditions? Hint: In order for the cylinder to be at a uniform temperature, it must sit in this environment for some short time; since we don't know the temperature of a burner, we can't just place the metal on the burner itself.

2. We would like the water to be at some cool, stable, and uniform temperature. Can you imagine what convenient temperature we can maintain for the water which satisfies these three conditions? HINT: The container for the water must also be in thermal equilibrium with the water before the unknown metal is added.

Note 5.2.1 (Assumption)**.** The aluminum cup is always at the same temperature as the water.

1. The specific heat is an inherent property of a material. Since the cup is aluminum, you can easily find it's specific heat with a CRC, or a textbook, or it may also be stamped onto your equipment.

2. When the metal and water (with container) are placed in thermal contact, they must be isolated from the external environment. With what equipment will this be done? (See your lab table.)

3. If some hot metal is held in the air, it cools down. What happens to the heat when hot metal is exposed to the air? Can we easily measure the heat lost to the air? How will this affect your experimental technique?

4. Think about Equation (5.2) and the likely values of c for the water and for the unknown metal. If there are equal masses of water and metal, then where (roughly) do you expect the final temperature to be (closer to T_i for water or T_i for metal)? What if you have more water?

5. If the final temperature is far from room temperature and the calorimeter is not well insulated, then where will the actual final temperature be? If the final temperature value is wrong in this way, then will your calculated c for the metal be wrong too high or wrong too low?

5.3 The Latent Heat of Fusion for Water

The following considerations should allow you to experimentally determine (with uncertainty) the latent heat of water. Use these questions to determine your procedure, with notes about where to be careful. Verify the procedure with the professor before beginning the experiment.

1. We would like the water to be at some warm, stable, and uniform temperature. Can you imagine what convenient temperature we can maintain for the water which satisfies these three conditions?

2. We would like the ice to be at some cool, stable, uniform, and known temperature. Can you imagine what convenient temperature we can maintain for the ice which satisfies these three conditions? HINT: Most freezers are colder than freezing.

Note 5.3.1 (Assumption)**.** The aluminum cup is always at the same temperature as the water.

1. When the ice and water (with container) are placed in thermal contact, they must be isolated from the external environment. With what equipment will this be done? (See your lab table.)

2. You will need to know the mass of the ice added. If you take the time to weigh it on a scale, it will melt. How can we determine the mass of the ice added without explicitly placing it on the scale before adding to the water?

3. Based on the expected value of the latent heat of fusion for water, how much ice should you use compared to the amount of water that you have?

4. When you add the ice, the mL term should only include the mass of the ice that will melt in the water. If you add water with your ice, then this value of m will not be accurate. How does this fact affect your procedure for adding ice?

5. If the final temperature is far from room temperature and the calorimeter is not well insulated, then where will the actual final temperature be? If the final temperature value is wrong in this way, then will your calculated L be wrong too high or wrong too low?

Last revised: Jan, 2010
A PDF version might be found at spheat.pdf (125 kB)

Lab 6

Thermal Expansion

Experimental Objectives

- In this lab, we will use the equation for thermal expansion to identify the composition of three different rods.

You may have noticed that most materials expand as they are heated. This can be seen in a wide variety of situations: Your front door doesn't seal out the colder air, bridges have a gap of a few inches at each end, stuck jars are easier to open when hot water is run over them, etc.

6.1 Pre-Lab Questions

Consider the following situations:

1. If a single rod, 1 m in length, expands by 1 mm when heated a specified amount, how much does a 2 m rod (made of the same material) expand when heated by the same amount as the 1 m rod?
2. If I have a glass jar with a metal lid and heat up both glass and lid by the same amount, do they expand the same amount? If not, which one expands more? Why is it possible to open the heated jar?
3. If my single, 1 m metal rod is heated some amount and expands 1 mm, how much does that same rod expand when heated by twice the original amount?

The answers to these questions show that the expansion of a material depends on it's original size, it's material composition, and the amount that the temperature changes. The equation for linear thermal expansion is

$$\mathbf{\Delta L} = \mathbf{L_0}\alpha\mathbf{\Delta T} \tag{6.1}$$

and α (lower-case Greek-symbol alpha) is the coefficient of linear expansion, which is different for each material.

Please note, ΔL is the **absolute expansion**, $\left(\frac{\Delta L}{L_0}\right)$ is the **relative expansion** (the expansion relative to the original length), and $\left(\frac{\Delta L}{L_0} \times 100\%\right)$ is the **percent expansion** (the relative expansion written as a percentage).

In order to experimentally measure the value of α, you must measure the relative expansion and the change in temperature.

1. Based on Equation (6.1), what are the units of α?
2. For reliable temperature measurements, the entire rod should be at the same temperature. This requires a stable temperature environment. List three temperatures that can be conveniently maintained.

3. Ice can be colder than 0 °C and steam can be warmer than 100 °C. How can we use either (specifically steam) to ensure a stable temperature environment?
4. If we immerse our meter stick into the steam bath with the rod to measure the expansion, then we *cannot* trust the reading of the meter stick to accurately determine the new length of the rod... WHY NOT? What does this require of our measuring device?
5. We have an apparatus which will allow steam to enter at one end and water to drain at the other. At what temperature do you expect the rod to be when it is immersed in this steam-water mixture?
6. With several groups creating steam in the same room, why should we worry about the value of "Room Temperature" when we make a second or third measurement?

6.2 The Experiment

Using room temperature and the water-steam temperature interface, experimentally determine the coefficient of linear expansion for three different types of metals. Based on the color, weight, and density, guess the metal composition. Carry out an error analysis and use your error-bars to verify the material of each rod.

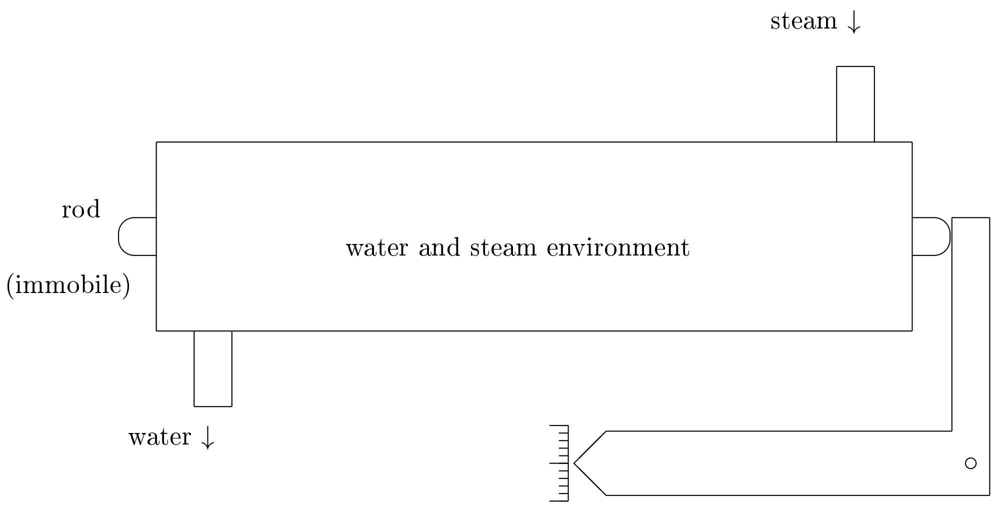

Figure 6.2.1: Apparatus for measuring the coefficient of linear thermal expansion.

Last revised: Jan, 2012
A PDF version might be found at thermal.pdf (87 kB)

Lab 7

Reflection and Refraction at a Plane Surface

Experimental Objectives

- Experimentally verify the law of reflection from a plane surface by tracing the paths of the incident and the reflected light rays.
- Experimentally verify the law of refraction from a plane surface by tracing the paths of the incident and the refracted light rays to calculate n for the glass,
- Experimentally verify the law of refraction from a plane surface by predicting the path a ray of light will emerge from a prism for a given incident angle, and
- Experimentally determine the critical angle for a piece of glass.

Sir Isaac Newton developed a particle theory of light (essentially photons) in order to use geometry to explain two commonly observed optical properties of light: reflection and refraction. Those interested in optics in Newton's time had observed that whenever light is incident upon any surface, some of the light is reflected off from the surface and some of the light is transmitted through the surface. When the incident light approaches along a line normal to the surface, it continues along its straight-line path. However, when the incident light approaches at an angle as in Figure 7.0.1, then the light changes direction. The transmitted light is said to refract. The property that determines the amount of the refraction is called the *index of refraction* and is denoted by n. By convention, the angles for the incident, the reflected, and the refracted light are all measured from the line normal to the surface.

Since the reflected light never sees the material with a different index of refraction, the reflection follows the law of reflection, which states that the angle of the incident ray is equal to the angle of the reflected ray:

$$\theta_{\text{incident}} = \theta_{\text{reflected}}.$$

The transmitted light, on the other hand, enters the material, which has a different index of refraction and follows the law of refraction or Snell's Law, named for Willebrord Snell (1591-1626). This law is expressed in terms of the sine of the incident and refracted angles, θ_i and θ_r:

$$n_i \sin\theta_i = n_r \sin\theta_r$$

where n_i is the index of refraction for the incident medium, and n_r is the index of refraction for the refracted material.

