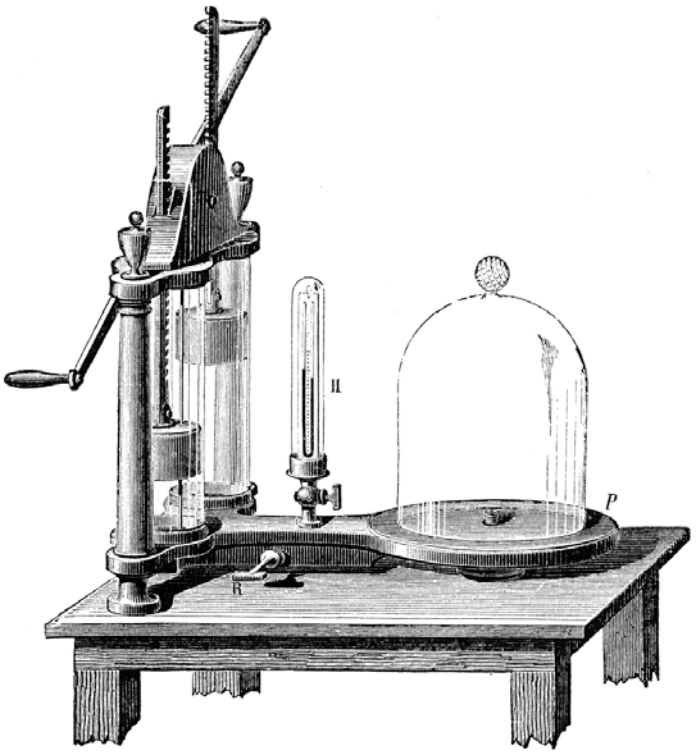
# INTRODUCTORY PHYSICS II

# PHYSICS 1020
# LABORATORY MANUAL




J.L. McClure, Professor of Physics
D.G. Simpson, Adjunct Professor of Physics
Prince George's Community College

Version 10B
Revised Spring 2013
Section LE-01

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... the eternally incomprehensible thing about the world is its comprehensibility.

A. Einstein

# Foreword

Laboratory work gives you first-hand experience with the basic laws and principles that you study in class. You get experience with the details and the problems associated with measurement. And you learn how to carefully traverse the sometimes complex road to the successful analysis of measured data. Hopefully, this "hands on" experience will increase your understanding of some of the basic ideas of physics and help you appreciate some of the difficulties in making good measurements and reporting the results of data analysis.

As you already know, most of the principles and laws of physics are somewhat *abstract* and often *mathematical* in nature which means that laboratory work in physics involves more that just looking and seeing. It involves following technical directions, adjusting apparatus, taking measurements, recording data, making calculations, graphing data, analyzing data and graphs, and otherwise trying to make sense out of a set of numbers. These are important skills in science. Therefore, another important purpose of your laboratory work is to gain experience using these skills.

Many of the laboratory exercises in this lab manual will require you to test or verify basic principles or laws. Other experiments will give you practice using some of the common instruments used to make measurements in electricity and optics. In both cases, you will set up apparatus, verify that it properly works, take data, analyze the data, and develop simple conclusions. Keep in mind that our apparatus is not perfect and you will experience some experimental error between your measurements and theory. When your experimental results are within *10% of the expected values,* you can assume good agreement between experiment and theory.

## Objectives of the Physics Laboratory

The basic objectives of your experimental work in the physics laboratory are to:

1. *gain* a better understanding of some of the basic physical principles of physics by working directly with them,
2. *learn* to work with a variety of instruments and to *use* them to make reliable measurements,
3. *learn* about precision in physical measurements and to *gain* experience in properly recording and measuring data,
4. *gain* experience doing calculations using measured data and organizing data sets,
5. *learn* how to express measured data and calculated results to the appropriate number of significant figures,
6. *gain* experience comparing experimental results to theory and drawing appropriate conclusions from the results,
7. *learn* how to graph experimental results and to *analyze* graphed experimental data,

8. *gain* experience using a graphing calculator (or computer) to organize, graph, and analyze experimental data,

9. *gain* experience in reading technical directions and following technical instructions,

10. *gain* experience in reporting experimental results in a logical and orderly manner including writing about technical information using well-organized information using well-organized complete sentences.

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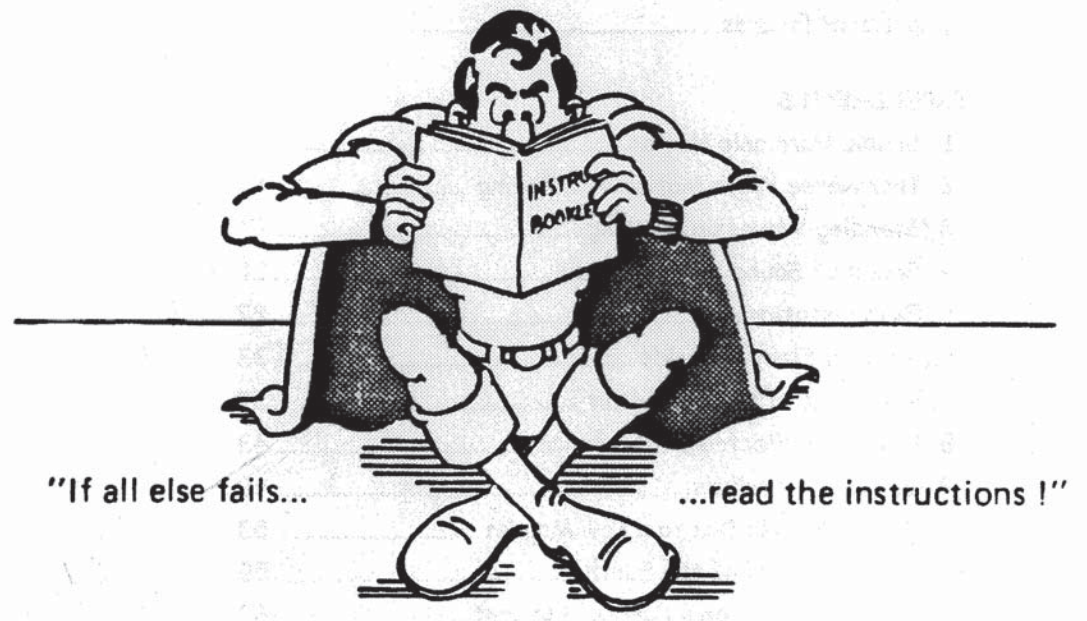

"If all else fails...
...read the instructions !"

# General Instructions

1. *For each experiment, you must write and submit a short laboratory report.* For a discussion about the purpose of the laboratory read the *Foreword* on page iii. For a detailed discussion on how to write a report read *The Laboratory Report* on page 3. The experiments require about one hour for setup and data collection and about an hour for analysis. Your instructor will tell you when the completed laboratory report is due.

2. *Your grade for each report is based on how well you understood the procedure* (as determined by what you include in your report and the completeness of the report), the proper use of significant figures in both data tables and in calculations, the proper documentation of calculations including units for all physical quantities, the completeness of the analysis, the degree of correctness of your responses to questions, and the validity of your conclusions. *Keep in mind that what you submit is a report and not just rough notes about the experiment.* Use complete sentences and a high quality reporting style.

3. *Write your reports on lined or unlined paper.* Reports written on paper torn from *spiral notebooks* will **not** be accepted unless the torn edges are trimmed. You are encouraged to use a pencil to write your reports because errors inevitably occur.

4. *To get credit for your report, you must be present to take your own data.* You cannot collect data from others and use it to write a report. *Reports turned in late will lose one grade and reports turned in more that one week late may or may not be accepted at the discretion of your instructor.*

5. Ideally, each of you would have your own apparatus and work alone on each experiment. However, there is not enough apparatus and there is considerable merit in working with partners, because much of modern research and technical work is done by people working in teams. You will work in groups of two, three, or four. Share the responsibilities associated with set up, measurements, data acquisition, and analysis. Give every person in your lab group a chance to touch the apparatus and conduct experimental trials. You may also freely consult with your instructor and other classmates while working on any part of the laboratory experiment.

6. Although you will work as part of an experimental group, *you are each individually responsible for the data, calculations, ideas, and comments in your own report.* Errors in procedure, wrong data, mistakes in calculations, wrong answers to questions, and inadequate or invalid conclusions cannot be blamed on your partners. Check up on your partners and ensure that their measurements are correct. When writing your report, *please express ideas and comments in your own words. Do not borrow the words, expressions, and sentences from your partners' reports.*[1]

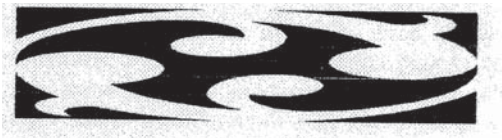
7. *Before coming to lab class,* please read carefully the *Objectives* and *Method* sections of the upcoming experiment to discover what you will be doing and how you will do it. Review the theory behind

[1] For a few experiments — numbers 6, 9, 13, and 14 — you will submit a single report for the entire group, as noted in the instructions for those labs.

the experiment and read the *Procedure* and *Analysis* sections so that you have a general idea of the equipment involved, the data to be collected, and the analysis required. At the beginning of each lab class, your instructor will give a brief overview of the experiment and explain how to use the equipment, but it will be assumed that you already understand the basic experimental procedure and the underlying theory. Be ready to ask questions about those parts of the procedure and method that you don't understand. Since you want to complete your measurements in the first hour of the lab, it is important to have a good idea of what you must do.

8. *Before taking data, ensure that your equipment is working properly.* It is your responsibility to understand how to use the equipment and to verify that it is working properly. Try a few test runs to get a feel for the equipment and how it works. Look at the measured data and ask yourself if it seems reasonable. If you suspect a malfunction or experience unreasonable data, discuss the situation with your instructor. Please treat all equipment with respect. Much of it is very expensive and some of it is very delicate. At the beginning of each lab period, your instructor will give a brief introduction to the experiment and its proper use so that you can use it safely without damaging it or yourself. *Before leaving the laboratory, please clean up the work area and restore the equipment to its original condition and replace it to its original position.* Please notify the instructor if any equipment is not working properly.

9. **No food or drink allowed in the laboratory.** After the experiment is in progress, you may move in and out of the lab as you wish. However, it is very dangerous to eat or drink in a physical laboratory. Dangerous not only to the equipment but to you. You are also encouraged to carefully wash your hands after leaving the lab, particularly before touching food or drink. Please consume snacks, coffee, *etc.* outside the lab.



## Supplies Needed for the Lab

1. **Pencils.** Mistakes will occur. You are encouraged to use a pencil to write your lab reports.

2. **Paper.** Lined or unlined paper can be used to write your lab reports. *Please do not submit paper torn from spiral notebooks unless the torn edges are trimmed.*

3. **Small Ruler.** A small 15 cm ruler (with a centimeter scale) will be useful. Larger straight edges and protractors are available in a drawer in the lecture table at the front of the physics lab.

4. **Graphing Calculator (TI-83, TI-83+, or HP-50g).** Laboratory analysis often involves graphing your data and performing a linear regression on the data. The TI-83, TI-83+, and HP-50g graphing calculators are supported in the physics laboratory.

# The Laboratory Report

To review the objectives for the physics laboratory, please read the *Foreword* on page iii. For general instructions concerning your laboratory report and working in the physics laboratory, please read *General Instructions* on page 1. Detailed instructions for writing your laboratory report are given below.

The major purpose of your laboratory report is to *organize* and to *document* your laboratory work in *as brief* and *complete* a manner as possible. The format for your laboratory report as described below is an abbreviated form of a standard format that is commonly used in scientific laboratories. It includes all the essentials, but no frills. The basic idea is that anyone, including your instructor, can pick up your report and quickly see *what your measured, how well it was measured, what you did with the measurements, what results you determined, what comments you made, and what conclusions you formed.*

Each laboratory report will have the following parts *in the following order*:

1. Cover sheet
2. Data sheet
3. Analysis pages
4. Appendix (miscellaneous calculations, printed graphs, etc.)

Please organize your report in the order given above with cover sheet first, followed by data sheet, analysis pages, and appendix last. *Please write the data sheet and analysis pages by hand* as if the pages were part of a laboratory notebook that was used in the laboratory. The cover sheet and items in the appendix may be typewritten. Detailed information about each part is given below.

1. **COVER SHEET.** The cover sheet identifies the experiment and date, the author (you), and your experimental team. It has two parts:

   (a) **Title, Name, and Date.** In the center of the upper half of the cover sheet, write the title of the experiment. Under the title, write your name and date. The name under the title is the author who gets the credit for this report. Occasionally you will do a group report where your group submits only one report. In such a case, the names of all partners will appear under the title.

   (b) **Partners.** Near the bottom *right*-hand corner of the cover sheet, write the full names (first and last) of your laboratory partners.

2. **DATA SHEET.** Proper organization and recording of data is essential in the laboratory. On your data sheet you will record *primary observations* made during the experiment, *comments* related to your observations, and *experimental data.* To avoid any controversy about the integrity of your data, develop the habit of *recording data on the data sheet as it is taken.* Please avoid the practice of writing data elsewhere and re-copying it later onto your data sheet. The data sheet must show the original handwritten data. *Keep the data sheet separate from the other parts of the laboratory report.* Do not

use the data sheet for computations or analysis.

**DATA SHEET GUIDELINES.** Please follow closely the guidelines below.

(a) **Title & Date.** At the top of the data sheet, write the *title of the experiment* and the *date*.

(b) **Sections.** Record your data, observations, and comments in the order of the procedure. Identify each section with the same number/letter used in the procedure.

(c) **Units.** Almost all measured quantities have units. Be sure to record the units.

(d) **Comments.** You will often encounter questions in the *Procedure* section. Treat each question as an item that *requires a comment* of one or two *sentences* rather than a one- or two-word answer. *Do not answer "Yes" or "No" to questions.* The reader of your report, including your instructor, does not know the question and will not understand the meaning of a one-word answer. *Use complete sentences to make your comments.*

(e) **Tables.** Record data in data tables whenever you can. In tables, write the units in the headings of the rows or columns. Avoid writing the units after the numbers recorded in the table. *When a table is used, you do not have to show your calculations.*

(f) **Precision.** All recorded data must show the precision of the original measurements. Do this by recording all the significant figures that the measuring instrument will allow. See the measurement rule in *Significant Figures* on page 7.

3. **ANALYSIS PAGES.** This is the heart of your report where computations are done, results reported and compared, comments written, and conclusions stated. In keeping with the desire to be brief and to the point, keep this section short. *Record only what is needed to document the work.*

**ANALYSIS PAGES GUIDELINES.** Please follow closely the guidelines below.

(a) **Sections.** Identify each section of your analysis with the same number/letter as that in the *Analysis* section of the lab directions.

(b) **Comments.** Treat each question in the analysis section as an important point that requires a comment of one to several sentences. The reader of your report does not know a question was asked. Use the question as an opportunity to comment upon your data, calculations, comparisons, to express opinions, or to explain your conclusions. *Use complete sentences to make your comments.*

(c) **Graphs.** Many experiments will require you to graph your data and to analyze the resulting graph. Rather than plot your data on graph paper, you will be asked to plot your data on a graphing calculator or a computer. In order to document what the graph looks like, just make a rough free-hand sketch of the resulting graph. The graph sketch should include the following:

(i) **Axes Labels and Units.** Label each axis with the *name* and *units* of its variable. You *do not* have to show numbers or the scale for each axis.

(ii) **The Shape of the Graph.** Sketch the graph freehand to show its general shape. You do not have to show the individual data points of the graph. The purpose of the sketch is to illustrate the general type of relationship shown by the data points, i.e. linear, quadratic, exponential, etc. *If you include computer-generated graphs (from Excel, Graphical Analysis, etc.), place these graphs in the appendix of your report.*

Note the technical use of the word *versus (vs.)* when describing a graph. By convention, the quantity *before vs.* is the ordinate (vertical axis), while the quantity *after vs.* is the abscissa (horizontal axis). For example, a standard $x$-$y$ graph would be described as "$y$ vs. $x$". Similarly, if you are

asked to plot "tension vs. velocity," you should have tension on the vertical axis and velocity on the horizontal axis.

(d) **Explicit Equations.** After performing a linear regression on your data, you will be asked to report the *explicit equation* from the regression. This means that you write the physical equation (i.e. the physics equation) with the actual values of the slope and $y$-intercept obtained from the regression analysis. For example, if the regression equation on your calculator is $y = 24.3x + 2.45$ from a regression analysis of *force data* as a function of *squared velocity data* and it represents the best fit of your data to the theoretical expression for centripetal force, $F = (m/r)v^2$, the *explicit equation* is $F = 24.3v^2 + 2.45$.