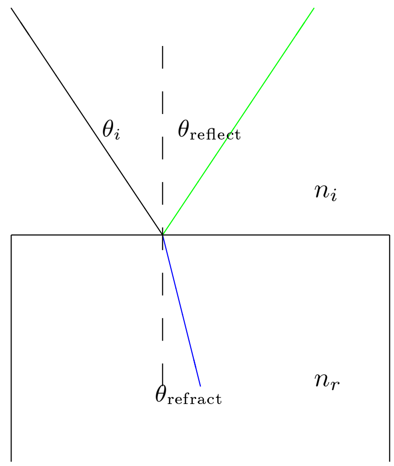

Figure 7.0.1: Some of the incident light from the upper left reflects to the upper right and the rest refracts into the material to the lower right.

The index of refraction determines the amount of refraction because it is a measure of the speed that light travels through the medium: $n = c/v$, where $c = 2.998 \times 10^8$ m/s is the speed of light in a vacuum and v is the speed light travels through the medium. The index of refraction for a vacuum is therefore identically 1. It happens that the index of refraction for air is close enough to 1 that we will not be able to measure a difference at our level of precision.

7.1 Pre-Lab Work

1. Since light travels faster in a vacuum than in any other material, $c > v$, determine if n has a maximum or a minimum value and what that might be.
2. Consider Snell's Law.
   (a) If it were possible to create two different materials with the same index of refraction, so that $n_i = n_r$, then comment on the relationship between the incident and refracted angles.
   (b) When light passes from a material with a small index of refraction to a material with a large index of refraction so that $n_i < n_r$, will θ_i larger than or smaller than θ_r? Draw an approximate diagram indicating if the light bends *towards* the normal, as in Figure 7.0.1 above, or if it bends *away from* the normal.
3. Critical Angle: It is possible, for the case where light is bent away from the normal (becomes more parallel to the surface), that it can be bent all the way over to actually being parallel to the surface. When this happens, the light is not transmitting into the new material and cannot be seen from the other side.
   (a) It is only possible to have a critical angle for either $n_i > n_r$ or $n_i < n_r$. For which of these cases is it possible?
   (b) Using Snell's Law above, derive an equation for the incident critical angle (the refracted angle is $90°$), in terms of the two indices of refraction for the two media.

7.2 Procedure

7.2.1 Refraction at a plane surface

Place the square piece of glass on the cardboard that has been covered with a piece of paper. Orient the frosted sides of the glass towards the short sides of the paper. Draw the outline of the glass on the paper and be careful to not move the glass. (You may want to use a pair of pins at the corners to fix the glass in place.)

Plug in and set up the PASCO light box to emit a single ray of light. Place the light box so that its single ray of light shines through the glass. Notice that the path the light follows through the glass is like the solid line in Figure 7.2.1 following points 1, 2, 3, and 4. Notice that the path the light follows above the glass is like the dashed line in Figure 7.2.1 following points 1, 2, 3′, and 4′.

To mark the incident path of the light, stick a pin in the paper at location 1, closest to the light box. You should see the shadow of the pin in the light beam. Place **pin 2** in the shadow of **pin 1**. You should also see the shadow of the pin in the exiting light beam. Place **pin 3** and **pin 4** so that each lines up with shadows of the previous pins.

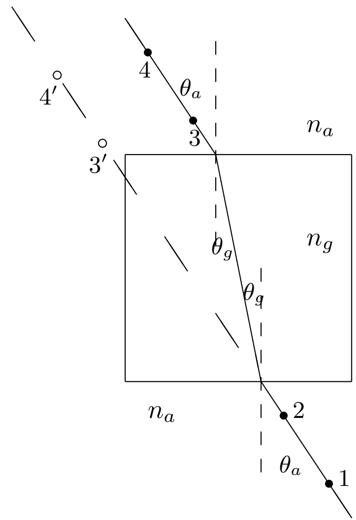

Figure 7.2.1: Square Glass Ray Diagram. The light travels from pin 1 past pin 2 through the glass to pins 3 and 4. At the first boundary, air is the incident material and glass is the refracting material. On the second, glass is the incident material and air is the refracting material.

Once you and all of your partners are satisfied with the location of the pins, verify that the glass has its outline drawn on the paper and remove the glass from the paper. You may also turn off the light box. Use a straight-edge to draw a straight line through each pair of pins up to the edge of the lens. Use a straight-edge to draw another line inside the glass connecting where the pin-lines meet the surface. Use the protractor to measure all incident and refracted angles. Look up the index of refraction of air and of glass and notice that they have a range of values. Select a reasonable value for n_{air} and use Snell's law to determine the index of refraction for the glass. This is your first verification of Snell's Law.

Notice that the angle decreases ($\theta_a > \theta_g$) when the light passes from small n (air) to large n (glass). This light is bent towards the normal. Similarly, when the light passes from large n (glass) to small n (air), the angle increases ($\theta_g < \theta_a$). This light is bent away from the normal.

7.2.2 Reflection at a single plane surface

Carefully replace the square piece of glass onto your diagram and turn the light box back on. Carefully re-align the light box to shine along the path that it previously followed. Now you should also notice that a portion of the beam reflects off of each interface. For the first boundary (after **pin 3**), place two pins along the beam that is reflected off of the glass. When you are satisfied that it is aligned as well as possible, turn off the light box and remove the glass. Measure the reflected angle and verify the law of reflection.

7.2.3 Predicting the Exiting Ray

Use the thin triangular prism in this part. Place the first two pins as indicated in Figure 7.2.2, which starts the drawing that you will need to complete. I have drawn the incident ray, the dashed normal line, and the refracted ray. You will need to figure out where the light hits the second boundary, draw a line normal to the second surface, and then use Snell's law to determine the direction that the light beam exits from the prism.

Step 1) Decide on a value for the incident angle. Assuming that the index of refraction of this glass is the same as what you calculated for the square glass, use Snell's law to determine the refracted angle.

Step 2) Notice that the light ray inside the prism forms a triangle with the apex of the prism. Since the angles of any triangle add to 180°, you can use the first refracted angle to determine the second incident angle. (Recall that a normal line makes a 90° with the surface.)

Step 3) Use Snell's Law to determine the exit angle.

Show your prediction to the instructor. Set up the triangular prism and the light box to verify your prediction. Your actual result will probably be noticeably different than your prediction. When you make your measurements your angles will not exactly match those you used in your prediction and the glass may have a different index of refraction. Use your measurements to determine the index of refraction for this piece of glass and verify that it is a reasonable value as your second verification of Snell's Law.

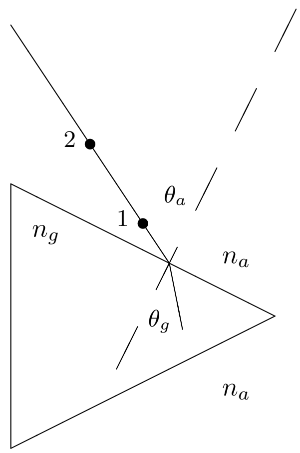

Figure 7.2.2: Triangular Glass Ray Diagram

7.2.4 The Critical Angle

Again consider the prism. Snell's Law makes an interesting prediction for large angle incident rays. This is the effect that allows optical fibers to carry signals without loss (unlike electrical cables which have resistance that degrades a signal). It is possible for light in a material with a high index of refraction that is incident upon a material with a low index of refraction to have total internal reflection — In our case, this means that the light does not refract out of the glass! To do this calculation you can repeat the steps of your previous calculation in the reverse order.

Step 3) Set your exit angle (the second refraction angle) to be 90°. Use Snell's Law to determine the second incident angle (inside the glass). This is the *critical angle*. Now we need to figure out how to set the equipment to produce this angle.

Step 2) Notice that the light ray inside the prism will again form a triangle with the apex of the prism. Since the angles of any triangle add to 180°, you can use the second incident angle to determine the first refracted angle. (Recall that a normal line makes a 90° with the surface.)

Step 1) Since you know the index of refraction of this glass, use Snell's Law and the first refracted angle to determine the first incident angle.

Set the light box off of the cardboard and paper so that you can rotate the cardboard to easily change the incident angle. Set the incident ray to be incident on one side at about ¼ of the way from the apex. If you set it right, then when you turn on the light you should see the light refracted off of the first surface, but then not exit the glass at the second surface. This may not actually be the case. Either way, slowly rotate the paper (and the prism) until you can see an exiting beam and then slowly rotate it again until the refracted ray is refracted by *just* 90°, the smallest angle that makes the light not exit the prism. The critical angle is now the incident angle at the second surface of the prism. Experimentally determine the critical angle for this piece of glass. Compare the predicted value of the critical angle to the measured value of the critical angle as your third and final verification of Snell's Law.

7.3 Questions

1. Explain why a plane mirror reverse left and right. It will help to draw a ray diagram that replaces a the pins with a wider object that has a clear left side and right side.

2. What happens to the speed that light travels through a medium a greater index of refraction?

Last revised: Spring, 2012
A PDF version might be found at refraction.pdf (139 kB)

Lab 8

Simple Lenses

Experimental Objectives

Through the various arrangements suggested below, you should be able to...

- ... figure out the definition of the following terms based on the images you observe
  - magnified versus minified
  - upright versus inverted
  - real versus virtual
- ... figure out the relationships between the measurable quantities:
  - the magnification, defined in terms of the image height and the object height: $M = \dfrac{h_i}{h_o}$
  - the image distance (from the lens) q
  - the object distance (from the lens) p
  - the focal length, f.

Anybody who has looked through glasses, microscopes, telescopes, a magnifying glass, or even a window has experienced a lens. We see images through lenses.

8.1 Procedure with Questions for the Analysis

Warning 8.1.1. The data you take in Subsection 8.1.2 will also be used in Subsection 8.1.3, so tabulate it in a coherent and clear format.