(e) **Calculations.** When the same calculation is repeated over and over, show the results in a *results table* with units in the column and row headings. *Avoid writing units after numbers recorded in a table. When a table is used, you do* ***not*** *have to show your calculations.*

(i) All calculations that are *not* in tabular form should be *documented* by reporting them in the following standard form:

$$\text{formula} = \text{substituted data} = \text{result with units}$$

$$\text{i.e.} \quad F = ma = (6\ \text{kg}) \times (10\ \text{m/s}^2) = 60\ \text{N}$$

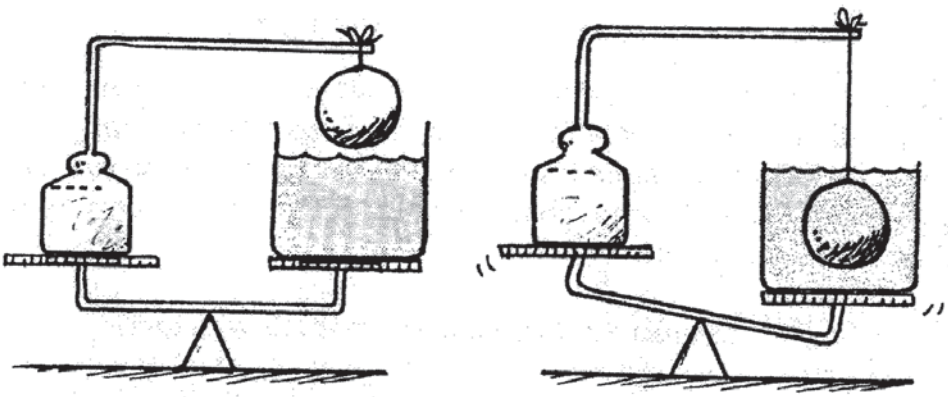
(ii) The results of all calculations must have units and obey the rules of significant figures. See the rules in *Significant Figures* on page 7.

(f) **Comparisons.** When a comparison between two quantities is asked for (i.e. compare $P$ to $M$), *always* compute a percent difference. To compute a percent difference, the quantity "compared to" is subtracted from the "first quantity", divided by the "compared to" quantity, and multiplied by 100. For example, when asked "compare quantity $P$ to quantity $M$", quantity $M$ is the quantity "compare to" and it appears second in the subtraction and is the divisor. The percent difference formula is given by

$$\%\ \text{difference} = \frac{P - M}{M} \times 100.$$

4. **APPENDIX.** Use the appendix for items that you want to include in your report but are not *required* as part of the data sheet or analysis pages. Such items include computer-generated data sheets (*your data sheet in the report must show the actual data recorded by hand during the experiment*), computer-generated graphs, computer-generated results from the linear regression analysis of data, and those calculations not required in the analysis that you wish to document. Note that an appendix is not required in any laboratory report. Items in the appendix can be typewritten.

## FIGURING PHYSICS



The weight of the stand and suspended solid iron ball is equal to the weight of the container of water as shown above. When the ball is lowered into the water, the balance is upset. The amount of weight that must be added to the left side to restore balance, compared to the weight of water displaced by the ball, would be

a) half

b) the same

c) twice

d) more than twice

# Significant Figures

A major part of any experiment is measurement. Because accurate and reproducible measurements are necessary to obtain reliable conclusiions from experimental data, it is important to have methods to describe how well a given quantity has been measured. Tow properties, *accuracy* and *precision*, can be associated with any measured number. Accuracy refers to how close a measurement is to the true value, while precision refers to the reproducibility of the measurement if it is repeated many times. Although related, accuracy and precision refer to different properties of measurement.

In our physics laboratory, you will not be required to specify the accuracy of the accuracy of your measurements, but you will be required to specify and maintain the precision of measured numbers. The precision of measured numbers is maintained by following the rules of *significant figures*. There are three rules:

1. **Measurement Rule.** In the physics laboratory, all measurements must be made and recorded to the limit of precision of the measuring instrument. This means that you must measure and record all the possible certain digits plus one estimated digit. The number of digits thus measured and recorded is called the number of significant figures of the number.

2. **Product/Division Rule.** The answer for multiplication or division using measured numbers can have only as many significant figures as the number with the least number of significant figures.

3. **Sum/Difference Rule.** Place the numbers ina column and find the leftmost column which contains an estimated digit (i.e. the last S.F. of that number). Since this column produces an estimated digit in the result, discard all the columns to the right of this column in the result. The remaining digits are the significant digits.

Examples:

(a)
$$\begin{array}{r} 10.45 \\ 2.6 \\ +\ 0.346 \\ \hline 13.396 \end{array} = 13.4$$

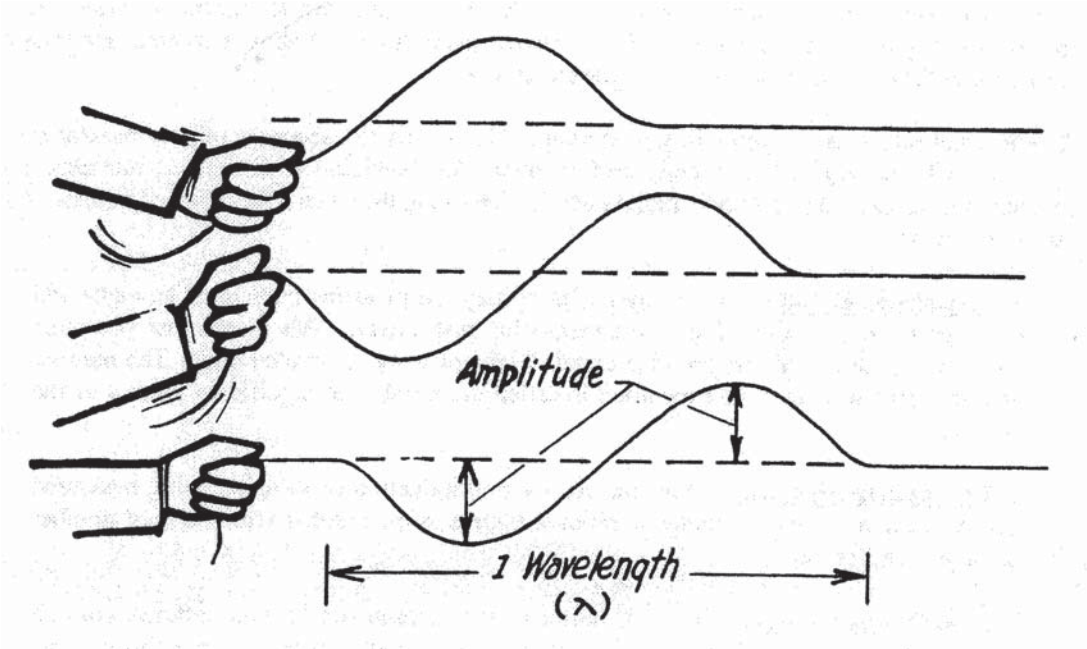
(b)
$$\begin{array}{r} 15.456 \\ -\ 6.9 \\ \hline 8.556 \end{array} = 8.6$$

(c)
$$\begin{array}{r} 0.14657 \\ -\ 0.14649 \\ \hline 0.00008 \end{array} = 8\times10^{-5}$$

(d) $$\frac{6.4+12.64}{0.1258} = 255$$

(e) $$\frac{36.22-35.98}{35.98} = 0.0067$$

(f) $$(20.64\times1.27)-(15.4\times1.6) = 2$$

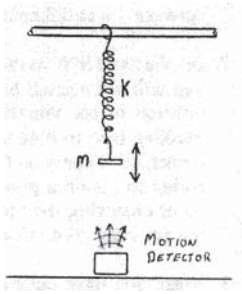

Amplitude
1 Wavelength
(λ)

# Experiment 1

# Simple Harmonic Motion

**Objective:** To investigate the vertical *up-and-down motion* of a mass attached to the lower end of a vertical spring. You will record the shape of the *position vs. time* graph for the motion and use the graph to determine the *period* and *amplitude* of the motion and to determine whether or not the motion is *simple harmonic motion* (SHM). You will also investigate the general relationship between *period* and *amplitude* and between *period* and *mass* for the vibrating mass. Finally, you will measure the spring constant of the spring and check the validity of the theoretical formula for the *period* of SHM.

**Method:** A spring will be hung vertically down from a support rod. A mass $m$ will be attached to the lower end of the spring (as shown in the sketch to the right) and allowed to come to rest at its *equilibrium position*. Then the mass will be placed into *vibratory motion* by pulling it down a few centimeters from its *equilibrium position* and releasing it from rest. The position of the vibrating mass will be recorded using a motion detector below the vibrating mass. A computer connected to the motion detector will display, in real time, the postion vs. time graph of the moving mass. Experimental data will be obtained from the graph.




| | | | |
|---|---|---|---|
| **Apparatus:** | Medium length spring | Small masses (3-20 g, 2-10 g, 1-5 g) | 5 g mass hanger |
| | Table support rod | Clamp and horizontal rod | Meter stick |
| | Motion Detector & LabPro | PC and the program *shm(1020)* | Masking tape |

**Theory:** The vibratory motion of a mass attached to a spring is called *simple harmonic motion* (SHM) if the spring force is a *linear restoring force* of the type expressed by the relationship $F = -kx$, where $F$ is the spring force in *newtons*, $x$ is the displacement in *meters* from the resting or *equilibrium position* of the spring, and $k$ is a constant in units of N/m called the *spring constant*. The spring constant is a measure of the strength of the spring. The minus sign in the formula indicates that the force is a restoring force; i.e. the force is positive for negative displacements and negative for positive displacements.

When a mass $m$ is attached to a hanging spring, the weight of the hanging mass pulls the spring down to a resting position called the *equilibrium position*. Let this position be $x = 0$. At the equilibrium position, the weight of the mass acting downward just balances the spring force acting upward. If the mass is now displaced above or below this equilibrium position and released, it vibrates with SHM. In SHM, a round trip of the mass from any position back to the same position (*moving in the same direction*) is called a *cycle* of the motion. The time interval for the mass to travel one cycle is called the *period* of the motion and the

maximum displacement of the mass, either positive or negative, is called the *amplitude* of the motion. An important property of SHM that distinguishes it from other types of harmonic motion is that *the period of SHM is independent of its amplitude*.

**Significant figure alert!** The motion detector acquires data at the rate of 30 or 40 samples per second, which gives a time resolution of 0.025 seconds between measured positions. For this experiment, adjust the computer program to show all times to 0.001 s and all measured positions to 0.001 m (0.1 cm). If you see that the program is not displaying positions and times to three decimal places, ask your instructor for help. Also assume that all masses are known to 0.1 g.

## Procedure 1 — Set Up and Test

Attach a horizontal rod to the vertical table support rod. Raise the horizontal rod so that it is about 85 to 95 cm above the tabletop and place the motion detector on the table under the rod. Slip one end of the spring over the horizontal rod and secure its position with a piece of masking tape. Hang the 5 g mass hanger from the other end of the spring and place 30.0 g on the hanger (total mass = 35.0 g). Adjust the position of the motion detector so that it is directly below the hanging mass.

1. If the proper software is not running, go to the folder *Tools for Scientific Thinking*, select the *Physics1020* folder, and start the program *shm(1020)*. After the program loads, you should see a position vs. time graph with the *time* axis between 0 and 5 seconds and the *position* axis from 0.0 to 0.8 meters. You can change the scale of either axis later.

2. Set the mass into vibration with a small amplitude of about 2 to 3 cm. At the top of the screen you will see a small box labeled **Collect**. Click on this box to obtain a real-time plot of the position of the vibrating mass as a function of time. If necessary, use a small piece of masking tape to hold the small masses in place if they tend to fall off the mass hanger. To repeat, click again on **Collect**. You may have to adjust the position of the detector and/or the spring to obtain a good plot. Keep testing and adjusting until you get a good motion plot. After observing the plot, you can adjust the vertical axis of the graph to increase the size of the displayed plot. Consult with your instructor if you have problems.

3. When you have obtained a good plot, *make a sketch of the position plot on your data sheet showing at least three complete cycles of the motion*. On your sketch, indicate *one cycle* of the motion and draw a vertical arrow on your sketch indicating the *amplitude* of the motion.

4. **Measuring *amplitude* and *period*.** The height of each peak (or depth of each valley) from equilibrium is the *amplitude* of the motion, and the time between adjacent peaks of the motion is the *period* of the oscillator. Note that the vertical distance from valley to peak is double the amplitude of the motion. The amplitude and period can be determined as follows: click on **Analyze** on the Menu Bar and then click on **Examine**. This brings up a small box that shows the position and time of the point under the cursor. The vertical line that moves back and forth along the graph as the cursor is moved, shows the position of the cursor. Choose a peak and record its position and then select an adjacent valley and record its position (be sure to record the appropriate number of significant figures in each case). Compute and record the amplitude of the motion. Then choose two adjacent peaks and record the time for each peak. Compute and record the period in seconds. To remove the coordinate box, click on the small box in its upper right-hand corner or click again on **Analyze** and them **Examine**.

## Procedure 2 — Measurements and Observations

1. **Relationship Between Period and Amplitude.** Set up a data table of three rows with columns for approximate initial displacement in *cm*, $t_1$ in *s* (time of a peak), $t_2$ in s (time of the next peak), and period in *s*.

   (a) With the total mass still equal to 35.0 g, displace the spring about 2 cm and release it. Obtain a graph of the motion. From this graph, record the times of two adjacent peaks. Compute and record the period of the motion.

   (b) Without changing the mass on the hanger, repeat the above trial and measurements for the larger amplitudes of about 4 cm and about 8 cm.

   (c) Examine your results. Comment on what conclusion you can obtain from your data concerning the relationship between the period of the motion and the amplitude of its motion. Can you conclude that this motion is SHM? Explain why or why not.

2. **Relationship Between Period and Mass.** Set up a new data table of four rows with columns for mass in *g*, $t_1$ in *s* (time of a peak), $t_2$ in s (time of the next peak), and period in *s*.

   (a) In the first row of your data table, write in data from any one of the measurements in the table above for 35.0 g.

   (b) Add additional mass to the hanger for a *total* of 45.0 g. Obtain a graph of the motioin using any amplitude and measure the period of the mass. Repeat for a *total mass* of 55.0 g and for a total mass of 70.0 g.

   (c) Examine your results. Comment on what conclusion you can obtain from your data concerning the relationship between the period of the motion and the mass attached to the spring. When the mass was doubled, did the period double?

## Procedure 3 — Measurement of the Spring Constant

Return the system to its original equilibrium position with a total of 35.0 g hanging from the spring. The spring constant of the spring can be determined from the spring force equation by finding the *new displacement* $\Delta x$ caused when an *additional mass* $\Delta m$ is added to the mass hanger. The spring force equation predicts that when an additional mass $\Delta m$ is added to the mass hanger, the spring will stretch a distance $\Delta x$ from its previous equilibrium position and, at the new equilibrium position, $k(\Delta x) = (\Delta m)g$. *Note that the original 35.0 grams on the mass hanger sets the original equilibrium position, but plays no role in causing the new displacement* $\Delta x$. *Also note that the minus sign disappears because you are working with magnitudes and not vectors.*

1. First determine and measure the original equilibrium position. To do this, first let the 35.0 g mass come to equilibrium. Then click on **Collect** to record the constant position of the mass. To find an average value, click on **Analyze** and then **Statistics**. A box appears with the average of all the position values. Record this position as the original equilibrium position.

2. Set up a new data table of three rows with columns for *added mass* $\Delta m$ in g, the weight $\Delta mg$ due to this added mass in *N*, new position in *m* (meters), displacement $\Delta x$ in *m*, and spring constant in *N/m*.

3. Add 20.0 g to the original 35.0 g mass hanger and record the *weight* of this *added mass* in *N*. Measure the new average position (as described above) and record this value as the new position. Determine the displacement due to this added mass and then compute a value for the spring constant in *N/m*.

4. *Remove* the 20.0 g mass and allow the system to return to its original equilibrium position. Now repeat the above for an added mass of 30.0 g and then for an added mass of 40.0 g.

5. Compute and report an average value for the spring constant of the spring in N/m.

## Analysis

The theoretical formula for the period of SHM is given by the expression

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{1.1}$$

where $T$ is the period in *seconds*, $m$ is the mass in *kg*, and $k$ is the spring constant in *N/m*.

1. Equation (1.1) above does not predict a linear relationship between period $T$ and the mass $m$ of the oscillator. However, if both sides of equation (1.1) were squared, then the resulting equation predicts a linear relationship between *period squared* $T^2$ and mass $m$.

   (a) Write down the period squared formula showing $T^2$ as a function of $m$. Then identify the terms that comprise the predicted slope of the theoretical formula and write down the formula for the predicted slope. Use the average value of your measured spring constant to compute a value for the predicted slope.

   (b) In Procedure 2 you measured the period for four different masses. This data can be used to check the validity of your expected linear equation. Enter your period and mass data into a graphing calculator or computer. *To avoid problems with units, convert the mass data to MKS units before entering the data.* If you were to plot period vs. mass, would you expect it to show a linear relationship? Comment.

   (c) Transform the period as suggested in part (a) above and obtain a graph of the transformed data. Does the transformed data show a linear plot? Comment.

   (d) Do a linear regression on the transformed data and record the slope and $y$-intercept with proper units. Write the explicit function for your data.

   (e) Compare your experimental slope to the expected slope. Comment on how well your data agrees with the prediction of equation (1.1).

2. If you wish to double the period of a mass-spring oscillator, by how much must you change the mass of the oscillator?

3. If you wish to double the period of a msss-spring oscillator by choosing a different spring and using the same mass, by how much must the spring constant be changed?

# Experiment 2

# Transverse Wave Motion on a Spring

**Objective:** To measure the wave speed of transverse waves on a spring using two different methods and to compare the measured speeds predicted by theory.

**Method:** Two different methods will be used to measure the speed of waves in a heavy spring. The first method is a *direct measurment* of speed where you will use a stopwatch to measure the time for a wave pulse to travel a given distance along the spring. This method is possible because waves travel relatively slowly on a heavy spring. The second method, using *standing waves*, will illustrate a common method for measuring wave speed.

**Apparatus:**

| | | |
|---|---|---|
| long spiral spring | spring balance | tape measure |
| triple beam balance | 500 g attachment for balance | stopwatch |

## Procedure 1

**Direct Measurement of Wave Speed.** Please note that the spiral springs used in this lab are easily damaged. Please treat them gently. They are particularly vulnerable to over-stretching at the place where you hold them. To avoid damage to the spring, please avoid *large amplitudes*.