8.1.1 Defining Your Terms

As a group, take one of the three lenses and your white screen into a dark room so that you can see a brighter room through a doorway. Have one person in the group go stand in the bright room and move around while another person looks through the lens. Then trade places until everybody has a chance to look through the lens.

Exercise 8.1.2.

1. As a group, decide how to describe the image in the terms above: **Magnified** or **minified**? **upright** or **inverted**? **real** or **virtual**?

2. While still in the darker room, notice that if you hold up your lens in front of a white screen (or a tee shirt) so that the lens is between the screen and the person in the other room, the image of the brighter room appears on the screen. (Have somebody dance and jump in the bright room while you watch the image on the screen.)

Take that same lens back into the room and have each person view this text through the lens.

Exercise 8.1.3.

1. As a group, decide how to describe the image in the terms above: **Magnified** or **minified**? **upright** or **inverted**? **real** or **virtual**?

2. Notice this time that the text appears to be on the same side of the lens as the actual text is. There is no place that you can put your white screen to have the words from the page appear on the screen.

Compare and contrast the image of the room to the image of the text.

Exercise 8.1.4.

1. If you had to choose between the names real and virtual, which image would you call real? which would you call virtual? why?

2. Decide if either of the images change based on the location of the lens relative to the object being viewed.

8.1.2 Quantify the Magnification

In order to make precise measurements, attach the screen to one end of the optical bench and the light source to the other side. The illuminated cross-hairs on the light source will be the object observed. Place a converging lens[1] on the optical bench between the object and the screen. Keep the screen and the light source fairly far apart (the convenient distance will depend on which lens you are using). Adjust the position of the lens until a clear image is formed on the screen.

Exercise 8.1.5.

1. Describe the image formed in the terms defined above.

Measure the distances between the lens and the image (image distance, q), and between the lens and the object (object distance, p). Measure the height of the image on the screen h_i and the height of the object on the light source h_o. (If the image is inverted, then h_i is a negative value.) Calculate the magnification factor of the image, $M = \dfrac{h_i}{h_o}$.

For this same lens, without changing the position of the screen or the light source, find a second image that has a different description using the defined terms above. Again, measure p, q, h_i, and h_o and calculate M.

Exercise 8.1.6.

1. Describe this second image in the terms defined above.

Repeat this for each of the other two lenses.

Exercise 8.1.7.

1. Determine the relationship between M, q, and/or p. Verify that your relationship works (to about two significant figures) for all six data sets separately.

[1] Converging lenses, also called convex lenses, bulge in the middle. Diverging lenses, also called concave lenses, bulge at the edges.

8.1.3 Quantify the Focal Length

The lens equation, $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$, shows the relationship between the image distance, q, object distance, p, and the focal length of the lens, f. Using your data from Subsection 8.1.2, determine the focal length of each lens. Each lens should have two values for f (one for each image).

Exercise 8.1.8.

1. For each lens separately, compare the average of these numbers to the accepted value.

The focal length of a lens may also be determined by forming the image of a very distant object on a screen. In this case, the object distance, p, becomes very large and therefore $1/p$ becomes very small. When this is the case, the lens equation may be written as $1/q = 1/f$, or more conveniently, $q = f$. Using a distant object in an adjacent room, measure the image distance and thereby determine the focal length for each lens.

Exercise 8.1.9.

1. Compare this with your results for f from the data in Subsection 8.1.2.

2. Describe the image formed by this distant object.

In principle, an object needs to be infinitely far away for this second method to be true. In practice, the object only needs to be "far enough." Determine, theoretically or experimentally, how far an object needs to be to get an accurate measurement of the focal length in this manner. If the day is sunny, ***under strict instructor supervision*** take a lens outside and, using the sun as "an infinitely far away object," measure the focal length by forming an image of the sun on your lab notebook. Take a minute or so to really visualize the sun on your paper. Predict the results.

Last revised: Aug, 2011
A PDF version might be found at simplens.pdf (108 kB)

Lab 9

Electric Field Lines

Experimental Objectives: Experimental Objectives

- In this experiment, you will map out the equipotential lines for a couple of given electric field configurations and determine the pattern of the electric lines of force for these configurations. You will then give a physical explanation of the terms “electric field” and “electric potential” and their relationship.

The effects of electric charges (positive and negative) can be seen in many electronic devices, like the radio. The effects of static electricity can be seen when clothing is pulled out of a dryer on a winter day. There is a force exerted on one charge by another charge and this can be either attractive or repulsive. This force is called the Coulomb force and is named after Charles Coulomb (1736-1806).

Physics relies on abstractions (new quantities and new names), with pictures to help convey information and ideas. The English scientist Michael Faraday (1791-1867) introduced the concept of lines of force, a force field, as an aid in visualizing the interactions of charges. These lines of force are a mental abstraction, but they can be visualized with the use of iron filings placed near a charge or a group of charges. These lines of force convey a picture of the interaction between one charge and another. The iron filings will align themselves when in the presence of a single charge. This conceptualizes the idea of the electric field strength E (electric force per unit charge) because it is convenient to know the electric force per unit charge at any point in space due to a nearby set of electric charges. The electric field strength though can not be easily measured with a meter.

It requires work to move a charge against an electric field. The ratio of the work done to the charge strength is called the potential difference (voltage) and it is measured in units of joules/coulomb and is called a volt. This potential difference is easily measured with a voltmeter. If the charge is moved along a path perpendicular to the electric field lines then there is no work done, it takes zero energy. This is because there is no force component in the direction of the path. The potential (voltage) is then constant along paths which are perpendicular to the field lines. Such paths are called equipotential lines. These equipotential lines can be measured with a simple voltmeter, and then from these the electric field lines can be deduced.

9.1 Pre-Lab Work

- Define Coulomb’s law.

- Give a definition of electric field, both mathematical and pictorial.

- Show a picture of the electric field near:

  a) a point charge,

  b) two equal and opposite point charges, and

  c) two equal positive point charges.

- Show from the above three cases (pictures), places where the electric field is zero.
- Show in a picture, the electric field inside and outside of a positively charged conductor (show that electric field lines will start from the surface of the charged conductor).
- Give an argument why two electric field lines can never cross.
- Give an argument why an electric field line is perpendicular to the equipotential line.

9.2 Procedure

- A special conducting plate with metal terminals will serve as the charge configuration. This plate should be fastened beneath the field-mapping board, without observing the specific charge configuration.
- An electric field is produced when a power supply (battery) is connected between the two terminals (points X and Y). Set the power supply at 10 volts.
- Points of equal potential (voltage) are found using a movable U-shaped probe which is connected to a voltmeter. Plot a series of points on your own graph paper which are at a constant potential (an equipotential line). Then repeat this for different potentials in steps of one volt. In this way the entire field is explored.
- Obtain an equipotential map and the electric field lines map (on graph paper) for three different charge configurations. Be sure to indicate the direction of the electric field lines on your maps.

9.3 Analysis

- Discuss the relationships between the voltage measurements and the electric field lines, and between the electric field lines and the charge configuration. Estimate the magnitude of the electric field at a few points on each map. Please write the electric field intensities in units of volts/meter.
- Discuss any irregularities in the field patterns which you have found.
- Discuss the spacing and what it represents, for the equipotential lines, and for the electric field lines.
- Indicate on your maps the location of the positive and negative charge distributions and their approximate shapes.

9.4 Questions

1. Can equipotential lines cross? Can electric field lines cross? Explain.

2. Why are there direction arrows on electric field lines but not on equipotential lines?

3. Why are the lines of force always perpendicular to the equipotential lines?

4. How is the electric potential affected by an insulator, and by a conductor, when they are placed in the electric field?

5. How is the electric field affected inside an insulator, and inside a conductor, when they are placed in the field?

Last revised: (March, 1997)
A PDF version might be found at EField.pdf (67 kB)

Lab 10

Internal Resistance of Batteries

Experimental Objectives

- In this experiment, we would like to consider the characteristics of a voltage source.

A voltage source, V, is anything that has a potential difference across two terminals: A liquid battery (such as in a car), a dry cell battery, a power plant (accessible through the wall socket), etc. An ideal voltage source, $\mathcal{E}$, will provide the same amount of voltage regardless of how much current is drawn from it. Physical voltage sources will approximate this to various degrees.

In order to determine how ideal a voltage source is, we will draw more and more current and measure how much voltage it is able to supply. If we attach a large resistance to the voltage source, then it will resist the current and we will only draw off a small current. If we attach a small resistance to the voltage source, then it will draw a large current.

Next week, you will consider the details of that relationship. Your resistors should already be ordered largest to smallest; don't worry about their actual values, but please try to keep them in order. Each of the resistors has multiple color bands on it. Please be diligent about recording the colors in order on each resistor. When you are finished with the lab, you should be able to sort them largest to smallest.

10.1 The Equipment

In the diagrams, A is an ammeter, which measures the current in amps (A), milliamps (mA), or microamps (μA). These measure the *current through* a wire and must be placed in series with the circuit element. Two circuit elements are "in series" if all of the current which goes through one also goes through the other. Current is the flow of charge (an amount of material); it does not diminish as it passes through the circuit elements.

In the diagrams, V is a voltmeter, which measures the voltage in volts (V). These measure the *voltage across* (the potential difference from before to after) a circuit element and must be placed in parallel with the circuit element. Two circuit elements are "in parallel" if the current gets split between one and the other. Voltage is related to the energy of the charges; it does diminish (or increase) as it passes through the circuit elements.