1. Wrap the spring loosely and place it on the balance pan of the triple beam balance. Since the mass of the spring is probably over 600 g, you will have to add the 500 g attachment to the balance. Measure and record the mass of the spring.

2. Set up a small table of six columns and two rows for your measured data. You need columns for tension in *N*, length of spring in *m*, total travel time in *s*, # trips, total distance traveled in *m*, and wave speed in *m/s*.

3. Select a spring balance and zero it by adjusting the tab at the top of the balance. Attach the spring balance to one end of the spring and stretch the spring out to a tenso of 10.0 N. By holding the spring balance by the ring at its top end, the spring balance can droop downward and follow the sag in the spring. This will minimize the friction on the tongue of the balance that holds the spring. The ring serves as a floppy handle that both holds the spring and allows it to droop. Assume that tensions measured with the balance can be read to 0.1 N. Stretch out a tape measure, allowing it to sag to follow the shape of the spring, and measure the length of the spring. Carefully read the tape measure to the nearest 0.2 cm and record the tension and length in your table.

4. While holding the spring balance, allow a member of your group to pull aside the spring near the balance and quickly release it. This sets up a horizontal wave pulse of *small amplitude* on the spring that travels down the spring, reflects from the far end and returns back to the balance. The pulse reflects from the balance and travels out again, making several round trips down and back along the spring. The person holding the balance can feel the return of the waves even after their amplitude is too small to observe. Thus, the *person holding the spring should also do the timing*. A partner can set the wave pulse in motion by pulling aside the spring and releasing it (remember—small amplitudes). The person holding the spring can begin the timing when the first pulse returns to the hand. Set up a wave pulse and measure the time for at least 5 trips (if possible). Record your data in the data table. Then determine the total distance traveled and use the distance and time to compute the wave speed.

5. Let a different person repeat these measurements for a tension of 12 N.

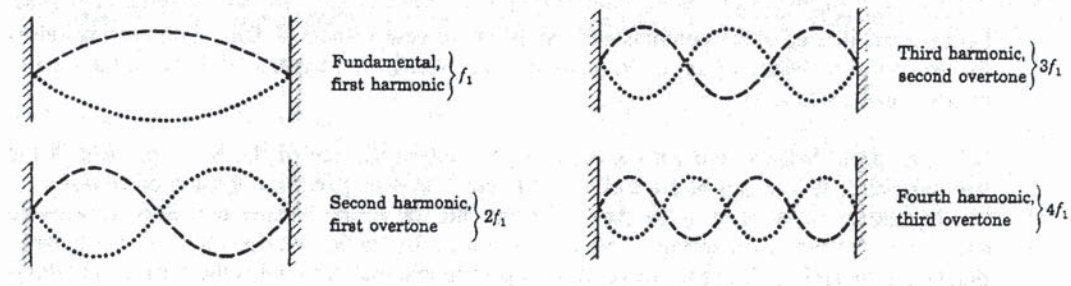
# Procedure 2

**Measurement of Wave Speed Using Standing Waves.** Another way to obtain the speed of waves is to use the expression

$$v = f\lambda \tag{2.1}$$

where $f$ is the frequency of the waves in hertz and $\lambda$ is their wavelength in m. Since the frequency of a wave is the same as the frequency of the vibrations that cause the wave, frequency is easily obtained by measuring the frequency of the vibrator. The major problem in using this method is measuring the wavelength of the waves because most waves move too fast to be measured. The trick is to somehow cause the waves to "stand still" so that you can determine their wavelength. This trick is accomplished by setting up *standing waves* on the spring.

Standing waves on a string or spring result when an infinite train of outgoing waves continually interferes with returning waves reflected from the far end. When standing waves exist the spring appears to vibrate transversely in segments as shown below. The two ends of each vibrating segment, which do not vibrate at all, are called *nodes*, and the midpoints of each vibrating segment, which vibrate with maximum amplitude, are called *antinodes*. The two fixed ends of the spring must always be nodes.




Standing waves on a spring can occur for only certain frequencies of wave motion. The reason for this is that the waves must produce nodes at each fixed end. This means that the *wavelength* of the standing waves must "fit" into the length of the spring between its fixed ends. In effect, the distance between the fixed ends of the spring becomes a *wavelength selector* for standing waves. The condition for standing waves to exist on a spring of length $L$ (fixed at both ends) is

$$n\frac{\lambda}{2} = L \tag{2.2}$$

where $n$ is an integer representing the number of vibrating segments in the standing wave pattern and $\lambda$ is the wavelength of the standing waves. When $n = 1$ the standing wave pattern exists as one vibrating

segment and length $L$ is one-half wavelength of the waves. When $n = 2$ the standing wave pattern has two vibrating segments and length $L$ is two half wavelengths of the waves. When $n = 3$, length $L$ is three half wavelengths of the waves and so on for all possible values of $n$. Thus, equation (2.2) can be used to determine the wavelength of waves on a string. Once you have the wavelength, the wave speed is then obtained using equation (2.1).

1. Set up a data table with eight columns and several rows. You need columns for tension in *N*, # of vibrating segments, length of the spring in *m*, wavelength in *m*, # of vibrations, total time for vibrations in *s*, frequency in *Hz*, and wave speed in *m/s*.

2. Carefully sketch the spring to a tension of 10 or 12 N (one of the tensions used above) and set up a standing wave pattern of 2 segments (one vibrating segment does not work well because of the spring's sag). **Keep the amplitudes small.** Large amplitudes will increase the spring tension to a value larger than that shown on the spring balance.

   (a) While the person holding the balance maintains the standing wave pattern, the other members of the group must measure the frequency of the waves. The frequency of the waves on the spring is the same as the frequency of a vibrating segment of the frequency of th hand sending out the waves. Use the stopwatch to measure the time for 5 to 10 cycles of the hand. Record the number of cycles and the measured time. Determine and record the frequency.

   (b) Assume the spring has the same length as recorded above for the same tension and use equation (2.2) to determine a value for the wavelength of the waves. Finally, compute a value for wave speed using equation (2.1).

3. Allow a different experimenter to repeat the above at the same tension for 3 segments. Although 4 vibrating segments is often difficult to do, try to get data for 4 vibrating segments. If successful, record the data.

4. Now stretch the spring to the other tension used above and repeat the standing wave experiments for two segments and three segments. As before, try to get data for 4 segments. Record the data, if successful.

5. For *each* spring tension, comment on how well the two (or three) standing wave measurements of wave speed agree with each other. If the values agree well, compute an average wave speed for each tension.

# Analysis

**Theory:** Transverse waves travel on elastic materials with a speed that depends upon the tension in the material and the linear density of the material. The theoretical expression for the speed of a *transverse* wave on a string or spring is given by the expression

$$v = \sqrt{\frac{F}{m/L}} \tag{2.3}$$

where $F$ is the tension in the material in *newtons* and $m/L$ is the linear density of the material in *kg/m*.

1. **Compare the Theoretical Predicted Wave Speeds to the Direct Measurements of Wave Speed.** Set up an analysis table with six columns. You need columns for tension in *N*, length of spring in *m*, linear density in *kg/m*, theoretical speed in *m/s*, directly measured speed in *m/s*, and percent difference.

   (a) For each tension, transfer the spring length from your data sheet and compute a value for the linear density of the spring. Use equation (3.1) to compute a value for the theoretical speed and record it in your analysis table. Transfer the directly measured speed from your data sheet and compare each theoretical speed to the directly measured speed.

(b) Comment on how well equation (3.1) predicts the speed of the waves that you measured using the direct method. Write your comments under the analysis table.

2. **Compare the Speeds Measured Using the Standing Wave Method to the Direct Measurements of Wave Speed.** Set up an analysis table with four columns. You need columns for tension in *N*, average speed as determined from the standing wave method in *m/s*, directly measured speed in *m/s*, and percent difference.

   (a) For each tension, transfre from your data sheet the average wave speed obtained from the standing wave method and the directly measured wave speed. Compare each standing wave speed to the directly measured wave speed.

   (b) Comment on how well the standing wave speed results agree with the directly measured wave speed results. Write your comments under the analysis table.

3. **Questions.**

   (a) By what factor must the tension in the spring be increased in order to double the wave speed on the spring? Explain.

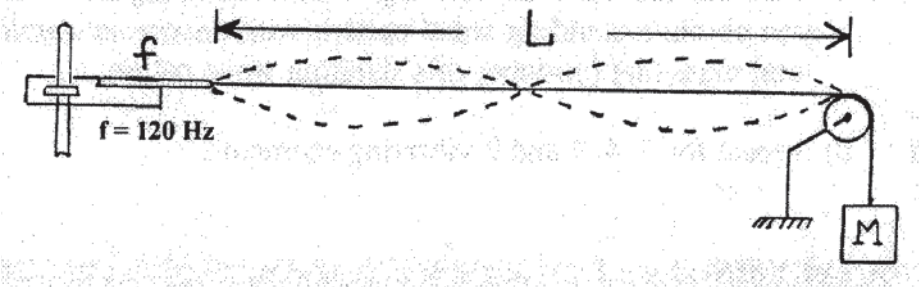
   (b) Suppose a *more massive spring* of the same length were used in this experiment. Would you expect the wave speeds on this new spring to be *faster* or *slower* than the values you measured above? Explain.

# Experiment 3

# Standing Waves on a String

**Objective:** To observe standing waves on a string and to investigate the relationship between wave speed and tension in the string. The measured data will be used to verify the theoretical formula for wave speed.

**Method:** The speed $v$ of waves on a stretched string will be determined using the basic wave relationship $v = f\lambda$, where $f$ is the frequency of the waves and $\lambda$ is their wavelength. A sketch of the experimental apparatus is shown below. One end of a string is attached to a vibrator of *fixed* frequency $f$ and the other end is passed over a pulley and attached to a hanging mass $M$. The *weight* of the hanging mass causes the tension in the string that determines the speed of the waves that travel on the string. The frequency of the electric current that drives the vibrator is 60 Hz, but since the vibrator vibrates twice for each cycle of electric current, its *frequency* is 120 Hz. Thus, the frequency of the waves on the string is $f = 120$ Hz.




As you learned in Experiment 2, the wavelength of a wave can be determined by setting up standing waves on the string. Since you want to collect wave speed data as a function of string tension, you need to adjust the string tension to values that will allow standing waves to occur on the string at frequency $f$. The *wavelength* of the waves is then determined from length $L$ (the vibrating length of the string) and the number of vibrating segments on this length (see equation (2.2) in Experiment 2). When both the frequency and the wavelength are known, the *speed of the waves* is determined using the frequency/wavelength formula given above. The wave speed vs. string tension data will be analyzed using a curve-fit program to determine the relationship between them.

**Apparatus:**

| | | | |
|---|---|---|---|
| 60 Hz string vibrator | string | mass set and hanger | metric tape |
| table support rod | rod clamp | table pulley | mg balance |

## Procedure

1. One end of the string has a loop to hold the mass hanger. Before tying the other end to the vibrator, you measure the linear density of the string. Measure and record the *entire* length of the string. Don't untie knots, just *estimate* the length of the string in each knot and add it to the measured length. Measure the mass of the string on a milligram balance and record. Use the measured mass and length to determine the linear mass density of the string in units of *kg/m*.

2. Attach the free end of the string to the vibrator. Use a knot that can be undone later. Run the string over the table pulley and hang the mass hanger on the other end. The mass of the hanger is 50 g. Adjust the vibrator so that the wave amplitudes will be horizontal to the top of the table.

   (a) Record the frequency of the vibrator.

   (b) To become familiar with the effect of the changing the string tension, turn on the vibrator and gently pull down on the mass hanger until a standing wave pattern is obtained. Try to obtain a number of different patterns. Question: *As string tension is increased, does the number of standing wave segments on the string increase or decrease?* Observe and comment.

   (c) Carefully measure and record the vibrating length $L$ of the string from the end of the vibrator to the top of the pulley. This distance is the length of string into which the standing wave segments will fit.

3. Set up a data sheet of 5 rows and 2 columns with a column for # vibrating segments and a column for hanging mass in $g$.

   (a) Place masses on the mass hanger until a standing wave pattern with 6 vibrating segments is set up on the string. The standing wave pattern is often sensitive to changes in tension due to mass changes as small as $\pm 2$ g. Continue to adjust the amount of mass on the hanger until you obtain a standing wave pattern with *maximum amplitude* at the antinodes. Record the total mass that produces this standing wave pattern.

   (b) Repeat for 5, 4, 3, and 2 vibrating segments.

## Analysis

1. Set up an analysis table of 5 rows and 4 columns with a column for # vibrating segments, wavelength in *m*, wave speed in *m/s*, and tension in *N*. For each experimental standing wave pattern, determine the wavelength of the waves and use the frequency/wavelength formula to determine *wave speed*. Then use the hanging mass for each case to determine the *tension* in the string.

2. **Graph wave speed vs. tension data.** Using a graphing calculator or computer, make a graph of wave speed (in *m/s*) as a function of string tension (in *N*). Draw a sketch of the resulting graph on your analysis page. Is the relationship linear? Comment.

   **Theory:** The theoretical formula for wave speed $v$ on a stretched string is

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

   where $F_T$ is the tension in the string (in *N*) and $m/L$ is the linear mass density of the string (in *kg/m*). Thus the theoretical formula for wave speed is not a linear function. However, if this equation is *squared*, it predicts that the speed squared, $v^2$, is a *linear function* of string tension $F_T$, with a slope

equal to the reciprocal of the linear density of the string. This formula can be verified using your experimental data by computing the square of your measured speeds and graphing a plot of $v^2$ vs. $F_T$.

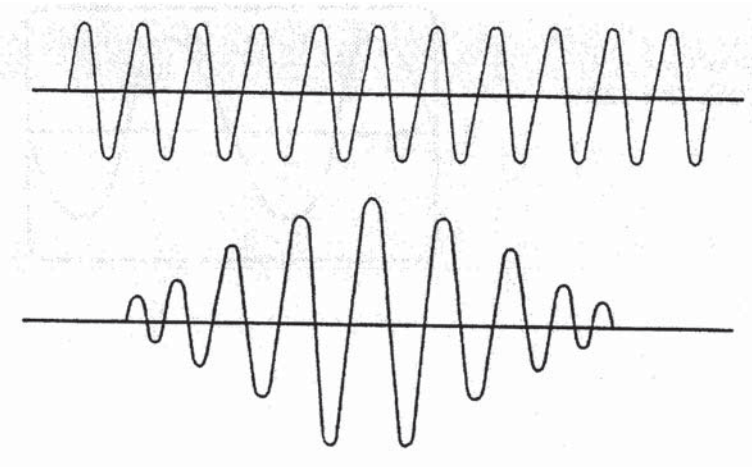
3. **Analysis of the $v^2$ vs. tension data.** Transform the speed to $v^2$ and plot $v^2$ vs. tension. Draw a sketch of the resulting graph on your analysis page. Is this relationship linear? If you obtain a linear relationship then you have verified the form of the theoretical formula.

   (a) Do a linear regression analysis of your transformed data ($v^2$ vs. $F$) and report the slope and $y$-intercept of your analysis with the proper units. Write the explicit function that describes your data.

   (b) You have verified the form of the theoretical formula for wave speed, but not the explicit formula. In order to completely verify the theoretical speed formula for transverse waves, your data must also correctly predict the slope of the theoretical formula. Determine and report the reciprocal of your measured linear mass density of the string. This is the theoretical value for the slope of your linear graph.

   (c) Compare your experimental slope to the theoretical slope. Does your data tend to verify the theoretical formula for wave speed, equation (3.1)? Comment.

4. To get a better sense of the speed of the waves along your string, convert the *fastest speed* to units of mph (miles per hour).



# Figuring Physics

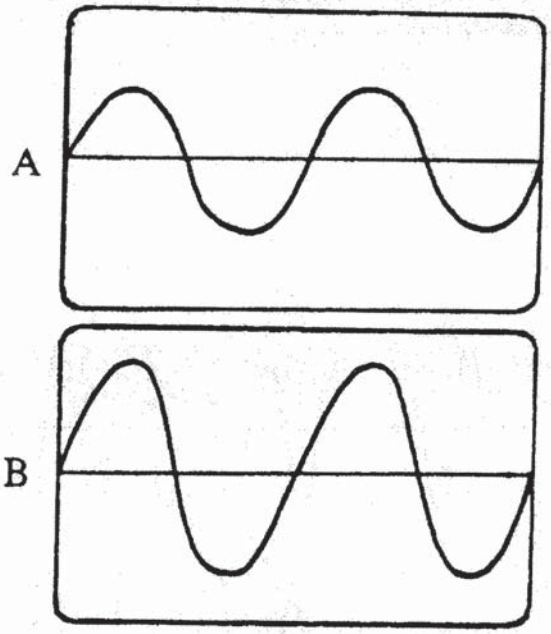
## CAN YOU HEAR THIS PICTURE?

Two musical notes A and B are shown, one at a time, on the oscilloscope. The note that has the highest frequency is

a) A
b) B
c) both the same

and the louder of these two notes is

a) A
b) B
c) both the same



# Experiment 4

# Speed of Sound in Air

**Objective:** To experimentally determine the speed of sound in air and to compare the experimental value to the theoretical value.

**Method:** Two methods will be used to determine values for the speed of sound: (a) a *direct method*, measured the time for a sound pulse to travel a known distance down and back in a closed-end tube, and (2) a method based on *standing waves*.