Figure 10.1.1 shows two configurations of ammeter and voltmeter. The small circles are the connections for the wires. In this lab, we are trying to measure the current drawn from the battery and the voltage output by the battery. On the left, the voltmeter is in parallel with the battery, but the ammeter is not in series with the battery. (V is correct, but I is too small.) On the right, the ammeter is in series with the battery, but the voltmeter is not in parallel with the battery. (I is correct, but V is too small.) You will be making a mistake either way, but hopefully neither is *too wrong.* For only your largest and smallest resistors, measure this both ways and see how large the effect is. (It is incorrect to use the voltage from one circuit and the current from the other.)

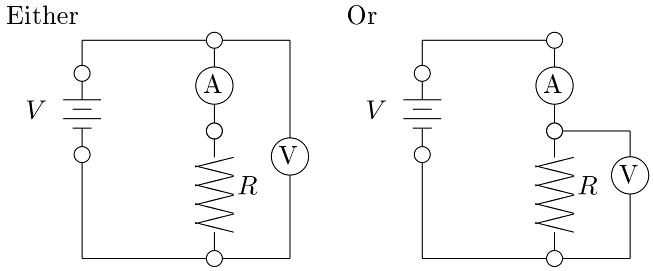

Figure 10.1.1: Measuring the voltage across "and" the current through a resistor.

10.2 The Experiment

You should consider (one at a time, of course) three voltage sources: a "good" dry-cell battery, a "bad" dry-cell battery, and a dc-power supply. To determine the characteristics of each battery, you will need to build the circuit in Figure 11.2.1 using some resistor, and then replace the resistor with 10 different resistance values, in order to vary the amount of current drawn. Measure the current (from the ammeter(A)) and the terminal voltage (from the voltmeter(V)) for each of these resistors. Figure out how the terminal voltage is related to the current drawn by graphing the voltage V versus the current I and considering the equation of the best trendline.

10.3 The Analysis

Comment on the following in your lab notebook, and use this information to enhance your analysis of the data.

1. Does the good battery provide a constant voltage? If so, tell the instructor to find smaller resistors for you. If not, try to figure out what is happening.
2. Discuss the units and the interpretation of the slope and intercept for each graph.
3. Compare the values of slope and intercept from the three graphs. It may be that they should not have the same value; but correlate the values to the voltage sources. If they have comparable voltages, then graph them on the same chart.

On your graph, extrapolate the trendline to determine what would happen if you had zero resistance. (***Do not*** actually use zero resistance; that would use up the battery "juice" ***very*** quickly.)

1. Which portion of the graph is large R and small R? How do you know?
2. In principle, if there were absolutely no resistance to the flow of current, how much current would flow?
3. Based on your graph, if you were to allow the resistance to be zero in the circuit, what would happen to the current? (This is called the "short-circuit current.")
4. Can you draw any conclusion about the resistance that is internal to the battery? (Be as quantitative as possible.)
5. Based on your graph, what characteristic distinguishes a "good" battery from a "bad" battery?

Last revised: Jan. 8, 2009
A PDF version might be found at intr.pdf (80 kB)

Lab 11

Using Ohm's Law to Determine Equivalent Resistance

Experimental Objectives

- In this lab, after empirically verifying Ohm's Law, you would like to empirically determine the equivalent resistance of two resistors in series and of those two resistors in parallel.

When current moves through a wire due to an electrical potential difference (a voltage), it is literally electric charges falling through the wire due to an electrical field. This is completely analogous to gravitational charges (masses) falling through the air due to a gravitational field. Different types and sizes (gauges) of wire resist this current by different amounts. Ohm's Law describes (for some materials) just how this resistance affects a current for a specified voltage, i.e., it relates the current to the voltage. Using the equipment in the lab, you too will be able to discover Ohm's law! Hooray! Furthermore, we can investigate the effect of *multiple* resistors on a current in some voltage.

For each of the cases outlined below, we will measure at least eight voltage values (from a dc-power supply) and the corresponding current for a specific resistor or combination of resistors.

11.1 Pre-Lab

Answer the following questions before you come into lab.

1. Look up Ohm's Law. If you plot V versus I, what do you expect the graph to look like?
2. What units should the slope and intercept have?
3. What values do you expect the slope and intercept to have?
4. Draw one circuit diagram each for resistors in series and for resistors in parallel.
5. Look up the resistor color code in your textbook.

11.2 The Equipment

In the diagrams, A is an ammeter, which measures the current in amps (A), milliamps (mA), or microamps (μA). These measure the *current through* a wire and must be placed in series with the circuit element. Two circuit elements are "in series" if all of the current which goes through one also goes through the other. Current is the flow of charge (an amount of material); it does not diminish as it passes through the circuit elements.

In the diagrams, V is a voltmeter, which measures the voltage in volts (V). These measure the *voltage across* (the potential difference from before to after) a circuit element and must be placed in parallel with the circuit element. Two circuit elements are "in parallel" if the current gets split between one and the other. Voltage is related to the energy of the charges; it does diminish (or increase) as it passes through the circuit elements.

Figure 11.2.1 shows two configurations of ammeter and voltmeter. The small circles are the connections for the wires. In this lab, we are trying to measure the current through the resistor and the voltage across the resistor. On the left, the ammeter is in series with the resistor, but the voltmeter is not in parallel with the resistor. (I is correct, but V is too large.) On the right, the voltmeter is in parallel with the resistor, but the ammeter is not in series with the resistor. (V is correct, but I is too large.) You will be making a mistake either way, but hopefully neither is *too wrong*. For only one of your resistors, measure the data both ways and see how large the effect is. (It is incorrect to use the voltage from one circuit and the current from the other.)

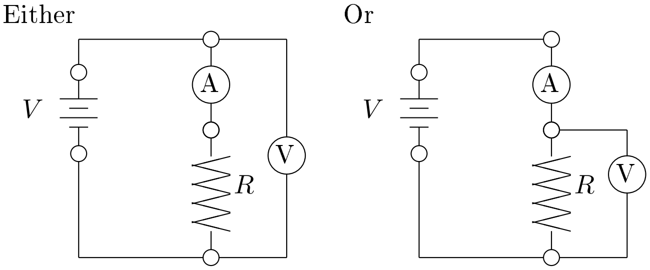

Figure 11.2.1: Determining Ohm's Law with a single resistor.

11.3 The Experiment

Please note Section 11.2 regarding the equipment as arranged in Figure 11.2.1. For one of your resistors arranged according to one of the circuits in Figure 11.2.1, measure the current (from the ammeter A) for several arbitrary and somewhat-evenly-spaced voltage values (as measured from V). Verify Ohm's Law by graphing the voltage V versus the current I and considering the equation of the best trendline. Repeat this for the second resistor. For at least one of your resistors, repeat this for the other configuration in Figure 11.2.1. Answer the first set of questions in Exercises 11.4.

Build the circuit in Figure 11.3.1 using your two resistors. Measure I from A for several V. Graph the voltages V_1, V_2, and V_t on the same graph, all versus the current I through the resistor. Consider the equations of the best trendlines. Answer Question 11.4.5, Question 11.4.6, and Question 11.4.7 about this data and graph.

Build the circuit in Figure 11.3.2 using your two resistors. Measure I from each A (I_1, I_2, and I_t) for several V. All on the same graph, plot the voltage V versus each current. Consider the equations of the best trendlines. Answer Question 11.4.9, Question 11.4.10, and Question 11.4.11 about this data and graph.

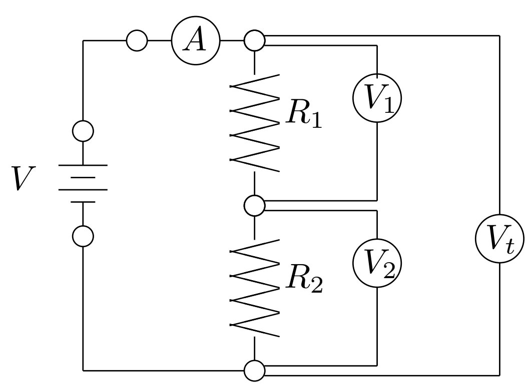

Figure 11.3.1: Using Ohm's Law with multiple resistors in series to find an equivalent resistance.

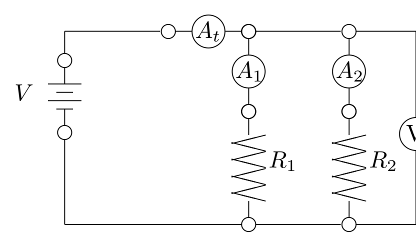

Figure 11.3.2: Using Ohm's Law with multiple resistors in parallel to find an equivalent resistance.

11.4 Questions

All of the following questions should be considered in your lab notebook and used to enhance the analysis of your report.
Regarding the individual resistors, answer the following questions:

1. Based on the color codes, do your resistor values agree with your graphs?

2. At the end of lab, the instructor will show you how to use the multimeter as an ohm-meter. Measure the resistance of your resistors and compare this value to the graphs.

3. Did the two configurations in Figure 11.2.1 give different values?

Regarding the series resistors, answer the following questions:

4. The series graph should have a plot of the individual resistors as well as the series combination. Do the individual series resistors on this graph agree with the individual values that you found on the plot in the first part? Are they too large or too small?

5. Use Ohm's Law to decide on the single equivalent resistor which could replace your two resistors without changing the current-voltage relationship.

6. Is the equivalent resistor larger than or smaller than the individual resistances?

7. Determine a relationship between your resistors, R_1 and R_2, and the equivalent resistance, R_{eq}.

Regarding the parallel resistors, answer the following questions:

8. The parallel graph should have a plot of the individual resistors as well as the parallel combination. Do the individual series resistors on this graph agree with the individual values that you found on the plot in the first part? Are they too large or too small?

9. Use Ohm's Law to decide on the single equivalent resistor which could replace your two resistors without changing the current-voltage relationship.

10. Is the equivalent resistor larger than or smaller than the individual resistances?

11. Determine a relationship between your resistors, R_1 and R_2, and the equivalent resistance, R_{eq}. (Hint: It may help to consider reciprocals of certain values; it may also help to look it up in your textbook.)

Last revised: Jan, 2006
A PDF version might be found at Req.pdf (104 kB)

Lab 12

Magnetic Field Demonstrations - An Exercise

The lab room has been set up with five lab stations; each involves a short experiment designed to demonstrate the characteristics of the magnetic field for various objects. Your group will move from table to table and carry out each of these experiments, making observations and collecting data as necessary. Listed below are questions which you should attempt to answer at each station. Instead of a lab report, you will need to write a half-page summary on each station. It should be thorough enough to explain the phenomenon to a colleague who missed today's lab.

You should form into four groups so that there is always an empty station. Take notes in your lab notebook, but then write up and turn in a formal document that discusses the relevant ideas for each station.

Warning 12.0.1. In all experiments, note that electronic equipment such as power supplies and computers produce magnetic fields that might impact your experiment. You should not measure your magnetic fields near other electronic devices. You should also be aware that strong magnetic fields can erase credit cards and other magnetic storage devices.

12.1 Data Studio's Magnetic Field Sensor (for reference, not an experiment)

To use the magnetic field sensor, turn on Data Studio, plug in the sensor, and activate the sensor in the usual manner. At the tip of the arm on the sensor are two white dots, one on the end of the tip and one on the side of the tip. Notice also the control buttons on the handle of the sensor. The first button has two settings: marked $\rightrightarrows$ and $\upuparrows$ and these are labeled [Radial/Axial]. The Radial setting measures magnetic field pointing into the side of the arm of the sensor, at the location of the white dot. The Axial setting measures magnetic field pointing into the end of the sensor, at the location of the white dot. Negative means that the magnetic field is out of the sensor instead of into the sensor.

When changing between Axial and Radial, the sensor must be tared. If you tare it while it is pointing in the direction of some magnetic field, then it cannot[1] measure that magnetic field.

12.1.1 Measuring the B of a Permanent Magnet

Determine the expected direction of the magnetic field. Set the sensor to either Radial or Axial, according to how you expect to hold it, and tare it. Verify that the scale is set to [1×] and plot in Gauss or Tesla, as appropriate. Place the tip of the sensor such that the white dot on the side (or top as necessary) is near the magnet pointing in the direction of the expected magnetic field.

[1] This is exactly analogous to tarring a scale with a cup on it; the scale only reads the mass of the material added to the cup after the tarring, not the mass of the cup itself.

12.1.2 Measuring the B of a Wire Loop

Use the right-hand rule to determine the expected direction of the magnetic field. Set the sensor to Axial and tare it. Verify that the scale is set to [1×] and plot in Gauss or Tesla, as appropriate. Place the tip of the sensor such that the white dot on the end is as close to the center of the wire loop as possible and points as perpendicular as possible to the plane of the coil.

If there is a cross-field (a field perpendicular to the field of the coil), then you might also try to measure that by removing the sensor from the vicinity of the coil, setting it to Radial, re-taring it, and then replacing the sensor into the center of the coil with the white dot on the side pointing in the direction of the cross field.

12.1.3 Measuring the B of a Solenoid

Use the right-hand rule to determine the expected direction of the magnetic field. Set the sensor to Axial and tare it. Verify that the scale is set to [1×] and plot in Gauss or Tesla, as appropriate. Place the tip of the sensor such that the white dot on the end is as close to the center of the solenoid as possible and points as close as possible along the axis of the solenoid.

You might also try to measure the radial component to the field by removing the sensor from the vicinity of the coil, setting it to Radial, re-taring it, and then replacing the sensor into the center of the solenoid with the white dot on the side pointing outwards towards the coil.

12.1.4 Measuring the B of a Long Straight Wire

Use the right-hand rule to determine the expected direction of the magnetic field. Set the sensor to Radial and tare it. Verify that the scale is set to [1×] and plot in Gauss or Tesla, as appropriate. Place the tip of the sensor such that the white dot on the side is in the vicinity of the wire pointing in the direction of the expected magnetic field.

If there is a cross-field (a field perpendicular to the field of the wire), then you might also try to measure that by removing the sensor from the vicinity of the wire, setting it to Radial, re-taring it, and then replacing the sensor into the center of the coil with the white dot on the side pointing in the direction of the cross field.

12.2 Magnetic Field of a Permanent Magnet - Iron Filings

You should have two cylindrical magnets, a coffee filter, a stiff plastic plate, some paper clips and nails, and a salt shaker of iron filings available at this station. Each magnet is labeled with either “N” or “S” to indicate the north or south pole of the magnet, respectively.

12.2.1 Magnets and Paper Clips

Consider how magnets and paper clips interact. In each of the following, you may replace the paper clips with nails if you like.

Exercise 12.2.1.

1. Describe any interaction you experience when you touch any pair of the paper clips together in the various possible orientations.

2. Describe any interaction you experience when you touch the magnets together in the various possible orientations.

   (a) Describe how you can pick one magnet up with the other.

   (b) Describe how you can knock one magnet over with the other (without making contact).

3. Describe any interaction you experience when you touch one of the magnets together with any one of the paper clips in the various possible orientations.

(a) Pick up one paper clip *with the narrow end* of one of the magnets so that the clip hangs straight out from the magnet. Then, while these are still in contact, touch a second paper clip with the end of the first clip. Now, while carefully holding the first clip near the magnet, carefully remove the magnet from the first clip. *After showing the result to your instructor*, describe and explain the result on the two paper clips.

(b) Predict what will happen if you brought either end of the magnet slowly towards the lower end of the dangling paper clip. Verify your predictions and provide an explanation for how and why your predictions were correct or incorrect. (Be sure to include comments about the orientation of the poles of the magnets as well as the poles of the paper clips.)

4. Explain why it is possible to stick either end of a paper clip to either end of a magnet, but you cannot stick one end of a magnet to either end of another magnet.

12.2.2 Magnets and Iron Filings

Iron filings act similarly to the paper clips. The iron filings are small enough that they allow us to "map" the magnetic field of an object. Each individual filing will align itself with the magnetic field.

Place the coffee filter on top of the clear, plastic plate. Sprinkle some iron filings on the coffee filter. Note: We are using a coffee filter because its shape allows us to minimize spilling the filings on the table, or worse, the floor. ***Be* very *careful not to spill the filings.*** Have one person hold the plate up with both hands high enough for another person to move one of the cylindrical magnets beneath it while you all watch what happens to the iron filings. Meanwhile, somebody else should place one of the cylindrical magnets underneath the sheet of paper so that everybody can observe the patterned displayed by the filings.

Exercise 12.2.2.

1. Determine if you can make any interesting patterns in the filings by placing or moving the magnet under the filings. When you think you have a good sense of the patterns, try to draw or describe some of what you found.

2. Without the magnet, try to smooth out the filings. (If you can't smooth them out well, then carefully hold the salt-shaker over the coffee filter and unscrew the cap, pour the filings back in, replace the cap, and re-sprinkle more filings onto the filter.) Predict what you should see if you had two magnets under the filings each with the North pole facing the other magnet. What if both South poles were facing each other? What if one North and one South pole faced the other?

3. While one person holds the plate with the filter and filings, have two people each hold a magnet under the filings as described in the previous question. Verify your predictions and provide an explanation for how and why your predictions were correct or incorrect.

12.3 Magnetic Field of a Permanent Magnet - Field Sensor

You should have a small, four-post, wooden stand with a hole in the top and a wooden cylinder taped to a ruler on a lab-jack. The wooden equipment was hand-made and is delicate; ***please be careful when handling the apparatus***.

Exercise 12.3.1.

1. Use the field sensor (as described in Section 12.1) set to Axial to measure (and record) the strength of the magnetic field *due to the permanent magnet* at various positions from the magnet. It will be useful to set the sensor 10.0 cm from the magnet and make a measurement at each 1.0 cm interval as you move towards the magnet.

2. Repeat this for the Radial setting.

3. Tabulate your results (you may also graph it *if you like*) and discuss the manner in which the field depends on distance. Is it linear? Polynomial? something else?

12.4 Magnetic Field of the Earth - Tangent Galvanometer

This station has a loop of wire connected to a power supply. There is also a compass needle balancing on a needle point located at the center of the loop. Verify that the power supply is connected to the wire. Without turning on the power supply, predict which way current will flow based on the connection. With the power supply off (not merely turned down), carefully and gently align the loop so that it rests along the line that the compass wants to rest. ***Before you turn on the power supply***, turn the voltage dial down to zero and the current dial up to some medium value. The HI-LO setting on the current dial should be set to LO. When current begins to flow through the coil, a magnetic field is generated whose direction can be found from the right-hand rule and whose magnitude can be calculated from

$$B_c = \frac{\mu_0 I N}{2R} \tag{12.1}$$

where B_c is the coil's magnetic field strength, I is the current (in amps), $\mu_0 = 4\pi \times 10^{-7}\ ^{\mathrm{N}}\!/_{\mathrm{A}^2}$, N is the number of turns of the wire in the coil, and R is the radius of the coil (which you will have to measure).

Exercise 12.4.1.

1. Using components, resultants, magnitudes and directions, devise a technique to combine the controllable magnetic field due to the coil with the uncontrollable, but fixed, magnetic field of the earth in such a way as to calculate the magnitude of the Earth's magnetic field. Several hints are given below.