1. Direct Method. A sound wave pulse is started by a finger snap at one end of a long *closed-end tube* (about 1.2 to 2.5 meters long). The wave pulse travels down the tube, reflects from the far end and travels back to the open end. A microphone, connected to a data acquisition system via a cmputer records the initial "snap" of the sound wave pulse and later records the reflected echo of the "snap" and plots the waveform results in real time on a pressure-time plot. From the plot you can determine the total travel time $t_m$ of the wave pulse down and back along the tube. The speed of sound is then computed from the speed formula,

$$v = \frac{2L}{t_m} \tag{4.1}$$

   where $L$ is the length of the long tube.

2. Standing Wave Method. The wave speed of traveling waves can also be computed from the relationship

$$v = f\lambda \tag{4.2}$$

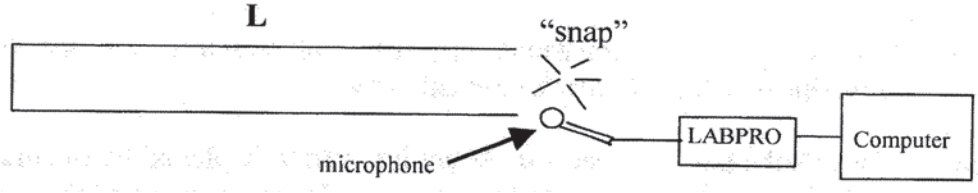
   where $f$ is the frequency of the waves and $\lambda$ is their wavelength. Because sound waves move too fast to directly measure their wavelength, the wavelength has to be indirectly determined using the standing wave method. This method consists of sending sound waves into a tube of length $L$ and varying the frequency of the waves until a frequency is found that sets up a standing wave pattern within the air column of the tube. The wavelength $\lambda$ is then determined from the length $L$ of the air column. You will use both "open-end" air columns and "closed-end" air columns for this experiment.

**Apparatus:**

| | | | |
|---|---|---|---|
| Direct Method: | Long cardboard tubes | Vernier microphone | clicker |
| | computer & LabPro | cables | |
| Standing Wave Method: | PASCO signal generator | speaker & double banana plug cable | |
| | Open and closed end tubes | Thermometer (placed in room) | |
| | Oscilloscope | Tie clip microphone & cable | |

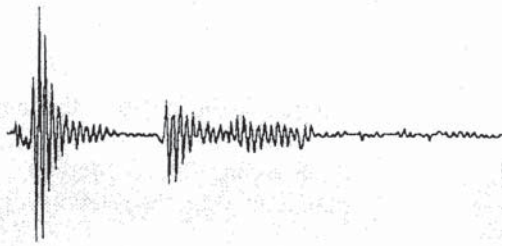
## Procedure 1 — Direct Method

Since the direct method requires very little time, only two or threee experimental stations will be set up, probably on the back counters. A diagram showing the tube and the associated apparatus is shown below.




1. Open the folder *Tools for Scientific Thinking* on the Desktop of the computer, open the Physics1020 folder and select the program **SpeedSound**. This program shows a graph of *sound pressure versus time* with pressure axis from 2 to 4 (arbitrary units) and a time axis from 0 to 0.03 seconds. To obtain data, click on **Collect**. This brings up a message that the program is waiting for a trigger. The program is waiting for a sound pulse to start the data recording. Experience has shown that a *finger snap* produces the best wave pulse for reliable measurements. Place the microphone very near the open end of the tube and try it. If you have trouble with the triggering, consult with your instructor.

2. The tube used for this experiment will be a long cardboard tube. Measure and record the *inside length* $L$ of the tube. If the far end of the tube is not closed, the *close it* by pushing it up against a hard surface such as a wall (the experiment works best with closed-end tubes). Then place the Vernier microphone near the open end of the tube, click on **Collect** and *snap your fingers* (or make a single "click" with the clicker) near the end of the tube. You should observe a waveform similar to the one shown above which shows the original sound pulse and a similar, but reduced, wave pulse of the return echo. Practice until you get a good result. Keep in mind that wave theory predicts that the wave pulse will undergo a *phase reversal* of 180 degrees upon reflection from the closed end so that a positive spike in the "snap" will reflect as a negative spike in the echo.

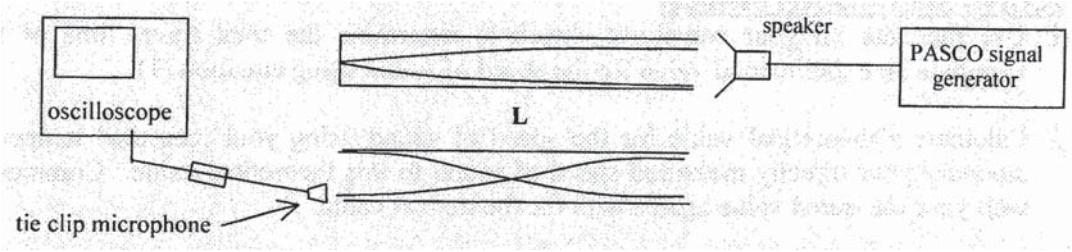


3. When you get a good experiment, make a rough sketch of the resulting waveform on your data sheet. Then identify a particular spike on the initial pulse that also has a corresponding spike on the echo (recall that the echo should be phase reversed by 180 degrees). You want to measure the time difference between these two points. The times can be determined as follows: click on **Analyze** on the Menu Bar and then click on **Examine**. This brings up a small box that shows the wave pressure (in arbitrary units) and the time for the point on the waveform that lies under a vertical line passing through the waveform. As you move the cursor back and forth, the line moves along the graph allowing you to obtain the coordinates of each point. Read the initial time and *record it on your sketch*. Repeat for the echo time.

4. Record the temperature on the thermometer placed in the room.

## Procedure 2 — Standing Wave Method

A diagram showing the apparatus for the standing wave method is shown below. A speaker is connected to a sound signal generator sends sinusoidal waves at frequency $f$ into the tube. You will adjust the frequency of the generator to determine the lowest frequency that produces standing waves in the air column of the tube, i.e. the fundamental frequency. You will be able to hear when the frequency has been adjusted to the resonance frequency because the tube will "sing" in resonance with the speaker, causing a noticeable increas in the loudness of the sound.




To help you determine the resonant frequency, you can connect the tie clip microphone to an oscilloscope as shown in the diagram. If you place the time clip microphone at an open end of the tube, you will be able to observe the amplitude of the waveform on the oscilloscope go through a maximum as the frequency goes through the resonant frequency.

1. You will work with four different open-end tubes and two different closed-end tubes. Set up a data table with 3 columns: type of air column (open-end or closed-end and color), length of tube in cm, and resonant frequency in Hz.

2. Select a tube and record whether it is open-end or closed-end and record its color. Measure and record its length.

3. You will have to place some support (a book or books?) under the tube so that the center of the tube is at the same height as the center of the speaker. A pair of meter sticks can be used to keep the tube from rolling sideways on its support. Place one end of the tube near the speaker witha bout 2 to 5 mm gap between the end of the tube and the speaker. Adjust the loudness of the speaker to be *fairly soft* and *starting* with a frequency of about 150 Hz, increase the frequency (medium quickly for the first try) until you hear the rapid increase and decrease in loudness associated with resonance as the frequency passes through its resonant value. Then you can adjust the frequency back and forth through the resonance to find its exact value. As you get near resonance, *decrease the volume of the sound*, since the sound can get very loud at resonance. *Continue to keep the sound level fairly soft.* When you find resonance, place the tie clip microphone near an open end and adjust the oscilloscope to observe the waveform. Then slowly tune the frequency back and forth across the resonance while observing its amplitude on the scope. Determine a record the frequency that produces maximum amplitude.

   (a) Repeat the above experiment for a total of four open-end tubes including a black tube and two closed-end tubes.

   (b) Measure and record the inner diameter of one of the tubes (all the colored tubes have the same diameter) and measure and record the inner diameter of the black tube. These measurements will be used to apply a small correction to the value for the measured length of the tube.

**Theory — Speed of Sound:** The speed of sound in air depends on the elasticity of the air and its density. Because these quantities depend somewhat on temperature, the speed of sound in air is temperature dependent. At one atmosphere of pressure, the approximate speed of sound in air is given by the expression $v = 331.0 + 0.600\,T$, where $v$ is the speed of sound in *m/s* and $T$ is the temperature in $^\circ C$. You can use

this formula to determine a value for the predicted (theoretical) speed of sound in air. Note that the predicted speed will have 4 significant figures.

## Analysis 1 — Direct Method

1. Use the data on your waveform sketch to determine the total travel time of the pulse. Compute an experimental value for the speed of sound using equation (4.1).
2. Calculate a theoretical value for the speed of sound using your measured temperature and *compare* your directly measured speed of sound to this theoretical value. Comment on how well your measured value agrees with the theoretical value.

**Theory — Standing Wave Method:** The total *vibrating length* of standing waves in a tube depends not only on the length of the tube, but also on the size and shape of the ends of the tube. The *effective length* of the standing wave pattern within the air column is a bit longer than the length of the tube. A correction for the length of a tube has been developed and is given by the expression $0.58\ D$ for *each open-end* of a tube, where $D$ is the measured diameter of the tube. Thus the effective length of a *closed-end tube* is $L_0 + 0.58\ D$ and the effective length of an *open-end tube* is $L_0 + 1.06\ D$, where $L_0$ is the measured length.

## Analysis 2 — Standing Wave Method

1. Set up an analysis table with 5 columns: type of tube (open-end or closed-end and color), resonant frequency in Hz, effective length in cm, wavelength (of the standing wave) in meters, and speed of sound in m/s.
2. For each experiment, record in your analysis table the type of tube and its color and the measured resonant frequency from your data sheet. Then determine the effective length of the tube and use this length to determine the wavelength of the standing wave in meters. Finally compute a value for the speed of sound using equation (4.2). *Note: if you find an unexpectedly large value for the speed of sound for one or both of the closed-end tubes*, the most likely reason is that the resonant frequency you measured was not the fundamental, but was the first overtone (i.e. 3rd harmonic). If this happens, make a note under your analysis table and re-compute a value for the wavelength of the standing waves using the standing wave pattern for the 3rd harmonic. Then re-compute a value for the speed of sound. Show these calculations under your data table (only if you recomputed the speed).
3. Examine your values for the speed of sound. Is there any evidence that the speed of sound depends upon the frequency of the sound? Comment. Determine and report an *average value* for the speed of sound using the standing wave method. (Write a * after any values that seem to you to be invalid and ignore them in your average.)
4. Compare your standing wave result for the speed of sound to the theoretical value calculated above. Comment on how well the standing wave value agrees with the theoretical value.
5. In your opinion, which method is better for measuring the speed of sound, the direct method or the standing wave method? Explain why you favor this method.
6. Suppose the temperature of the room were to fall several degrees. Would the resonance frequency of an open-end tube be higher or lower than the value you measured above? Explain?
7. If helium gas replaced the air in the tubes, would the resonance frequency of an open-end tube be higher or lower than the value you measured above? Explain.

8. What is the best answer to the question below and why?

## Figuring Physics

A large soda bottle is about half full of soda when Oscar decides to blow across the top of the open bottle. While blowing across the top, he hears a characteristic note sounded by the bottle. Oscar then drinks a bit more of the soda from the bottle and again blows across the top. The pitch of the note sounded by the bottle is now

a) higher than before.
b) lower than before.
c) the same as before.

## JAR OF ELECTRICITY

A Leyden Jar is an old-fashioned capacitor. Now a capacitor, or condenser as they are sometimes called, consists of metal surfaces that are separated from one another. They are storehouses of electric energy when one surface is charged + and the other surface −. Two hundred years ago capacitors were made by putting one piece of metal foil on the inside of a bottle and one piece on the outside. The bottle was called a Leyden Jar because the first were made at the University of Leyden in Holland—the Cal Tech of its day. The energy stored in a charged Leyden Jar is actually stored

a) on the metal foil inside the jar
b) on the metal foil outside the jar
c) in the glass between the inner and outer foil
d) inside the jar itself

# Experiment 5

# Electrostatics

**Objective:** To observe the behavior of electrically charged objects and to use the electron model of electricity to *explain* your observations.

**Method:** Plastic strips rubbed with fur and silk will be used to generate electrostatic charges. A *pith ball* on a stand will be used to test the basic behavior of charged objects. *Charging by conduction* and *charging by induction* will be investigated using an electroscope and an electrophorus.

**Apparatus:**

| | | |
|---|---|---|
| pith ball on stand | electrophorus | black plastic strip (vinyl) |
| electroscope | white fur and silk | clear plastic strip (acetate) |

**Comments:** In the 17th and 18th centuries electrostatic phenomena were sued in many parlor games. One such amusing winter pastime was to ask an attractive young damsel to shuffle her feet on a wool rung and then to stand on a low stool. A gentleman would step forward and attempt to kiss the young lady on the cheek. As he came close, zap! He would get a jolt of electricity. King Louis XIV of France arranged 180 soldiers of the guard into a circle holding hands and then discharged a Leyden jar through them. An observant historian wrote "to a man they leaped several feet in the air". And our own Benjamin Franklin is said to have dispatched a large turkey using the charge stored in a Leyden jar. Nobody understood electricity, but the games were fun and sometimes deadly.

The Greeks were familiar with many electrostatic effects. Certain substances, particularly *amber*, when rubbed with fur, attracted small bits of straw, hair, or dry parchment. William Gilbert, court physician to Queen Elizabeth I, coined the word "electricity" for this phenomenon (from the Greek word $\eta\lambda\varepsilon\kappa\tau\rho o\nu$ for amber) and in 1600 published everything that was known about electricity in his book *De Magnete*. The study of electricity progressed little until 1765 when Benjamin Franklin proposed his one-fluid theory. He proposed that all substances contained a fluid that he called "electrical fire" and that an excess of this fluid caused a body to become *positively charged* while a deficiency caused it to become *negatively charged*. That is, there are two kinds of electricity, positive ($+$) and negative ($-$). With one addition, his idea is in use today. We now know that the "fluid" is really a collection of electrons which are negatively charged and that a positively charged object is caused by a *deficiency of electrons* instead of an excess of electrical fire.

**Theory:** Our modern ideas about electricity are based on the simple atomic model of matter that places the protons (all the positive charge) in the nucleus of the atom and the electrons (all the negative charge) moving in selected orbits around the nucleus. The following ideas about electricity and charged objects are based on the nuclear model of the atom.

1. All matter contains electrons. An object with an excess of electrons is negatively ($-$) charged, while

an object with a deficiency of electrons is positively (+) charged.

2. If neither object is a conductor, rubbing one object with another (for example, rubbing rubber with fur) can rub electrons off the one object and onto the other object. The rubber becomes negatively charged while the fur becomes positively charged.

3. Electrically charged objects exert forces on one another. Objects with *like charges* **repel** one another, while objects with *unlike charges* **attract** one another.

4. Amost all materials can be put into one of two electrical classes: *conductors* in which electrons can move freely throughout the material, and *insulators* in which electrons are almost immobile. Metals and people are conductors of electricity, and glass and plastics are insulators.

5. When a *charged conductor* is touched to a neutral conductor, some charge flows onto the neutral conductor. The exact amount depends upon the size and shape of the conductors.

6. When a *charged insulator* comes very close to either a neutral conductor or a neutral insulator, some charge may jump through the air to the neutral object. The air, ionized by the presence of the charged object, acts as a conductor of charge and you will often see and hear the electrical spark associated with the charge transfer.

7. When a *charged object* (either a conductor or insulator) comes close to a neutral conductor or a neutral insulator, and *no spark is allowed to jump between the objects*, the charged object causes a local rearrangement of the electrons in the neutral object. It occurs because the charged object either repels or attracts electrons near the surface of the neutral object and the local area of the neutral object nearest to the charged object will become charged with the opposite sign compared to the charged object. The neutral object remains neutral, but a local charge separation (in conductors) or a local polarization (in insulators) occurs. Because of the charge separation or polarization, a net *force of attractiion* will act on the neutral object. This effect is called *electrostatic induction*.

8. An *electrical ground* is a very large conductor with the ability to supply or receive an unlimited number of electrons while itself remains electrically neutral. The earth is the best example of an electrical ground. Any charged object that is connected to the earth (i.e. grounded) immediately gains or loses all its excess charge and becomes electrically neutral. Your body will act as a ground for the small conductors used in this experiment. Using your hand to ground charged objects during this experiment is not dangerous, even though the voltages may be as high as 10,000 to 30,000 volts. The lethal apsect of electricity is related to the *amount* of charge that flows through your body. In this experiment, the amount of charge that will flow through you is extremely small. Because electrons cannot flow in or on insulators, you have to touch insulators over their entire surface to ground them.

**NOTES:** In this laboratory exercise you ill gain some experience working with electrically charged objects by doing some experiments similar to those done by Gilbert and Franklin. Each experiment consists of *observations and explanations*. There is no analysis. Just carry out each procedure and record your observations and write explanations as required. All explanations should use the electron theory of electricity as described above. In particular, note that *electrons are the mobile charges. Positive charges do not flow through conductors or onto insulators.* You may have to repeat an experiment a number of times to see what is happening and to understand how it happens. If you become puzzled about what you see, consult with other groups and with your instructor. In your written observations and explanations, *please use complete sentences*. Keep your written comments as bried as possible *by sketching diagrams that show the positions of charges and their movement onto and out of objects.*

## Procedure 1 — Charging by Rubbing

1. Set the *pith ball* stand in front of you (pith is the soft center of reeds) and gently touch it to ground it. Then rub the plastic strip with white fur and slowly bring the strip toward the ball until the ball touches the strip. Observe carefully. Before repeating this experiment, be sure to ground the ball. *Record* your observations, noting each effect and the order in which they occurred.