   (a) If the field due to the loop were the only field present, which way would the compass needle point after you turned on the current? What would happen if you changed the direction of the current?

   (b) If there were two magnetic fields present, along which (if either) would a compass point?

   (c) Can you control the direction of any magnetic field present? Why might you want the wire to line up with the direction that the compass points before turning on the current? How are the directions of the components of a vector "aligned"?

   (d) Can you control (and know the value of) the magnitude of any magnetic field present? What would the compass needle do as you slowly turn this up from zero to some very large value?

   (e) Can you relate components to resultants and vice versa?

2. Turn on the power and very slowly turn up the voltage while watching the ammeter; the ammeter should not go above 4 or 5 mA. Describe the effect this has on the compass needle. Predict and explain what *would* happen if you swap the direction, but not the magnitude of the current. ***Do not actually swap the direction of the current at this point.***

3. Let the compass needle settle into whatever orientation it likes while the power continues to be supplied to the circuit. While you wait, record the value of the current and use the field sensor (as described in Section 12.1) to measure (and record) the strength of the magnetic field *due to the loop* at the center of the compass. After the compass needle settles in, place a protractor on the top of the wire loop and measure (and record) the angle of the deflection. Without turning off the power supply, unplug the cables that provide current to the circuit *from the power supply, not from the wire loop, which should not be bumped*. Plug the cables in the other way to flip the current. Describe what happens to the compass. Remeasure (and record) the current, the magnetic field, and the angle of deflection for this direction. Calculate the magnetic field of the Earth based on the average measured B and the average deflected angle. Despite the large uncertainty, compare it to the known value.

12.5 Magnetic Field of a Solenoid

Before you turn on the power supply, set the current all the way down and the voltage up at some intermediate point. The HI-LO setting on the current dial should be set to LO.

12.5.1 The Small Solenoid

Exercise 12.5.1.

1. Without turning on the power supply, connect the positive and negative terminals of the power supply to the terminals of the smaller solenoid. Note the direction of current flow and predict the direction of the magnetic field.

2. Use the field sensor (as described in Section 12.1) set to Axial to measure (and record) the strength of the magnetic field *due to the solenoid*. Insert the sensor as far along the axis of the solenoid as possible and try to keep your hand as steady as possible. Turn on the power supply and slowly turn up the current to some intermediate value. Move the sensor around a little inside the solenoid and discuss the results.

3. Repeat the previous step with the sensor set to Radial. What variables does the magnetic field due to a solenoid depend on? Does it follow the predicted equation for a solenoid?

Turn the power supply off. Disconnect the wire from the solenoid.

12.5.2 Measurements with the Large Solenoid

Before connecting the large solenoid, measure the number of turns per length, $n = \frac{N}{L}$. Do not measure the full number of loops nor the full length. Find some portion of the coil and measure the number of coils and the length in that small sample size. When you calculate n, notice that the solenoid is wrapped four coils deep, so multiply your N by 4. In this problem, you can measure B and I in order to find μ_0 to verify the equation of a solenoid.

Exercise 12.5.2.

1. Connect the power supply in series with an ammeter and then the solenoid before completing the circuit back to the power supply. Be sure that the ammeter reads several amps. Insert the field sensor set to the appropriate settings as close as possible to the axis of the solenoid. Predict what you will measure for the Radial and Axial measurements above.

2. Measure the current from the ammeter, the magnetic field from the sensor and calculate a value for μ_0 based on the equation for a solenoid. Compare this to the accepted value in your book. Draw a conclusion about the equation of a solenoid.

12.6 Magnetic Field of a Wire

Before you turn on the power supply, set the current all the way down and the voltage up at some intermediate point. The HI-LO setting on the current dial should be set to HI. (You will be using a current of about 8 A.)

Notice that the wire connects are exposed. Be careful not to touch the connections when the current is on.

Exercise 12.6.1.

1. Without turning on the power supply, connect the positive and negative terminals of the power supply to opposite ends of one of the three wires inside the **Romex**™ cable. Be sure, based on color, to connect them to *the same* wire. Straighten a long section of the wire as well as possible. Note the direction of current flow and predict the direction of the magnetic field.

2. Use the field sensor (as described in Section 12.1) set to Radial to measure (and record) the strength of the magnetic field *due to the long straight wire*. The sensor should lie along the direction of the wire and must be touching the wire to make any measurement. Turn on the power supply and turn up the current to about 8 A. (You may change the current in order to see the effect of current on the size of the magnetic field.) Move the sensor to different radii and discuss the results. Place the sensor close to the wire and slowly vary the strength of the current using the knob on the power supply. Discuss the results.

3. Repeat the previous step with the sensor set to Axial.

4. Turn the power supply off. Disconnect the wire from the power supply. Connect the red terminal to one side of the white wire and the black terminal to the black wire so that both connections are at the same end. On the far end, connect the black and white wires (this is where the lamp goes and you should not actually do this at home where there is *significantly* more current able to flow! *Really*!). Predict what you will measure for the Radial and Axial measurements above.

5. Repeat Questions Question 12.6.1.2 and Question 12.6.1.3 for the two wire case. Verify your predictions and provide an explanation for how and why your predictions were correct or incorrect.

Last revised: Apr 6, 2009
A PDF version might be found at Magneticdemo.pdf (172 kB)

Appendix A

Managing Uncertainties

One of the fundamental aspects of science is knowing the reliability of results. The mechanism for gaining this knowledge is first to gauge how well one knows any given measurement and then to propagate this to an indication of the reliability of the results that depend on those measurements. The primary goal in attending to the propagation of the uncertainty is that it allows scientists to determine which measurement is causing the most uncertainty in the result so that future experimenters know which measurement to improve to get an improved result.

In this section we will learn the terminology, determine how to gauge the measurement uncertainty, learn how to propogate this information through a calculation, and learn how to discuss this analysis in your lab reports.

A.1 Experimental Uncertainties, Defining "Error"

Measurements are never exact. For example, if one apple is divided among three people, your calculator will tell you that each person has 0.3333333333 of an apple. A measurement of each slice will tell you two pieces of information: (1) how many 3s to keep and (2) how well you know the final 3. In this example, both 0.33 ± 0.01 and 0.33 ± 0.04 imply that the measurement is accurate to two decimal places, but the first implies that you trust the second 3 more than if you report it as the second number.

> **CAUTION:** Because physicists "know what we mean", they are often sloppy with their language and use the words "error" and "uncertainty" interchangeably.

Some technical terms and their use in physics (which may differ from common use):

accuracy How close a number is to the true (but usually unknowable) result. This is usually expressed by the (absolute or relative) error.

precision How well you trust the measurement. This is vaguely expressed by the number of decimals, or clearly expressed by the size of the (absolute or relative) uncertainty.

uncertainty The **uncertainty in a number** expresses the precision of a measurement or of a computed result. This can be expressed as the **absolute uncertainty** (explained in Finding the Precision of a Measurement), the **relative uncertainty**, or the **percent uncertainty**.

$$\text{relative uncertainty} = \left|\frac{\text{(absolute uncertainty)}}{\text{measured value}}\right|$$

$$\text{\%-uncertainty} = 100\% * \left|\frac{\text{(absolute uncetainty)}}{\text{measured value}}\right|$$

error The **error** is a number that expresses the accuracy by comparing the measurement to an accepted ("true") value. This can be expressed as the **absolute error**, the **relative error**, or the **percent error**.

$$\text{absolute error} = |\text{true value} - \text{measured value}|$$

$$\text{relative error} = \left|\frac{(\text{true value} - \text{measured value})}{\text{true value}}\right|$$
$$\text{\%-error} = 100\% * \left|\frac{(\text{true value} - \text{measured value})}{\text{true value}}\right|$$

difference The **difference** is a number that expresses the consistency of a multiple measurements by comparing one measurement to another. This can be expressed as the **absolute difference**, the **relative difference**, or the **percent difference**. You should notice that since we don't know *which* measurement to trust, we take the absolute difference relative to the *average* of the measurements (rather than choosing one measurement as "true").

$$\text{absolute difference} = (\text{measurement}_1 - \text{measurement}_2)$$
$$\text{relative difference} = \frac{(\text{measurement}_1 - \text{measurement}_2)}{\left[\frac{(\text{measurement}_1)+(\text{measurement}_2)}{2}\right]}$$
$$\text{\%-difference} = 100\% * \frac{(\text{measurement}_1 - \text{measurement}_2)}{\left[\frac{(\text{measurement}_1)+(\text{measurement}_2)}{2}\right]}$$

Note A.1.1 (compare)**.** Whenever you are asked to "compare" values, it is expected that you will not only compute a %-error or %-difference (as appropriate, according to the above considerations); but will also comment on if the uncertainty of the values overlap. Recall that the uncertainty means that your measurement does not distinguish between values within that range, so if the uncertainties overlap, then the values are "the same to within your ability to measure them."

A.2 Writing an Analysis of Error

The conclusion of your lab report should be based on an analysis of the error in the experiment. The analysis of error is one of the most certain gauges available to the instructor by which the student's scientific insight can be evaluated. To be done well, this analysis calls for comments about the factors that impacted the extent to which the experimental results agree with the theoretical value (what factors impact the percent error), the limitations and restrictions of the instruments used (what factors impact the uncertainty), and the legitimacy of the assumptions.