2. Now use the electron theory to *explain* each of your observations. By definition, the charge on the black strip after rubbing is negative. Make liberal use of *diagrams* and *sketches* to help explain what you saw and use complete sentences in your explanation. The *initial motion* of the neutral pith ball is important. It may require some subtle reasoning, but work it out and explain how it happens.

3. A *negatively* charged pith ball can be used to determine the sign of the electrical charge on charged objects. For each experiment below, the pith ball should be initially charged (−) using the black strip.

   (a) Rub the clear plastic strip with silk and slowly bring it near the (−) charged pith ball (don't allow the pith ball to hit the strip). *Record* your observation. What sign charge is on the clear strip rubbed with silk? *Explain* how you know.

   (b) Now rub the clear plastic strip with white fur and determine what sign charge is on the clear strip. Then rub the black plastic strip with silk and determine what sign charge is on the black strip. Report your result.

4. Suppose a *positively* charged rod attracts a pith ball. Think carefully: what can you conclude about the *sign of the charge* on the pith ball?

## Procedure 2 — Charging by Conduction

The *electroscope* is a simple electrical instrument that is used to investigate the sign and relative magnitude of charged objects. It can be charged by *conduction*. It consists of a metal rod with a metal knob at its upper end and two light gold foil leaves hanging from its lower end. The leaves are usually in a box with windows to shield the leaves from air currents. The knob, the rod, and the leaves of the electroscope are electrically insulated from the box.

1. Charge the black plastic strip (−) by rubbing it with white fur and then transfer the charge by conduction to the electroscope by touching the strip to the knob of the electroscope. Observe what happens to the leaves. *Record* and then *explain* your observations.

2. The electroscope is a better device than the pith ball for determining the relative magnitude and sign of the charge on a charged object.

   (a) With the electroscope charge (−) as above, observe the effect when the charged *clear* plastic strip, rubbed with silk, is brought close to, *but not allowed to touch* the knob of the electroscope. Don't allow a spark to jump between the knob and strip. *Record* and then *explain* your observations.

   (b) With the electroscope charged (−) as above, observe the effect when the charged *black* plastic strip, rubbed with white fur, is brought close to, *but not allowed to touch* the knob of the electroscope. Don't allow a spark to jump between the knob and the strip. *Record* and then *explain* your observations.

## Procedure 3 — Charging by Induction

So far, you have used two methods to charge objects: charging by rubbing and charging by conduction. There is a third way to charge objects called *charging by induction*. This method is explored in this section.

1. *Ground the electroscope* so that it is neutral. Rub the *black* plastic strip with the white fur and slowly bring the strip toward the knob of the electroscope, but do not let it touch the knob and do not allow a spark to jump to the knob. Carefully observe the leaves of the electroscope during this procedure. *Record* and then *explain* your observations.

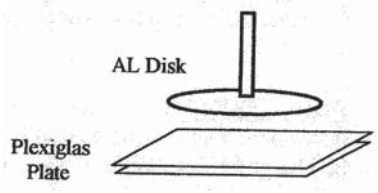
2. The effect you observed above is called *electrostatic induction*. Electrostatic induction occurs when a *neutral object*, such as the leaves of the electroscope above, shows an electric response to a charged object.

   (a) Now repeat step 1 above, but while the charged black strip remains close to the knob of the electroscope, reach in with your finger and touch the knob of the electroscope (i.e. ground it). Remove your finger and then remove the charged strip (in that order). You should observe that the electroscope has been charged. It has been charged by induction. *Determine* and *record* the sign of the charge on the electroscope.

   (b) Now *explain*, in detail with diagrams, how the electroscope was charged by induction. To aid your thinking, you can do the following experiment: Repeat the above experiment, but after touching the knob with your finger, remove the strip first and then your finger. This procedure does not charge the scope and may perhaps give you a clue about how the charge gets on the electroscope.

## Procedure 4 — The Electrophorus

The *electroscope* is a two-piece apparatus consisting of a Plexiglas plate and an aluminum disk mounted on an insulating handle. The *aluminum disk* can be given a large amount of charge as follows: rub the Plexiglas plate vigorously with the white fur, place the aluminum disk on the Plexiglas plate, briefly touch the top surface of the aluminum disk, and then pick up th disk by its handle. It is now charged, which you can verify by discharging it on a water pipe (do *not* use the gas pipe). Without *additional rubbing of the Plexiglas plate*, this procedure of charging and discharging can be repeated almost without limit.




1. Charge the aluminum disk as described above and discharge it on a water pipe. Repeat this many times (without additional rubbing of the Plexiglas plate) until you tire of the exercise. If the Plexiglas plate was the source for the charge acquired by the aluminum disk each cycle, then the charge on the Plexiglas plate would rapidly diminish reducing the amount of charge supplied to the aluminum plate each time you touched it. Is there any indication that the charge given to the aluminum dish by the Plexiglas plate is diminishing as it is repeatedly charged and discharged?

2. To determine how the aluminum disk becomes charged, it is good to know the sign of the charge on both the aluminum disk and the Plexiglas plate.

   (a) Use a charged electroscope to determine the sign of the charge on the aluminum disk. *Record* your results.

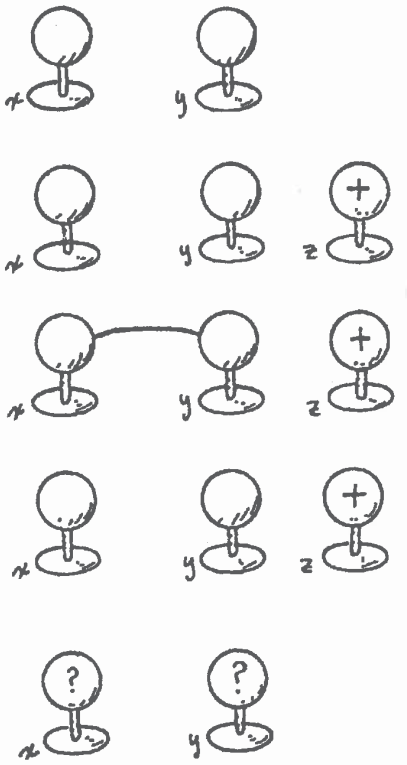
(b) Repeat to find the sign of the charge on the Plexiglas plate. *Record* your results.

(c) Now *explain*, in detail with diagrams, how the aluminum disk of the electrophorus acquires its charge each cycle.

3. Consider the question below. Determine the best answer and explain the reasons for your answer.

**UNDER THE INFLUENCE**

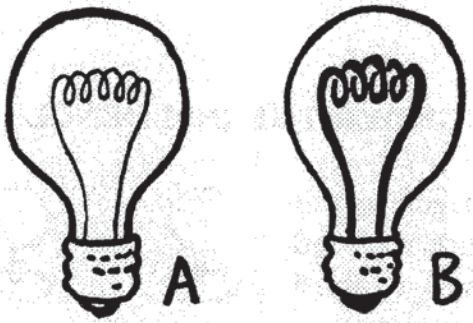
Two uncharged metal balls, X and Y, stand on glass rods. A third ball, Z, carrying a positive charge, is brought near the first two. A conducting wire is then run between X and Y. The wire is then removed, and ball Z is finally removed. When this is all done it is found that




a) balls X and Y are still uncharged
b) balls X and Y are both charged positively
c) balls X and Y are both charged negatively
d) ball X is + and ball Y is −
e) ball X is − and ball Y is +

## THIN AND FAT FILAMENTS

Light bulbs **A** and **B** are identical in all ways except that **B**'s filament is thicker than **A**'s. If screwed into 110-volt sockets,




a) **A** will be the brightest because it has the most resistance
b) **B** will be the brightest because it has the most resistance
c) **A** will be the brightest because it has the least resistance
d) **B** will be the brightest because it has the least resistance
e) Both will have the same brightness

# Experiment 6

# Mapping Electric Fields

**Objective:** To determine the shape of the equipotential surfaces that exist in the space between two oppositely charged conductors and to use these surfaces to map the electric field by drawing the lines of force that exist between the conductors. Also to use the potential gradient to investigate the magnitude of the electric field at selected points between the conductors.

**Method:** A digital multimeter (DMM) will be used to map the shape of equipotential surfaces at 3.00-volt intervals between two oppositely charged conductors. From the shape of the surfaces, you will draw the lines of force between the two conductors and compute some representative values for the electric field.

**Apparatus:**

| | | | |
|---|---|---|---|
| 2 pre-drawn conductor patterns | probe | 3 connecting wires | corkboard |
| power supply 0–22 VDC | DMM | 2 metal push pins | 3 alligator clips |

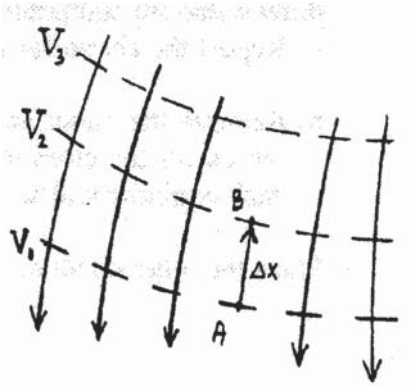
**Comments:** An electric field is mapped using lines of force. A line of force is a smooth line drawn in space that shows the path a *ver small positive* test charge would follow if it were allowed to move *very very slowly* pulled by the electric field. These lines, also called *electric field lines*, are drawn such that they start on positive charges, continue smoothly through space without cutting through other lines of force, and end on negative charges. If the charges are on the surface of an electrical conductor, the lines of force must leave the $(+)$ charged surface *perpendicular* to the surface and arrive at the $(-)$ charged surface *perpendicular* to the surface. The electric field is related to lines of force in the following two ways:

1. the direction of the electric field at any point in space is *tangent* to the line of force at that point, and

2. the magnitude of the electric field at any point is proportional to the density of the lines of force in the area about that point.

In practice, it is difficult to actually map an electric field using the definition of lines of force. There are no simple instruments that measure the magnitude and direction of the electric field at a point in space. The method most commonly used to map electric fields is to first map *surfaces of equipotential* and then to use these surfaces to draw the lines of force. A surface of equipotential is a surface of constant electrical potential energy (i.e. constant voltage). A positive test charge can be moved freely over an equipotential surface without doing any work on it because all points on the surface are at the same voltage. This means that there can be no component of electric field parallel to any equipotential surface. Thus, the lines of force must be everywhere *perpendicular* to the surfaces of equipotential. The shape of equipotential surfaces is easily determined with a voltmeter. When several surfaces are known, as shown in the figure at the right, the lines of force are easily

drawn with the direction of the lines going from higher to lower potential (i.e. from higher PE to lower PE).



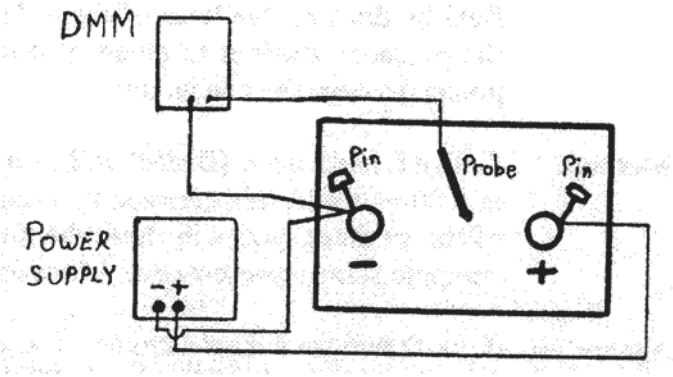

## Procedure

You will be furnished with two pre-drawn conductor patterns drawn in silver ink onto a special carbon impregnated paper. The two patterns are:

1. an electric dipole — two equal circles that will be given equal, but opposite charges,
2. parallel plates – the cross-section of two equal-sized plates which will be given equal, but opposite charges.

Work together with your group on the experiments and analysis. Let each person in your group have a chance to find and mark the equipotential points. Submit only one report for your group.

1. Choose one of the patterns and place it on the corkboard. Push a metal push pin through the back surface of each conductor. Don't allow the pins to wobble as they are pushed in. This could break the contact between the pin and the conductor. Connect the power supply to the pins using alligator clips. Use a pencil to mark the positive $(+)$ and negative $(-)$ conductors.




2. Connect the DMM as shown above. *Let your instructor inspect the circuit before you turn on the power supply to ensure that there are no electrical problems.* Turn on the power supply, touch the probe to the positive pin, and adjust the voltage so that the DMM shows 15 volts DC. *Do not use the scale on the power supply to set the voltage.* Do not exceed 15 volts since excessive voltages can cause currents that burn the paper.

(a) Now touch the probe to various places on the (+) conductor to verify that all of it is at the same 15 volts. Then touch the probe to the negative pin to ensure that its voltage is zero. Then touch various places on the (−) conductor to verify that all of it is at zero volts. A large deviation at either conductor indicates that a hairline crack may exist somewhere on the conductor. If you suspect a crack, ask your instructor to repair it.

(b) Now touch the probe to any place on the paper and move it about. Note how the potential increases as the probe nears the (+) conductor and how the potential decreases as the probe nears the (−) conductor.

3. Touch the probe to the paper and find a point where the potential is 3.00 volts. Hold the probe almost vertical and don't push too hard into the paper. Use a pencil to mark the probe position with a small dot. Locate and mark other points at 3.00 volts until you have enough points to draw a smooth equipotential line *from one edge of the paper to the other edge of the paper*.

   (a) Repeat the above for voltages of 6.00 volts, 9.00 volts, and 12.00 volts.

   (b) Remove the paper and use a *pencil* to draw smooth lines thorugh your points. Each line represents the cross section of an equipotential surface at that voltage. Label the voltage of each equipotential surface.

4. Place the other conductor pattern on the corkboard and repeat the above steps.

**Theory:** Any pair of equipotential surfaces can be used to compute an *average value* for the magnitude of the electric field between the surfaces. To find the formula for $E$, imagine that a charge $Q$ is moved along line $AB$ from point $A$ on equipotential $V_1$ to point $B$ on equipotential $V_2$ as shown in the diagram on page **??**. This work is equal to $Q\Delta V$, where $\Delta V = V_2 - V_1$ is the potential difference between the two surfaces. The work is also given by $F\Delta x = QE\Delta x$ where $QE$ is the force that must act on the charge to move it through the displacement $\Delta x$. In this expression, $E$ is the magnitude of the average electric field between the two equipotential surfaces. Since the two works are equal, $\Delta V = E\Delta x$, or

$$E = \frac{\Delta V}{\Delta x} \tag{6.1}$$

where the change in voltage per unit displacement, $\Delta V/\Delta x$, is called the *potential gradient of the electric field*. The units of potential gradient are *volts/meter*. You can show that these units are identical to the original units for electric field, N/C. Since $E$ is an average value, it can be assigned to the position exactly halfway between the two equipotential surfaces.

# Analysis

1. To make the lines of force stand out from the surfaces of equipotential, use a piece of white chalk to carefully draw lines of force between the electrode patterns. Draw enough lines so the electric field is easily visualized. Be sure to use arrows to show the direction of each line.

2. Electric Dipole. Compute the electric field halfway between each pair of equipotential surfaces (including the surface of each conductor) along the line that goes directly between the two charged circles.

   (a) Is the electric field a minimum or a maximum at the midpoint of the charges? Comment.

   (b) Carefully measure and record the distance between the centers of the two charged circles and divide it by 2. This is the distance from the center of each charge to the midpoint of the charges. Write down the formula that expresses the magnitude of the electric field at the midpoint between two equal, but opposite charges. Then, using the measured values obtained above for the electric

field at the midpoint of the charges and the distance from each charge to the midpoint, compute a value for the magnitude of charge $Q$ that resides on each of the charged circles. From your experience, comment on whether this is a large amount of charge or a small amount of charge.

3. Parallel Plates. Beginning at the center of the negative plate, compute a value for the average electric field between each pair of equipotentials (including each plate) along a line perpendicular to the plate.

   (a) Is the electric field approximately uniform between the plates? Comment.

   (b) Does the electric field appear uniform between each end of the two plates? Comment.

   (c) If an electron, $Q = 1.602 \times 10^{-19}$ C and mass $= 9.11 \times 10^{-31}$ kg, were placed just outside the negative plate and released from rest, how fast would it be going when it hit the positive plate?

# Experiment 7

# Half-Time of the RC Circuit

**Objective:** To acquire the voltage-time graph for a discharging RC circuit and to use it to determine the half-time for the circuit.

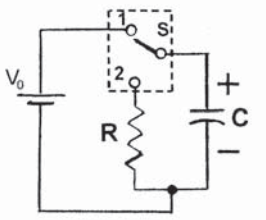
**Comment:** The rate at which electric charges flow from a charged capacitor is directly proportional to the amount of charge remaining in the capacitor. Thus the discharge rate (i.e. electric current) is large when the remaining charge is large, but the rate becomes slower and slower as the amount of charge remaining in the capacitor becomes smaller and smaller. In nature, whenever the rate of change of a quantity is proportional to the present amount of that quantity, the time graph for that quantity is an *exponential function*. An important property of *exponentially decreasing* functions is that they have a *constant half-time*. The half-time for a *discharging capacitor* is the time that it takes for the amount of charge in the capacitor to decrease from its present value to one-half that value. The half-time is completely independent of how much charge is left in the capacitor. No matter if the remaining charge in the capacitor is very large or almost near zero, the time for the present charge to fall to one-half that value is the same constant time. This behavior implies that the time for an *ideal capacitor* to completely discharge is infinite! Since capacitor voltage is directly proportional to capacitor charge, the amount of charge in the capacitor will be measured using its instantaneous voltage.

**Method:** The discharge of a charged capacitor in an RC circuit will be investigated by obtaining the voltage vs. time graph of the discharging capacitor using a voltage probe connected to a computer via the LabPro data acquisition system.

**Apparatus:**

| | | |
|---|---|---|
| 0–22 VDC power supply | slow RC circuit | 2 short wires |
| large DPDT switch | Vernier voltage probe | 3 alligator clips |
| computer, LabPro & USB cable | 2 long wires | 3 spade lugs |

**Theory:** The RC circuit—a capacitor $C$ connected in series to a resistor $R$—is a common circuit in electronics. Because the RC circuit has a characteristic charging and discharging time, it is often used in timing circuits for devices such as traffic lights, camera flashes, heart pacemakers, etc. The RC circuit used in this experiment is in the shape of a "U" as shown at the right. A battery or power supply $V_0$ is connected across the capacitor $C$ via a double-throw switch $S$. When switch $S$ is thrown to position 1, resistor $R$ is not part of the charging circuit and the capacitor is charged immediately to the battery voltage $V_0$. When switch $S$ is thrown to position 2, the battery is removed from the circuit and the capacitor is allowed to discharge through resistor $R$. Because the resistance of $R$ limits how fast the charge can flow out of the



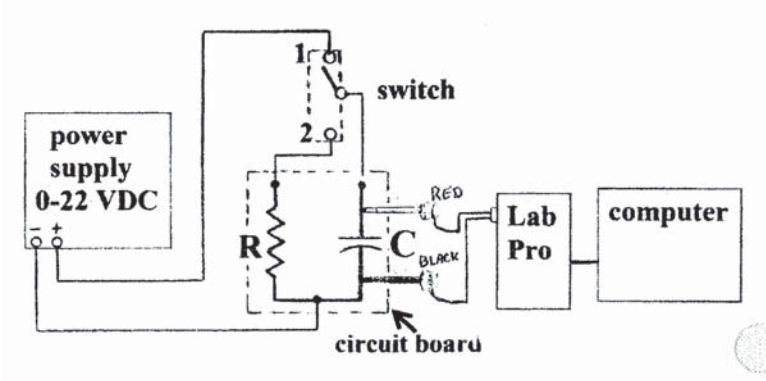
capacitor, the capacitor does not discharge immediately, but rather the charge in the capacitor decays exponentially. Since capacitor voltage is directly proportional to the charge in the capacitor, we expect that capacitor voltage will follow an exponential decay curve as the capacitor is discharged. The theoretical formula for capacitor voltage as the capacitor discharges is given by the exponential expression

$$V = V_0\, e^{-t/RC} \tag{7.1}$$

where $V_0$ is the initial voltage across the capacitor, the letter $e$ represents the base of the natural logarithms, $R$ is the resistance of the resistor in ohms, and $C$ is the capacitance of the capacitor in farads. The expression $RC$ is often called the *time constant* for the RC circuit. It can be shown that the half-time for the RC circuit is given by the expression

$$t_{1/2} = RC \ln 2. \tag{7.2}$$

# Procedure




1. **Set Up.** Select an RC circuit board and record the values of $R$ and $C$ written on the bottom of the circuit.

   (a) Prepare the switch. The switch can be a bit confusing until you realize that it is two double-throw switches glued together side-by-side. You will use just one side. The switch has three terminals, a center terminal at the foot of the throw arm and terminals 1 and 2 at either end of the switch. Insert the three spade lugs under the three terminals by unscrewing each terminal just enough to slide the spade lug under the terminal and tighten the terminal. The spade lugs allow wires to be connected to the switch.

   (b) Connect circuit and switch. Clip an alligator clip to each of the terminals on the RC circuit. The alligator clips allow wires to be connected to the circuit board. Use two short wires to connect the RC circuit to the switch as shown in the diagram above. One wire goes from the top of the capacitor (+ side) to the middle terminal of the switch. The second wire goes from the top of the resistor to terminal 2 on the switch.

   (c) Connect the power supply. Using two long wires, connect the 0–22 VDC power supply to the switch and circuit as shown in the diagram above; the (+) output of the power supply to terminal 1 on the switch and the (−) output of the power supply to the bottom of the RC circuit. ***Observe carefully that the positive terminal of the capacitor will be connected to the positive output of the power supply when the switch is thrown to terminal 1.*** The capacitor is an electrolytic capacitor and such capacitors can overheat and explode if connected backwards. Note that charging

will occur almost immediately when the switch is thrown to position 1 because the resistance is practically zero in the charging circuit.

(d) Connect the LabPro. The tips of the red and black voltage probes are small hooks that are pushed out when the wide end of the probe is pushed in. These hooks are designed to clip onto bare wires for voltage measurements. Clip the two probes across the capacitor as shown in the diagram above observing the proper polarity. Connect the other end of the probes into CH1 of the LabPro. The LabPro connects to the computer via the USB connector.

(e) ***LET YOUR INSTRUCTOR CHECK YOUR WIRING BEFORE TESTING THE CIRCUIT.***

2. **Test the Data Acquisition Software.** *Please note that the maximum voltage that can be measured by the LabPro is ± 10.0 V. Please keep the power supply voltage below 10.0 volts.*

(a) From the desktop of the computer, select *Tools for Scientific Thinking*, select the folder *Physics 1020*, and double-click on the program **RC_Circuit**.

(b) When the software appears, a Page Information box is displayed. Read the information box and click **OK**. On the screen you should see a graph of Capacitor Voltage (V) vs. Time (seconds) with the voltage scale from 0.5 V to 11 V and the time scale from 0 to 100 seconds. There is also a meter that will show the present voltage across the capacitor and a table that will store the measured time and voltage data. There is a third column in the table, which computes **ln V** (the natural logarithm of voltage $V$) to be used later.

(c) As a test, throw switch $S$ to position 1, turn on the power supply, and use the meter on the computer screen to adjust the voltage to about 8 volts. To start data collection, click on **Collect** at the top of the screen (note that **Stop** appears in the box after the click) and the system immediately begins to collect, record, and plot the measured voltage vs. time data. Allow the system to record a few seconds of constant voltage data and then throw switch $S$ to position 2 to discharge the capacitor and observe the voltage graph for several seconds. If the voltage graph does not show the shape of an exponential decay, consult with your instructor to determine the problem.

3. **Acquire a Good Discharge Graph.** Throw switch $S$ to position 1 and adjust the capacitor voltage to about 9.7–9.8 volts.

(a) Click on **Collect** to start data collection and allow the system to record a few seconds of constant voltage data and then throw switch $S$ to position 2 to discharge the capacitor. Continue data collection until the capacitor voltage has fallen below 0.50 V. To stop data collection, click on **Stop**.

(b) On your data sheet, draw and label a sketch of the capacitor discharge graph. Does your graph have the shape that you expected for the discharge of a capacitor? Comment.

4. **Measurement of the Half-Time.**

(a) Set up a data table of 5 rows and 5 columns with columns for $V_1$ in volts, $t_1$ in s, $V_2$ in volts, $t_2$ in s, and half-time in s.

(b) To obtain data from your graph, select **Analyze** on the **Menu Bar** and click on **Examine**. This brings up a small box that shows the values (voltage, time) of each point on the graph. As you move the mouse, a line on the plot moves back and forth along the graph allowing your to see the coordinates of any given point.

(c) Select an initial voltage near 9 volts and record both voltage and time. Then record one-half that voltage and find the time when that half-voltage appears (you may have to do a little interpolation to get a good value for the time). Record the time. Determine and record a value for the half-time.

(d) In theory, the half-time is independent of where in the discharge you choose to start the half-time measurement. To check this out, select a voltage near 8.0 V and determine the half-time for the voltage to fall to one-half this value. Record the data in your data table. Repeat these measurements three more times, determining the half-time for the voltage to drop from about 6.0 V, from about 4.0 V, and from about 2.0 V.

(e) Do your half-time measurements tend to remain constant as you change the voltage range of the measurements? Comment.

(f) Determine a single experimental value for the half-time of your circuit by finding the average of the above values.

5. **Compare Measured Discharge Rate to Theory.** To be able to compare your experimental graph to the result expected from equation (7.1), you need to fit your experimental data to the function predicted by equation (7.1). Since we believe that the best way to test measured data to theory is to do a *linear regression* of transformed data, you need to transform your measured data before doing a linear regression analysis. Fortunately, the data acquisition program that graphed the experimental data has already done the transformation.

   (a) Equation (7.1) can be transformed to a linear function by taking the *natural logarithm* of both sides to obtain the expression

   $$\ln V = \ln V_0 - \frac{1}{RC}\, t$$

   which is a linear function for $\ln V$ as a function of $t$ with slope equal to $-1/RC$ and $y$-intercept equal to $\ln V_0$.

   (b) Since your program has already computed $\ln V$, you can quickly check the shape of the graph $\ln V$ vs. $t$:

   - On the graph, click on the *label* of the vertical axis. This brings up a box with choices for what data to plot on the vertical axis. Select *ln(v)*. To expand vertically the new graph, change the vertical scale by right-clicking anywhere on the graph and selecting *Graph Options* and then *Axis Options*. Change the vertical scal to 3.0 or to whatever value seems best for your data.
   - Draw and label a sketch of your new graph. Does the transformed data plot as a straight line? Comment.

   (c) Linear Regression of the Experimental Graph. Before doing a linear regression, you must *select* that part of the data that you want to fit. To select a portion of the graph, place the cursor at the upper left of the region you wish to select and, while holding down the left mouse button, scroll the cursor *across and down* through the region. As you do this, the selected region is highlighted. Only the data in this highlighted region will be used for the linear fit.

   - Select the linear portion of your graph that you wish to use for a linear regression analysis.
   - To do a linear fit of your selected data, click on **Analyze** on the **Menu Bar**, select **Curve Fit**... and under *General Equation:* you will see a list of regression equations. Select the linear equation $mt + b$ and click on **Try Fit** and then **OK**. The program will display a box with the slope and $y$-intercept of the fit (ignore the $\pm$ error information and other statistical information). The program will also plot the linear regression line on the plotted data. The box can be moved to any convenient position by clicking and dragging it. You can remove the box by clicking on the $x$-mark in the upper left hand corner of the box.
   - Record the slope and $y$-intercept with proper units (note that $\ln V$ and $\ln V_0$ lost their units in the transformation process) and write the explicit function for the transformed data.

   (d) Close the computer program *without saving* and turn OFF the computer.

## Analysis

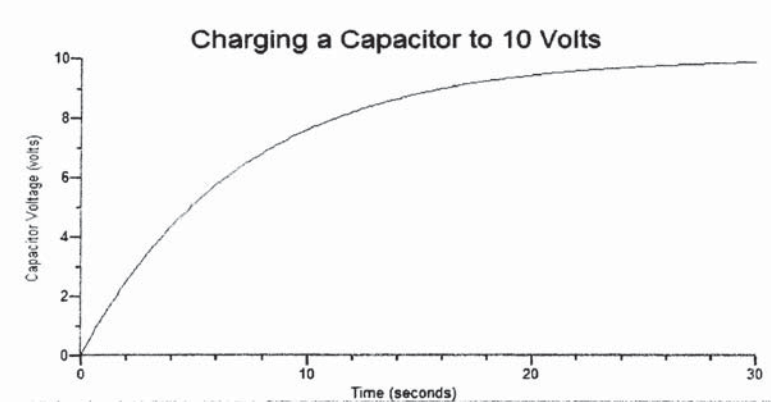
1. Compute a theoretical value for the half-time of the RC circuit using your recorded values for $R$ and $C$ in equation (7.2).

2. Compare your experimental value for half-time (the average value determined above) to the theoretical value. How well does theory predict your experimental result? Comment.

3. Record the linear regression function you obtained from your experimental data. Use the value of the slope from the regression analysis to determine a second experimental value for the half-time of this RC circuit. Compare this second experimental value to your directly measured experimental value. Comment on how well your experimental values agree or disagree.

4. Starting with equation (7.1), show mathematically how to derive equation (7.2).

5. Consider the question in Figure 7. Which is the best answer and why?



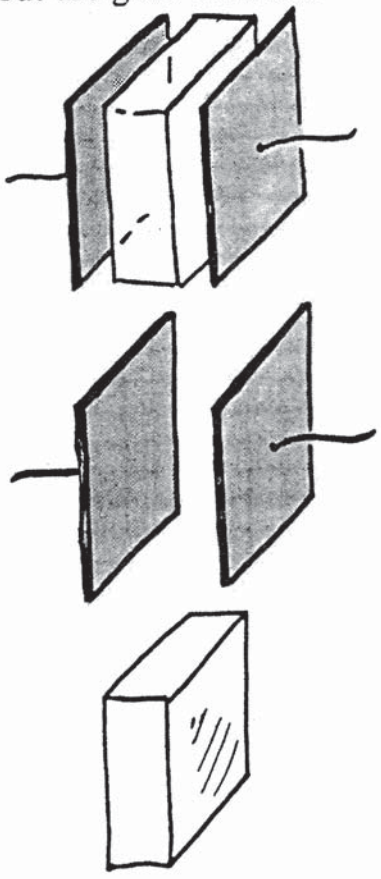
## GLASS CAPACITORS

Capacitors may have an airspace between their plates, or have glass, plastic, wax paper, or oil between the plates. In the days of Benjamin Franklin capacitors were the previously mentioned Leyden Jars—so you are now learning 200-year-old physics. If a glass capacitor is charged, but the glass between the plates is removed before it is discharged, the spark will be

a) bigger than it would have been if the glass were left in at discharge

b) smaller than it would have been if the glass were left in at discharge

c) the same as it would have been if the glass were left in at discharge



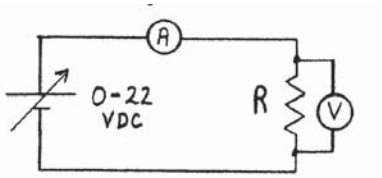
# Experiment 8

# Measuring Electrical Resistance

**Objective:** To use the voltmeter/ammeter method to measure the resistance of a power resistor and a pilot lamp. to use an ohmmeter to measure the resistance of several different types of resistors.

**Method:** The resistance of a conductor of electricity is defined to be

$$R = \frac{\Delta V}{I} \tag{8.1}$$




where $\Delta V$ is the potential difference applied across the conductor and $I$ is the current that flows *through* the conductor. The *direct method* of measuring resistance, called the *voltmeter/ammeter method*, is to connect the conductor to a known DC potential difference, $\Delta V$, measure the resulting current $I$ that flows through the conductor, and use equation (8.1) to compute its resistance. If the resistance remains approximately constant as current increases the conductor obeys Ohm's law and the conductor is said to be *ohmic*. If the resistance of the conductor changes as the current increases, then the conductor is *non-ohmic*. The general circuit diagram for the voltmeter/ammeter method is shown at the right, where $R$ represents the conductor whose resistance is to be measured. The power supply that you will use is a variable 0 to 22 V DC power supply that is capable of supplying current up to a maximum of 4 amperes at any voltage between 0 and 22 volts DC. The voltage (potential difference) across the conductor is measured using a *voltmeter*, labeled $V$ in the diagram and the current through the conductor is measured using an *ammeter*, labeled $A$ in the diagram.

Another method for measuring resistance is to use an *ohmmeter*, an instrument designed to directly measure the resistance of any conductor connected across it. The digital multimeter (DMM), a common laboratory instrument, is a multipurpose instrument that can be switched to become a voltmeter, and ammeter, or an ohmmeter. You will use the DMM as a voltmeter and later as an ohmmeter. Since there is some danger to the DMM when used as an ammeter, a standard dial-type ammeter will be used to measure current.

**Apparatus:**

| | | |
|---|---|---|
| 150 ohm power resistor | DMM | carbon resistors |
| 28 volt pilot lamp | PASCO ammeter | 2 alligator clips |
| 0 – 22 VDC power supply | long leads | |

**Comments.** An important consideration when using resistors in an electric circuit is their ability to dissipate heat energy. Electric current flowing through a resistor generates heat in the resistor at a rate given by the power formula $P = I^2R$, where $P$ is the power developed in *watts* (joules/second). This heat energy is

often called *Joule heat*. The maximum power that can be dissipated by a conductor is called its *power rating*. Almost every electrical conductor that you use will have a power rating. For example, hair dryers are rated 900 W, or 1200 W, or even 1500 W. The higher the rating, the greater is the current that can pass through the conductor.

Using Voltmeters. A voltmeter is always connected in *parallel* between the two points where the potential difference is to be measured. The high potential lead of the voltmeter (usually the red lead) is connected to the point of *highest potential* and the low potential lead (also called *common*, the black lead) is connected to the low potential point. To do otherwise will harm a dial-type voltmeter, but a DMM voltmeter just displays a negative voltage. An ideal voltmeter has infinite resistance so that it draws no current from the circuit. A real voltmeter is less than ideal and the internal resistance of an inexpensive meter can be as low as 2000 ohms for each volt of measured potential difference. The digital multimeter (DMM) used in this experiment has an internal resistance of 10 megohms.

Using Ammeters. An ammeter is always connected in *series* with the circuit branch that carries the current you want to measure. The circuit must be opened at the point where you want to measure the current and the ammeter inserted so that the current flows into the $(+)$ terminal of the ammeter and flows out of the $(-)$ terminal of the ammeter. The ammeter can be damaged if it is connected backwards in the circuit. An idea ammeter has zero resistance so that id does not disturb the current being measured. A typical laboratory ammeter has an internal resistance of about one milliohm. **Note:** When you do not know what scale to use on an ammeter, the safest procedure is to use the highest scale of the instrument. The reduce the scale until you obtain a measurable reading.