Physicists usually use the phrase "sources of error" (or "sources of uncertainty") to describe how the limits of measurement propagate through a calculation (see Propagation of Uncertainties) to impact the **uncertainty** in the final result. This type of "error analysis" gives insight into the **accuracy** of the result. Considerations for the Error Analysis provides questions that can help you describe which of several measurements can most effectively improve the **precision** of the result so that you can gain insight into the **accuracy** of the result. The accuracy allows one to gauge the veracity (truth) of an underlying relationship, but precision allows you to gauge accuracy. Said another way, a small **percent difference** usually is used to imply a small **percent error**. Said another way, imprecise measurements always *seem* accurate.

A.2.1 Technically, Errors are not Mistakes

Your report should not list "human error" because most students misunderstand this term to mean "places I might have made a mistake" rather than "the limiting factor when using the equipment correctly." Finding the Precision of a Measurement discusses measurement uncertainties as defined above.

In the example of the apple above, the fact that one person has 0.33 ± 0.04 of an apple does *not* reflect a "mistake" in the cutting, but rather reflects that the cutter is limited in their precision. What is important is to use the uncertainty to express how well one can repeated cut the apple into thirds. The absolute uncertainty of 0.04 is generally interpreted to say that most instances (roughly 68%, as explained in Uncertainty of multiple, repeated measurements) of the cutting of an apple in this way will result in having between 0.29 to 0.37 of an apple for any given slice.

When describing the cause of an error (difference from the theoretical value) or of an uncertainty (the extent you trust a number), you can usually categorize this source of error as a random error (a cause that could skew the result too large *or* too small) or as a systematic error (a cause that tends to skew the result in one particular direction).

Random Error An environmental circumstances, generally uncontrollable, that sometimes makes the measured result too high and sometimes make it too low in an unpredictable fashion. Random errors may have a statistical origin – that is, they are due to chance. For example, if one hundred pennies are dumped on a table, on average we expect that fifty would land heads up. But we should not be surprised if fifty-three or forty-seven actually landed heads-up. This deviation is statistical in nature because the way in which a penny lands is due to chance. Random errors can sometimes be reduced by either collecting more data and averaging the readings, or by using instruments with greater precision.

Systematic Error A systematic error can be ascribed to a factor which would tend to push the result in a certain direction away from the theory value. The error would make all of the results either systematically too high or systematically to low. One key idea here is that systematic errors can be eliminated or reduced if the factor causing the error can be eliminated or controlled. This is sometimes a big "if", because not all factors can be controlled. Systematic errors can be caused by instruments which are not calibrated correctly, maybe a **zero-point error** (an error with the zero reading of the instrument). This type of error can usually be found and corrected. Systematic errors also often arise because the experimental setup is somehow different from that assumed in the theory. If the acceleration due to gravity was measured to be $9.52\ \mathrm{m/s^2}$ with an experimental uncertainty (precision) of $0.05\ \mathrm{m/s^2}$, rather than the textbook value of $9.81\ \mathrm{m/s^2}$, then we should be concerned with why the accuracy is not as good as the precision. This is most likely to mean that there is a significant systematic error in the experiment, where one of the initial assumptions may not be valid. The textbook value does not consider the effects of the air. The effects of the air may or may not be controllable, and the difference between the theory and the data may be (within appropriate limits or tests) considered a correction factor for the systematic error.

A.2.2 Considerations for the Error Analysis

In order to help you get started on your discussion of error, the following list of questions is provided. It is not an exhaustive list. You need not answer all of these questions in a single report.

1. Is the error large or small? Is it random or systematic? ... statistical? ... cumulative?
   (a) What accuracy (precision) was expected? Why? What accuracy (precision) was attained? If different, why?
   (b) Was the experimental technique sensitive enough? Was the effect masked by noise?
2. Is it possible to determine which measurements are responsible for greater percent error by checking items measured and reasoning from the physical principles, the nature of the measuring instrument, and using the rules for propagation of error?
   (a) Is the error partly attributable to the fact that the experimental set-up did not approximate the ideal that was required by the physical theory closely enough? How did it fail?
   (b) If a systematic error skews high (low), then is your result too high (low)? Is this a reasonable explanation? Is the size of the skew enough to explain the result?
   (c) What can be done to improve the equipment and eliminate error? How can the influence of environmental factors be diminished? Why is this so?
3. Is the error (deviation) in the experiment reasonable?

Note A.2.1 (compare)**.** Whenever you are asked to "compare" values, it is expected that you will not only compute a %-error or %-difference (as appropriate); but will also comment on if the uncertainty of the values overlap. Recall that the uncertainty means that your measurement does not distinguish between values within that range, so if the uncertainties overlap, then the values are "the same to within your ability to measure them."

A.3 Finding the Precision of a Measurement

A.3.1 Uncertainty of a single measurement

All equipment has a finite precision. For example, if you are stepping off the length of a room by placing one foot in front of the other and counting steps, then you are measuring in "shoe-lengths". You can likely estimate a half-show length or a third-of-a-shoe-length, but it might be difficult to accurately gauge smaller intervals of a shoe-length. Conveniently for me, my size 11 shoe is 12 in long. So, I can replace a shoe-length with a "foot". Furthermore, I could replace my measurement technique with a yard-stick (or better yet a meterstick). Since a meter-stick has increments of millimeters on it, it is straightforward to measure the distance to the nearest millimeter. In fact, you can probably guess the nearest half-millimeter. The uncertainty in your shoe-measurement is about 4 in (or about 10 cm = 100 mm). The uncertainty in the meter-stick measurement is about 0.5 mm, significantly better than your shoe.

In addition, to how well the equipment can make a measurement, there is also how well you can gauge the measurement with that piece of equipment. If you measure the length of the room using 12 in rulers, then you will need quite a few of them. It is possible that with so many individual rulers, you will either not measure in exactly a straight line or you might not be able to keep the rulers exactly parallel to each other. Both of these (inappropriate but difficult to control) uses of the rulers will introduce error and, since you can't necessarily judge if you are doing this (especially since you are trying to not do so), you are introducing uncertainty. You do not necessarily know what errors are actually happening when they are so small. Nonetheless, you need to account for the possibility of such errors in your uncertainty. (Recall the types of error in Technically, Errors are not Mistakes.) In each of the cases mentioned here, the error would necessarily increase the measurement value to a number larger than the actual value. There are other instances (perhaps using a string to measure distance and mis-gauging the tautness of the string) where the value might be systematically small or perhaps randomly distributed.

To get a sense of how large the possible variations are due to this measurement uncertainty, it is advisable to always take more data. Having more data is always better (statistically). If you measure a quantity many times and you do not see any variation, then the precision of the instrument dominates the uncertainty; that is, your instrument is less precise than your technique. If you measure a quantity many times and see some variation, then your measurement technique dominates the uncertainty; that is, your technique is less precise than your instrument. Usually the actual uncertainty will be a combination of both. For our purposes, we will consider 10-20 measurements to be "many", and hope it is sufficient. If you are asked to do a lab exercise on "Standard Deviation", then you will explore what a "sufficient number of measurements" means.

In the next subsection (Uncertainty of multiple, repeated measurements), we will discuss how to do the statistics to account for multiple measurements.

A.3.2 Uncertainty of multiple, repeated measurements

Calculate or estimate the precision of a measurement by one or more of the following methods:

1. by the precision of the measuring instrument, and take into account any uncertainties that are intrinsic to the object itself;

2. by the range of values obtained, the minimum and/or maximum deviation (d);

$$d_i = |X_i - X_{\text{ave}}|$$

3. by the standard deviation, which is the square root of the sum of the squares of the individual deviations (d) divided by the number of readings (N) minus one;

$$\sigma = \sqrt{\frac{1}{(N-1)}\sum d^2} = \sqrt{\frac{1}{(N-1)}\sum_i |X_i - X_{\text{ave}}|^2}$$

4. by the standard deviation of the mean, which is the standard deviation divided by the square root of the number of readings;

5. by the square root of the number of readings ($\sqrt{N}$), if N is considered large;

If many data points were taken and plotted on a histogram, it would smooth out and approach the symmetrical graph typical of the binomial distribution (Recall the histogram in the Standard Deviation Lab of PHY121). This distribution and many others in statistics may be approximated by the gaussian distribution.

The standard deviation, σ, can be estimated from the above graph. It is a measure of the "width" of the distribution. For the case shown, the standard deviation has the value of five. The greater the standard deviation, the wider the distribution and the less likely that an individual reading will be close to the average value. About 68% of the individual readings fall within one standard deviation (between 45 and 55 in this case). About 96% of the readings fall within two standard deviations (between 40 and 60 in this case).

As more and more readings are taken, the effect of the random error is gradually eliminated. In the absence of systematic error, the average value of the readings should gradually approach the true value. The smooth curve above was drawn assuming that there was no systematic error. If there were, the graph would merely be displaced sideways. The average value for the number would then be say 55.

The distribution of many average (mean) readings is also gaussian in shape. Comparing this to the distribution for individual readings, it is much narrower. We would expect this, since each reading on this graph is an average of individual readings and has much less random error. By taking an average of readings, a considerable portion of the random error has been canceled. The standard deviation for this distribution is called the standard deviation of the mean (σ_m). For this distribution, 68% of the averages of the readings are within one standard deviation of the mean, and 98% of the average readings fall within two standard deviations of the mean.

The standard deviation of the mean tells how close a particular *average* of several readings is likely to be to an overall average when many readings are taken. The standard deviation tells how close an *individual* reading is likely to be to the average.

There is one case for which the standard deviation can be estimated from one reading. In counting experiments (radioactivity, for example), the distribution is a Poisson distribution. For this distribution, the standard deviation is just the square root of the average reading. One reading can give an estimate of the average, and therefore, give an estimate of-the standard deviation.