# Procedure 1

**Measuring Resistance Using the Voltmeter/Ammeter Method.**

1. **Power Resistor.** Nominal resistance is 150 ohms at 10 watts. Power resistors are used in electrical circuits where large currents are expected. The power rating is the *maximum power* that the resistor can absorb without damage.

   (a) Record the nominal value of the resistor and its power rating.

   (b) Using the circuit diagram on the previous page, connect the power resistor to the power supply, inserting the ammeter as shown. Switch the DMM to an appropriate VDC scale (switch the scale so that you always measure three significant figures for voltage) and use two leads to connect the DMM across the power resistor. LET YOUR INSTRUCTOR CHECK THE CIRCUIT BEFORE TURNING ON THE POWER.

   (c) Set up a data table with a column for voltage in *volts*, current in *amps*, calculated resistance in $\Omega$, and power in *watts*.

   (d) Increase the power supply voltage until the DMM shows 5.00 volts. Read and record both meters. Compute a value for the resistance and the power delivered to the resistor.

   (e) Repeat these measurements at 5-volt intervals until you reach 30.0 volts. *Do **not** exceed 30 volts.* At 30 V, *very carefully* lightly touch the resistor. Is it warm? Comment.

2. **Pilot Lamp.** The pilot lamp is rated at 5 watts at 28 volts. A pilot lamp is a small lamp used on control consoles or older hi-fi sets to provide low-level illumination for dials or to indicate the status of switches, etc. The pilot lamp that you will use is a small tungsten bulb, similar to a flashlight bulb. The rating gives the power required when the bulb is run at its *maximum voltage* of 28 volts.

   (a) Record the power rating of the lamp.

(b) Replace the power resistor in your circuit with the pilot lamp and set up a data table similar to that for the power resistor.

(c) Increase the power supply voltage until the DMM shows 1 volt. Read and record both meters. Compute a value for the resistance and the power delivered to the lamp.

(d) Repeat these measurements at 2, 5, 10, 15, 20, and 25 volts. Do *not* exceed 25 volts. Below your data table, record the voltage at which the lamp just shows visible light.

(e) Dismantle your circuit and return the power supply and ammeter to their storage places.

Using an Ohmmeter. Ohmmeters are designed to measure the resistance of conductors connected across its terminals. However, ohmmeters have their own internal power supply and *must **NEVER** be connected across an active circuit or any conductor that is already carrying current.* Ohmmeters are used to measure the resistance of passive conductors only. An internal battery (usually 9 volts) applies a small voltage to the leads of the ohmmeter. When connected across a resistance, this voltage causes a small current to flow through the resistance. This tiny current is measured and amplified by the meter and a value for resistance is displayed directly in ohms ($\Omega$), kilohms ($k\Omega$), or megohms ($M\Omega$). An ohmmeter is one of the important functions included in digital multimeters (DMM).

# Procedure 2

**Measuring Resistance Using an Ohmmeter.** Switch the DMM to an OHM ($\Omega$) setting, and insert leads into the OHM terminal and COMMON terminal on the DMM. To measure resistance, insert the leads into plugs at either side of the resistance or place alligator clips on each lead and grab the wire on each side of the resistance. After connecting to a resistance, adjust the resistance scale until *three significant figures* are displayed. The value displayed on the meter is the measured resistance in the units of the scale you have selected (either ohms ($\Omega$), kilohms ($k\Omega$), or megohms ($M\Omega$).

1. Measure and record the resistance of the *power resistor* and the *pilot lamp*.

2. Measure and record the resistance across your body from hand to hand.

3. Select three different carbon resistors and set up a data table to record their measurements. You will need a column for colors (e.g. red-black-brown-silver), the expected resistance in *ohms* from the color code, the tolerance from the color code, measured resistance in *ohms*, and percent difference.

   (a) For each resistor, record the four-color code (three colors and a tolerance). Determine the expected resistance and tolerance from the color code and record.

   (b) Using alligator clips on the ends of the DMM leads, grab each side of a resistor and measure and record its resistance. The compare your measured value to the color code value.

# Analysis

1. Which, if either, of the conductors you measured using the voltmeter/ammeter method is ohmic? Comment.

   (a) If the power resistor is ohmic, determine and record an average value for its measured resistance. Comment on how well the value for resistance measured using the ohmmeter agrees with this averge measured value.

(b) If the pilot lamp is not ohmic, use the smallest resistance you measured (*use the ohmmeter value, if it is lower than the value measured using the voltmeter/ammeter method*) to compute *the percent increase* in resistance from its smallest measured value to its highest measured value. Explain why the resistance of the pilot lamp increased so much.

2. A current of 30 mA (0.030 A) flowing across the upper body of a person is sufficient to paralyze the breathing mechanism. From your measured hand-to-hand resistance, compute what hand-to-hand voltage would produce this current through your body.

3. Use the power rating of the power resistor to determine the maximum voltage that can be placed across it without damage to the resistor. Use the power rating of the pilot lamp to compute the maximum current that can flow through the lamp without burning it out.

4. Do all the carbon resistors meet their tolerance levels? Comment.

5. What harm would come to the voltmeter if it were connected as an ammeter in this circuit? Explain.

6. What harm would come to the ammeter if it were connected as a voltmeter in this circuit? Explain.

Carbon Resistor Color Code

Black ..... 0
Brown ..... 1
Red ..... 2
Orange ..... 3
Yellow ..... 4
Green ..... 5
Blue ..... 6
Violet ..... 7
Grey ..... 8
White ..... 9
.....
Gold ..... 5%
Silver ..... 10%

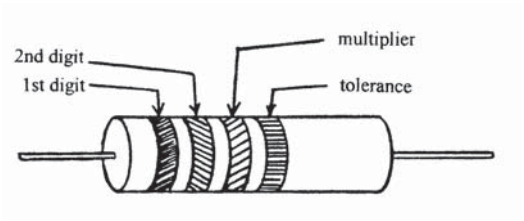
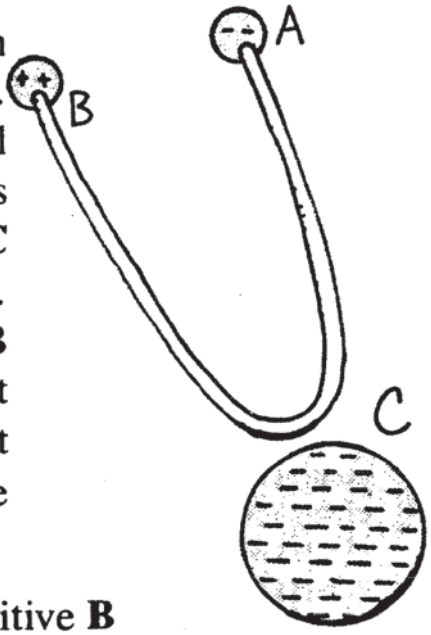



Figure 8.1: Resistor color code. Tolerance is the maximum expected percentage error between the true resistance and the color-code resistance.

Example: red-orange-blue-silver $= 23 \times 10^6$ ohms with 10% tolerance

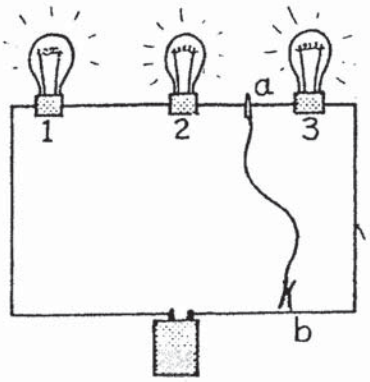
## ELECTRIC PIPE




This is an important question so be careful with this one. Suppose object **A** has a small negative charge and object **B** has a small positive charge. Object **C** has a very large negative charge. Further suppose that **A** and **B** are joined by a copper wire that goes very close to but does not touch **C**. What will happen is the negative charge from **A** will

a) flow through the wire to positive **B**
b) not flow to **B** because of the repelling influence of **C**

# FIGURING PHYSICS




The simple series circuit consists of three identical lamps powered by battery. When a wire is connected between points *a* and *b*,

a) what happens to the brightness of lamp 3?

b) does current in the circuit increase, decrease, or remain the same?

c) what happens to the brightness of lamps 1 and 2?

d) does the voltage drop across lamps 1 and 2 increase, decrease, or remain the same?

e) is the power dissipated by the circuit increased, decreased, or does it remain the same?

Hewitt Drew it!

# Experiment 9

# DC Circuit Analysis

**Objective:** To assemble a series DC circuit and a parallel DC circuit, connect each to a power supply, and measure the circuit current, the potential difference across each resistor and the electric current that flows through each resistor. Then, to theoretically analyze each circuit and determine the expected values for each of the measured quantities and determine how well the circuit analysis predicted the results of measurement.

**Method:** You will first draw a circuit diagram of the circuit, showing where the meters should be placed. Using the diagram as a guide, you will wire the circuit, connect the power supply and meters, and measure the required electric currents and voltages. When the measurements are complete, you will analyze the circuit, finding predicted values for the equivalent resistance, circuit current, the current through each resistor, and the voltage across each resistor.

**Apparatus:** power resistors ($R_1$ through $R_4$) connecting leads (long and short) Pasco ammeter
DMM 0–22 VDC power supply

**Comments:** *Circuit analysis* is the process of calculating expected values for the electrical currents and voltages in a given circuit. The method of analysis is to reduce the series and parallel combinations of resistors to a single *equivalent resistance*. When the equivalent resistance $R_e$ of the circuit is known, the *circuit current* $I_c$ is obtained from the expression

$$I_c = \frac{V}{R_e} \tag{9.1}$$

where $V$ is the voltage of the *source*. The circuit current is then used to compute the currents and voltages associated with the individual resistors in the circuit.

The *power input* to a circuit is computed from the expression

$$P = I_c V \tag{9.2}$$

where $P$ is the power in watts, $I_c$ is the circuit current, and $V$ is the voltage of the source. The power dissipated (or *power output*) in each resistor $R$ is computed from the expression

$$P = I^2 R \tag{9.3}$$

where $I$ is the current *through* the resistor $R$. From conservation of energy, the input power should equal the total dissipated power.

**Notes:** There is *not* a separate analysis sheet for this experiment. Work together to draw the circuit diagram on your data sheet for each circuit as requested. When it is time to wire a circuit, divide your group into two and allow each group to wire one of the circuits (with your advice, of course). ***Be sure to have the wiring checked by your instructor.*** You will be provided with a data/analysis sheet for each circuit. Record all the required measurements and do all the required calculations on these sheets. You may use the back of each sheet, if needed.

# Procedure

Each data sheet for this experiment has a box near the top in which you will draw the circuit diagram and a two-row table at the bottom. Your measured results are recorded in the bottom row of the table and the results of your analysis will be written in the top row of the table. The large space at the middle of each sheet is for your analysis. You can use the back of each sheet if you need additional space for analysis, comments, and responding to questions. *Turn in one report for your group.*

1. Each of the resistors, $R_1$ through $R_4$, is *rated* at 10.0 watts. Switch the DMM to its ohmmeter function and measure the resistance of each resistor. Recall that the method for using the DMM is to adjust the scale to get three significant figures for each measurement. Record these values at the top of the first data sheet.

2. **Circuit 1. Series circuit.** In the box at the top of your data sheet, draw a circuit diagram showing how you would connect $R_1$, $R_2$, and $R_4$ in *series* to the power supply. Use a circle with an A in it to show where the ammeter should be placed to measure the circuit current. Use a battery symbol for the power supply and record its voltage to be 20.0 volts. *When finished, show the circuit diagram to your instructor for comments.*

   (a) Now, *using your circuit diagram as a guide*, use leads to wire your circuit. Include an ammeter to measure the circuit current. Switch the DMM to a DC Volts scale and connect it *across the power supply* to measure the circuit voltage. ***Let your instructor check your circuit before turning on the power!***

   (b) After getting the OK from your instructor, turn on the power and adjust the power supply voltage to 20.0 VDC. *DO NOT USE THE METER OF THE POWER SUPPLY TO SET THE VOLTAGE; USE THE DMM.* Record the power supply voltage in the data table. Then, read and record the circuit current. Since the same current must flow through each resistor, record this current as the current through each resistor.

   (c) Carefully remove the DMM from the power supply and use it to measure the voltage across each resistor. Recall: adjust the scale to obtain three significant figures for each measurement. Record your measurements in the data table.

3. **Circuit 2. Parallel circuit.** In the box at the top of your data sheet, draw a circuit diagram showing how you would connect $R_3$ and $R_4$ in *parallel* to the power supply. As above, use a circle with an A in it to show where the ammeter should be placed to measure circuit current. Use a battery symbol for the power supply and record its voltage to be 10.0 volts. *Also show, using dotted lines, where the ammeter should be placed to measure the current through each individual resistor. When finished, show the circuit diagram to your instructor for comments.*

   (a) Using your circuit diagram as a guide, wire the circuit including the ammeter. Adjust the DMM to a DC Volts scale and connect it *across the power supply* to measure the circuit voltage. ***Let your instructor check your circuit before turning on the power!***

(b) After getting the OK from your instructor, turn on the power and adjust the power supply voltage to 10.0 VDC. *DO NOT USE THE METER OF THE POWER SUPPLY TO SET THE VOLTAGE; USE THE DMM.* Record the power supply voltage in the data table. Then read and record the circuit current.

(c) Carefully remove the DMM from the power supply and use it to measure the voltage across each resistor. Adjust the scale setting to obtain three significant figures for each measurement. Record your measurements in the data table.

(d) *Without changing the voltage setting on the power supply*, turn off the circuit at the power supply, remove the ammeter, and re-connect it to read the current through $R_3$. *Have your instructor check the circuit before turning it back on.* Then turn on the power supply and read and record the current ($I_3$).

(e) Repeat procedure (d) for resistor $R_4$.

## Analysis — Circuit 1

1. As a group, work together to analyze the circuit. Show your work in the large space in the middle of the data sheet. Your analysis should include an expected value for the *equivalent resistance* of the circuit, the *circuit current*, the *current* through each resistor, and the *voltage* across each resistor. Record your results in the summary table at the bottom of the data sheet.

2. Using your *measured values* of currents and voltages, compute the *input power* to the circuit. Then compute the *dissipated power* absorbed by each resistor (also using the measured values for each resistance) and then determine the *total output power*. Do your results tend to verify the law of conservation of energy? Comment.

3. In part 2, it often occurs that the *output power* is a bit less than the *input power*. Is this to be expected? If yes, why? Comment.

## Analysis — Circuit 2

1. As a group, work together to analyze the circuit. Show your work in the large space in the middle of the data sheet. Your analysis should include an expected value for the *equivalent resistance* of the circuit, the *circuit current*, the *current* through each resistor, and the *voltage* across each resistor. Record your results in the summary table at the bottom of the data sheet.

2. Using your *measured values* of currents and voltages, compute the *input power* to the circuit. Then compute the *dissipated power* absorbed by each resistor (also using the measured values for each resistance) and then determine the *total output power*. Do your results tend to verify the law of conservation of energy? Comment.

3. In part 2, it often occurs that the *output power* is a bit less than the *input power*. Is this to be expected? If yes, why? Comment.

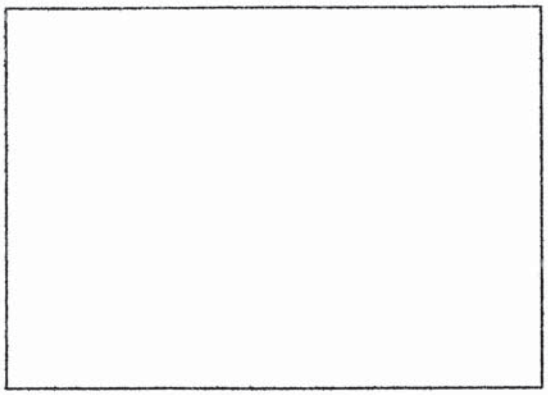
## Questions

1. For series circuit 1, compute the *maximum current* that can flow through each resistor. From these results, determine which resistor is in danger if the voltage becomes too large. Use this knowledge to determine the *maximum voltage* that can be applied to this series circuit. Show all your work.

2. For parallel circuit 2, compute the *maximum voltage* that can be connected across each resistor. From these results, determine which resistor is in danger if the voltage becomes too large. Use this knowledge to determine the *maximum voltage* that can be applied to this parallel circuit. Show all your work.