A.4 Propagation of Uncertainties

The previous sections discussed the uncertainties of directly measured quantities. Now we need to consider how these uncertainties affect the rest of the analysis. In most experiments, the analysis or final results are obtained by adding, subtracting, multiplying, or dividing the primary data. The uncertainty in the final result is therefore a combination of the errors in the primary data. The way in which the error propagates from the primary data through the calculations to the final result may be summarized as follows:

1. The error to be assigned to the sum or difference of two quantities is equal to the sum of their absolute errors.

2. Relative error is the ratio of the absolute error to the quantity itself. The relative error to be assigned to the product or quotient of two quantities is the sum of their relative errors.

3. The relative error to be assigned to the power of a quantity is the power times the relative error of the quantity itself.

These rules are not arbitrary, but rather they follow directly from the nature of the mathematical operations. These rules may be derived using calculus.

Exercise A.4.1 (Try Propagating the Uncertainty When Adding Numbers)**.** Compute the perimeter of a table that is measured to be $176.7\,\mathrm{cm} \pm 0.2\,\mathrm{cm}$ along one side and $148.3\,\mathrm{cm} \pm 0.3\,\mathrm{cm}$ along the other side.

Hint 1. To find the perimeter, add the four sides of the rectangle. Use the values, but not the uncertainty.

Hint 2. To find the uncertainty, use Rule 1.

Answer. The perimeter is $P = 650\,\mathrm{cm} \pm 1\,\mathrm{cm}$.

Solution. The perimeter can be found as:

$$P = (176.7\,\mathrm{cm}) + (148.3\,\mathrm{cm}) + (176.7\,\mathrm{cm}) + (148.3\,\mathrm{cm})$$
$$P = 650.0\,\mathrm{cm}$$

but we do not know the precision (appropriate number of decimals) until we compute the uncertainty, which is

$$\Delta P = (0.2\,\text{cm}) + (0.3\,\text{cm}) + (0.2\,\text{cm}) + (0.3\,\text{cm})$$
$$\Delta P = 1.0\,\text{cm}$$

The value of the uncertainty determines where you round the result. Because the first digit of the uncertainty is in the "one's place", we round *both* the value and the uncertainty to that place.

The perimeter is $P = 650\,\text{cm} \pm 1\,\text{cm}$.

Exercise A.4.2 (Try Propagating the Uncertainty When Multiplying Numbers)**.** Compute the area of a table that is measured to be $176.7\,\text{cm} \pm 0.2\,\text{cm}$ along one side and $148.3\,\text{cm} \pm 0.3\,\text{cm}$ along the other side.

Hint 1. To find the area, multiple the length and width of the rectangle. Use the values, but not the uncertainty.

Hint 2. Because the area of the table is calculated using multiplication, use Rule 2to find the uncertainty.

Answer. The area is $A = (2.620 \times 10^4) \pm (0.008 \times 10^4)\text{cm}^2$.

Solution. The area is found to be (significant digits are underlined)

$$A = (176.7\text{cm}) \times (148.3\text{cm})$$
$$A = \underline{2620}4.61\text{cm}^2$$

The rules for **significant figures** gives a guide for the precision (appropriate number of decimals), that is only an approximation. To know with certainty, we need to compute the uncertainty, which is

$$\%\text{-uncertainty} = \left(\frac{.2\text{cm}}{176.7\text{cm}}100\%\right) + \left(\frac{0.3\text{cm}}{148.3\text{cm}}100\%\right)$$
$$\%\text{-uncertainty} = (.11\%) + (.20\%) = (.31\%)$$

Insignificant Please be aware that the reason some digits are called **insignificant** is that they are *insignificant*:

$$(.31548\%) \times (26204.61) = 82.67$$
$$(.31\%) \times (26204.61) = 81.23$$
$$(.31\%) \times (26200) = 81.22$$
$$(.3\%) \times (26204.61) = 78.61$$
$$(.3\%) \times (26200) = 78.60$$

All of these round to an uncertainty of $80\,\text{cm}^2$.

To find the uncertainty, we calculate

$$(.31\%) \times (\underline{2620}4.61\text{cm}^2) = 81.23\text{cm}^2$$

This tells us that we need to round at the "ten's place". We can write the area in a variety of ways:

$$\begin{aligned} A &= (2.620 \times 10^4\,\text{cm}^2) \pm 0.3\% \\ &= (2.620 \times 10^4) \pm (0.008 \times 10^4)\,\text{cm}^2 \\ &= 2.620(8) \times 10^4\,\text{cm}^2 \end{aligned}$$

A.5 Significant Figures only *approximates* Uncertainty

The precision/accuracy of any measurement or number is approximated by writing the number with a convention called using **significant figures**. Every measuring instrument can be read with only so much precision and no more. For example, a meter stick can be used to measure the length of a small metal rod to one-tenth of a millimeter, whereas a micrometer can be used to measure the length to one-thousandth of a millimeter. When reporting these two measurements, the precision is indicated by the number of digits used to express the result. You should always record your data and results using the convention of significant figures.

To give a specific example, suppose that the rod mentioned above was 52.430 mm long. When making this measurement with the meter stick, you would count off the total number of millimeters in the length of the rod and then add your best guess that the rod was four-tenths of a millimeter longer than that. Using the micrometer, you would count off the hundredths of a millimeter and then add your best guess of the number of thousandths of a millimeter, to complete the measurement. How would you communicate the fact that one measurement is more precise than the other? If you wrote both quantities in the same way, you could not tell which was which.

The rules for **significant figures**:

1. Significant figures include all certain digits plus the first of the doubtful digits. (Note Convention A.5.1.)
2. Zeros to the right of the number are significant; zeros on the left are not. (Note Convention A.5.2 and Example A.5.3.)
3. Round the number, increasing by one the last digit retained if the following digit is greater than five. (Note Convention A.5.4.)
4. In addition and subtraction, carry the result only up to the first doubtful decimal place of any of the starting numbers.
5. In multiplication and division, retain as many significant figures in the answer as there are in the starting number with the smallest number of significant figures.

Convention A.5.1 (One doubtful digit)**.** (Note Rule 1.) The reading obtained from the meter stick would be written as 52.4 mm; all digits up to and including the first doubtful digit. The reading from the micrometer would be written as 52.430 mm. The first doubtful digit in the case of the meter stick is .4 mm. The first doubtful digit in the case of the micrometer is zero-thousandths of a millimeter. Note that the number of significant figures is related to the precision of the measuring instrument – it is not an abstraction about the number.

Sometimes the character zero is confusing. See Rule 2.

Convention A.5.2 (Dealing with Zero)**.** (Note Rule 2 and Example A.5.3.) In the example above, the reading of the micrometer was given as 52.430 mm. The zero is a significant figure, it communicates the fact that the micrometer measurement is good to a thousandth of a millimeter. Zeros used to the left of significant digits to position the decimal point are not significant. They are not communicating the precision of the measurement. For example, if the measurement from the meter stick were written as 0.0524 meter, the zeros would not be significant digits. Because of the units (meters instead of millimeters), the decimal point had to be moved to the left. This measurement still has only three significant figures.

Example A.5.3 (Handling Zero)**.** Suppose that you wished to give the meter stick measurement in terms of microns (μ) (1 micron = 1 millionth of a meter). We determined that the meter stick reading has 3 sig. figs., one good way to write this is to use scientific notation. Write the number as 5.24×10^4 microns. The factor of 10^4 shows the order of magnitude, while the 5.24 retains the proper number of significant figures. Study the following examples:

5.24 cm	3 significant figures
52.4 mm	3 significant figures
0.0524 m	3 significant figures
$5.24 \times 10^4\ \mu$m	3 significant figures
52.430 mm	5 significant figures
0.052430 m	5 significant figures
$5.2430 \times 10^4\ \mu$m	5 significant figures
52430 μm	4 significant figures
52430. μm	5 significant figures

Because all measurements are limited in their precision, then all results derived from these measurements are also limited in their precision. Many students get carried away with the number of digits produced by a calculator and mislead the reader by reporting their results with more significant figures than their data permits. Form the habit of rejecting all figures which will have no influence in the final result and report the result with only the number of significant digits allowed by the data. The following rules will help you do this successfully.

Convention A.5.4 (Rounding)**.** (Note Rule 3.) Because the use of significant digits is meant to be an approximation to the more precise use of measurement uncertainty, the convention for the rounding of the final digit is not critical and is treated a little differently by different scientists. Some round-up anything five-or-more. Some round-down anything five-or-less. Some round the five up or down based on whether the next digit is even or odd. This third choice is intended to express that we don't actually know which way to round it and letting the randomness of the next digit make the determination is like flipping a coin. ***You should ask your instructor, which approach they prefer.***

When determining or estimating the experimental uncertainty, the precision of the measuring instrument is important, as shown in the above examples. But you must also be aware of other experimental factors. For example, a good stopwatch may have a precision of 0.01 seconds. Is this the total uncertainty of the measurement? You must remember that our physical reaction time maybe another 0.3 seconds. This is more than 10 times larger than the precision of the timer. This is very significant. Another example is trying to measure the diameter of a fuzzy cotton ball with a micrometer. Why is this not a very productive procedure? There are major uncertainties here that are intrinsic to the object itself and are unrelated to the measuring instrument. One must use common sense when estimating these uncertainties.

The **actual uncertainty** written in the units of the measurement, may not convey a sense of how good the precision is. A better measure of the precision is given by the relative uncertainty. This is defined as the actual uncertainty divided by the measurement itself and multiplied by 100, the **relative uncertainty** does not carry any units, just a %.