# DATA SHEET

**Series Circuit (circuit 1)** Date _____

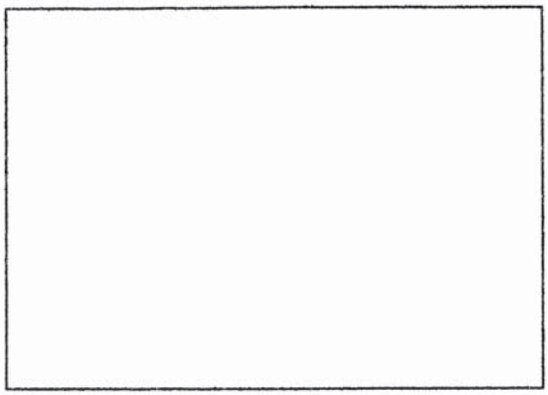


| | |
|---|---|
| $R_1$ = | $R_3$ = |
| $R_2$ = | $R_4$ = |

| | $\mathcal{E}$, volts | $I_c$, amps | $I_1$, amps | $I_2$, amps | $I_4$, amps | $V_1$, volts | $V_2$, volts | $V_4$, volts |
|---|---|---|---|---|---|---|---|---|
| analysis | 20.0 | | | | | | | |
| measured | 20.0 | | | | | | | |

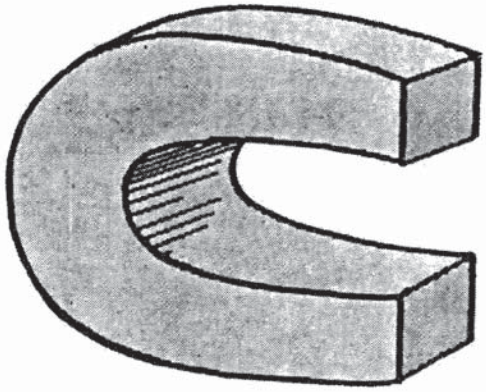
# DATA SHEET

**Parallel Circuit (circuit 2)** Date _____



| | $\epsilon$, volts | $I_c$, amps | $I_3$, amps | $I_4$, amps | $V_3$, volts | $V_4$, volts |
|---|---|---|---|---|---|---|
| analysis | 10.0 | | | | | |
| measured | 10.0 | | | | | |

# FIGURING PHYSICS



Compared to the huge force that attracts an iron tack to a strong magnet, the force that the tack exerts on the magnet is

a) relatively small

b) equally huge

Hewitt Drew it!

# Experiment 10

# Magnetic Field due to a Cow Magnet

**Objective:** To investigate the relationship between the magnitude of the magnetic field along the axis of a cow magnet and the distance from the center of the magnet.

**Method:** A Hall effect magnetic field sensor connected to a data acquisition system via a computer will be used to measure the magnitude of the magnetic field along the axis of a bar magnet. The relationship between field and distance will be investigated using regression analysis of the measured data.

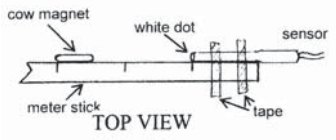
**Apparatus:**

| | | |
|---|---|---|
| Vernier magnetic field probe | cow magnet | masking tape |
| computer, LabPro with USB cable | meter stick | methyl alcohol |
| permanent marking pen | paper towel | |

**NOTES:** The Vernier magnetic field probe has a Hall effect sensor that produces a voltage proportional to the component of the magnetic field perpendicular to the white dot on the end of the sensor tip. The tip of the sensor can be rotated to measure magnetic fields either parallel or perpendicular to the long axis of the sensor. The switch on the sensor shaft is used to select the sensitivity range of the sensor. The 6.4 mT setting can measure fields from $-6.4$ mT to $+6.4$ mT with the positive readings occurring when the sensor points toward a *south pole*. Thus the sensor can detect both the *magnitude* and *direction* of a magnetic field.

## Setup and Preparation

The magnetic field sensor will be used at the 6.4 mT setting with the sensor lying flat on the tabletop. Tape a meter stick down on the tabletop. Since the magnet wants to slide in the range from 10 cm to 40 cm, you may wish to avoid tape in that region.




1. **The Sensor.** Connect the sensor to CH1 of the LabPro and check that it is switched to the 6.4 mT setting. Place the sensor flat on the table resting against the edge of the meter stick and tape the sensor in place so that its tip (the white dot) is *exactly* at 10.0 cm, as shown in the sketch at the right. Be sure that the long axis of the sensor is parallel to the meter stick. When lying in this manner, the sensor tip has the same height as the axis of the cow magnet.

2. **Load the Program.** On the desktop of the computer, double-click on *Tools for Scientific Thinking*, select the folder *Physics1020* and double-click on the progam **CowMagnet(1020)**.

(a) When the software appears, a Page Information box is displayed. Read the information in the box and click **OK**. The screen should show a graph of Magnetic Field vs. Distance with the $y$-axis from 0 to 6.0 mT and the $x$-axis from 0 to 0.30 meters. There is also a live meter readout showing the present magnetic field in mT and a table to store the measured distance and field data. There is a third column in the table, which computes $(1/r^3)$ to be used later.

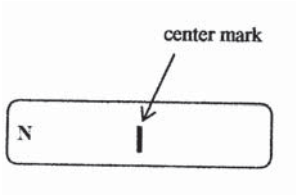
(b) Place the cow magnet next to the meter stick, using the edge of the meter stick as a guide to slide the magnet back and forth. Note the changes in the measured field as the magnet gets closer and farther from the sensor. Turn the magnet around and do the same thing with the other end. If the end pointed at the sensor a *north* pole, the reading will be negative and decrease to a minimum value of about $-5$ to $-8$ mT. If the end pointed at the sensor is a *south* pole, the reading will be positive and increase to a maximum value of about 5 mT to 8 mT. *Note that these maximum and minimum values can be somewhat different than the values described here because they depend on both the individual sensor, its zero setting, and the strength (magnetic dipole moment) of the cow magnet.*

(c) **Zero the sensor.** In addition to the field from the magnet, the sensor also detects a component of the Earth's magnetic field (about 50 $\mu$T or 0.050 mT) and whatever stray magnetic fields exist near your tabletop. This field must be zeroed out. *Remove all magnets to at least 2 meters from the sensor* and then click on the box labeled **Zero** at the top of the screen. After the sensor is zeroed, the field readings will be about zero.

3. **Prepare the Cow Magnet.** If the magnet already has markings on it, remove them using a paper towel slightly wetted with methyl alcohol.

(a) When the sensor is zeroed, its maximum and minimum readings will be different than before. To determine which pole you want to point toward the sensor, place the cow magnet next to the meter stick and slide it toward the sensor, noting at what approximate value the measured reading seems to "max out". This occurs because the sensor becomes saturated; i.e. it has almost reached the largest magnitude it can measure and the reading will hardly change even as the magnet is pushed closer to the sensor. Turn the magnet around and do the same with the other pole. Select the the south $(+)$ pole and mark this pole using the permanent marker. Also note the position where saturation seems to begin. All of your measurements must be made at positions greater than this saturation position.

(b) The distance between the magnet and the sensor is the distance from the *center of the poles* to the sensor. Since you usually don't know exactly where the two poles are in the magnet, assume that the center of the two poles is at the center of the magnet. Carefully determine the center of the magnet and use a permanent marker to mark a short line on the magnet at this position as shown in the sketch below.



## Procedure

Although the data is recorded by the computer, it is a good idea to record it also in a data sheet in case the computer program "crashes". Set up a data table of two columns and 10 rows with a column for distance in meters and a column for magnetic field in mT. Don't record the third column.

1. Before starting the measurements, record under your data sheet which pole you have selected to point toward the sensor. Then place the cow magnet with its selected pole facing the sensor and determine its position (i.e. the position of the center mark of the magnet) where the magnet shows about 5–6 mT. Back off from this position a bit for your first measurement so that you know that the magnet is beyond its saturation position.

2. As each data point is determined and recorded, it is automatically plotted on the graph. Plan to take readings of the magnetic field in a range from a maximum magnitude just below saturation to a minimum magnitude of about $|0.50|$ mT or even lower.

   (a) When you are ready to collect data, click on **Collect** at the top of the screen. This button will change to **Stop** and a new button, called **Keep**, will appear next to it. Note that the magnitude of the magnetic field reading is marked on the graph with a red dot. You can slightly adjust the magnet to an *exact position* if you want. When you are happy with the situation, click on **Keep**. This brings up a box where you enter the *distance* of the center of the magnet from the sensor. *Remember that the white dot of the sensor is at 10.0 cm and thus the distance is 10.0 cm less than the position of the magnet.* Note that the distance from the sensor is entered in units of *meters*. Click **OK** and the data is recorded and plotted. The **Keep** button returns and the computer is ready for the next data point.

   (b) Plan to take 8 to 10 readings. Note that the present field reading is always displayed as a light red point on the graph. This allows you to observe the relative vertical position of the next data point. Select the approximate position you want, then adjust the magnet to an *exact position* and click on **Keep**. Continue taking data for 8 to 10 readings. Space out the magntitudes of the readings so that you get 3 or 4 points in the tail of the graph.

   (c) *When you are finished collecting data, click on **Stop***. Do not close or otherwise disturb your computer results since the data collection program can also analyze the data. You don't have to use the computer to analyze your data, but the analysis goes very quickly and the computer makes the analysis easy to do. The alternative to computer analysis is to enter your data into a graphing calculator and use the calculator to do the analysis.

3. Note that data collection goes very fast which means that you can easily re-do the entire experiment if you want to. To repeat the experiment, click on **Data** on the **Menu Bar** and select **Clear All Data**.

   (a) If you are happy with your data, *record* the data on your data sheet.

   (b) Under your data table, draw and label a sketch of the resulting magnetic field vs. distance graph.

   **Theory:** As you look at the graph of your experimental results, you might try to guess the relationship between magnetic field **B** and distance. The shape is similar to an inverse square function of even a decreasing exponential function. If you recall that gravitational and electric fields vary as the inverse square of the distance from their sources and that the cow magnet is a *magnetic dipole* with a $(+)$ magnetic charge very near the position of a $(-)$ magnetic charge, you might guess that the field decreases with the distance as an inverse relationship with a higher power of distance than power 2. Such a guess would be correct. Consulting a physics text, you will find that the magnetic field of a magnetic dipole

varies inversely with the *cube* of the distance along the axis of the dipole. The exact relationship is given by

$$B_{\text{axis}} = Ar^{-3}, \qquad \text{where} \quad A = \frac{\mu_0 M}{2\pi} \tag{10.1}$$

where $r$ is the distance from the center of the magnet to a point on the axis of the magnet, $\mu_0 = 4\pi \times 10^{-7}$ T m $A^{-1}$, and $M$ is the magnetic dipole moment of the magnet. Thus, theory predicts that the relationship between $B$ along the axis of the magnet and the distance from the center of the magnet is a power law relationship with the power equal to $-3$. The magnetic moment of the magnet is a measure of the magnetic strength of the magnet. The MKS units of magnetic moment are *ampere-meter* (A m), which is equivalent to N m $T^{-1}$.

**Curve Fitting Procedures.** To be able to compare your experimental graph to the result predicted by fitting equation (10.1), you need to curve-fit your experimental data. You will do two curve fits of your experimental data: a *power law fit*, and a *linear fit* of transformed data. Fortunately, the data collection program has all the necessary regression tools to quickly do both regressions. The instructions below show how to analyze the data using the computer program. If you choose to use your calculator, then do both of these regression analyses on your calculator.

4. **Power Law Regression Analysis.** To fit your data to a power law, click on **Analyze** on the Menu bar; and from the drop-down menu, select **Curve Fit...**. From the list of equations, select the function *Power* of the form $A\,D^B$, where $D$ plays the role of the distance variable $r$ and the $B$ is the power of the best-fit power function. Click on **Try Fit** and then **OK**. A box appears with the function and the best-fit values.

   (a) Record your values for $A$ and $B$ with proper units (ignore all the plus/minus and RMSE error information). Then write the explicit function for your experimental data. The function box can be deleted by clicking on the small $X$ in its upper left corner.

   (b) Comment on how well the experimental power from the fit agrees with the predicted value of $-3$. Keep in mind that all experimental data will have some degree of measurement error.

5. **Linear Regression of Transformed Data.** Equation (10.1) can be transformed to a linear function by the transformation $z = 1/r^3$, which gives the transformed function $B_{\text{axis}} = Az$ where $A$ is a constant. This form of equation (10.1) is a linear function of slope $A$ and $y$-intercept equal to zero. If your transformed experimental data plots as a straight line, then you know immediately that there is good agreement between your data and theory. Since your program has already computed $1/r^3$, you can quickly check the shape and fit of the graph $B$ vs. $z$.

   (a) Click on the *label* of the horizontal axis of your plotted graph to get a box with choices for what data to display on the horizontal axis. Select *inverse* $r^3$. Since you changed the horizontal variable, you need to adjust the horizontal scale. Right click on the graph, select Graph Options and then Axes Options. Look at the values in the inverse $r^3$ column of the table to choose a good value for maximum $x$, perhaps 5000 or 6000.

   (b) Draw and label a sketch of your new graph. Comment on how well the transformed data plots as a straight line.

   (c) Do a linear fit of this data. Record the slope and $y$-intercept with proper units and write the explicit function for the transformed data.

6. Close the computer program *without saving* and turn OFF the computer.

## Analysis

1. In order to determine how well your experimental data agreed with the prediction of Equation (10.1), you subjected the data to a power law regression analysis and subjected transformed data to a linear regression analysis. In your opinion, which analysis offers the stronger conclusion that your data agrees with the theoretical prediction of Equation (10.1)? Explain why.

2. Each regression analysis gave you an experimental value for the coefficient $A$ in equation (10.1). Compare these two values. How well are they on agreement with each other?

3. Using either value of $A$ (or an average if you wish), use equation (10.1) to determine a value for $M$ (in units of A m), the magnetic moment of the cow magnet. (Remember to convert your recorded magnetic field data from mT to T so that $M$ will have the correct units.) Ask another group to give you their value for $M$ and compare your value to their value. Which group had the strongest magnet?

4. Recall from electricity that the magnitude of the electric field near a small charge varies as the square of the distance from the charge. Can you think of a reason why the magnitude of the magnetic field near a small magnet varies as the inverse cube of the distance from the magnet? Comment.

*Figuring Physics*

**CURRENT AND COMPASS**

If a current-carrying wire runs directly over a magnetic compass, the needle of the compass will

a) not be affected by the current
b) point in a direction perpendicular to the wire
c) point in a direction parallel to the wire
d) tend to point directly to the wire

## What Are Cow Magnets?

Cow magnets are popular with dairy farmers and veterinarians to help prevent hardware disease in cattle. While grazing, cows eat everything from grass and dirt to nails, staples and bits of bailing wire (referred to as *tramp iron*). Tramp iron tends to lodge in the honeycombed walls of the reticulum, threatening the surrounding vital organs and causing irritation and inflammation, known as *hardware disease*. The cow loses her appetite and decreases milk output (dairy cows), or her ability to gain weight (feeder stock). Cow magnets help prevent this disease by attracting stray metal from the folds and crevices of the rumen and reticulum. One magnet works for the life of the cow!

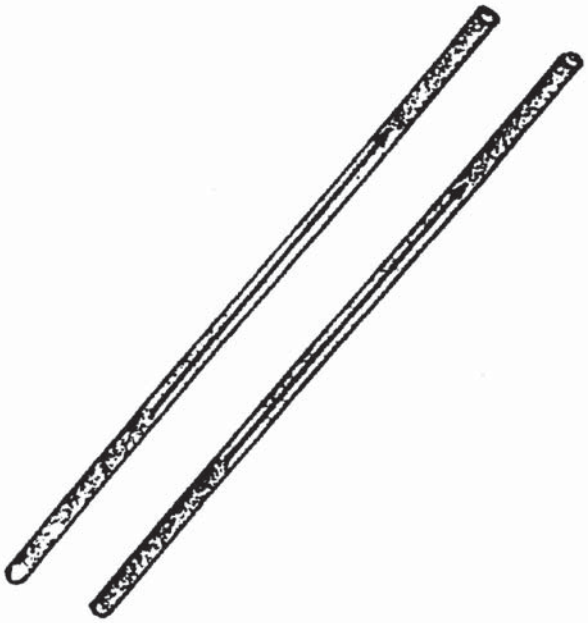
(From Master Magnetics Inc., `http://www.magnetsource.com/Solutions_Pages/cowmags.html`)

## FIGURING PHYSICS

### PINCH

When electric current in two parallel wires is flowing in the same direction, the wires tend to

a) repel each other
b) attract each other
c) exert no force on each other
d) twist at right angles to each other
e) spin



# Experiment 11

# Magnetic Field of the Earth

**Objective:** To obtain an estimate of the magnitude of the *horizontal component* of the Earth's magnetic field at Prince George's Community College.

**Method:** A circular coil of radius $R$ is used to set up a magnetic field perpendicular to the *horizontal component* of the Earth's field. A compass, placed at the center of the coil, is used to determine the direction of the resultant magnetic field. From the direction of the resultant field and the magnitude of the coil's field, and estimate of the magnitude of the horizontal component of the Earth's magnetic field is obtained.

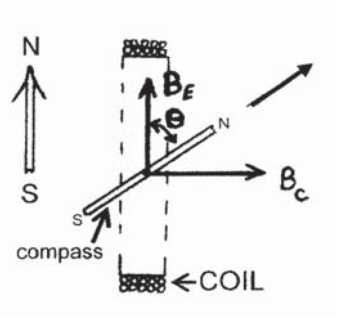
**Apparatus:**

| | | | |
|---|---|---|---|
| 10-turn circular coil | 5 ohm rheostat | black ammeter | compass |
| 0–22 VDC power supply | hookup wires | 4 spade lugs | |

**Theory:** The magnitude of the magnetic field $B_C$ at the *center* of a circular coil of radius $R$ that is carrying current $I$ is given by the expression

$$B_C = \frac{\mu_0 N I}{2R} \tag{11.1}$$

where $N$ is the number of turns of the coil, and $\mu_0 = 4\pi \times 10^{-7}$ T m A$^{-1}$. The direction of this field is perpendicular to the *plane* of the coil along its axis as shown in the diagram at the right. If a compass is placed at the center of the coil and the coil oriented so that its plane is in a north-south line as shown, when current flows in the coil, the compass will rotate through angle $\theta$ and come to an equilibrium position pointing along the direction of the *resultant* magnetic field. As can be seen in the diagram, the relationship between angle $\theta$ and the horizontal component of the Earth's magnetic field $B_E$ is given by the expression

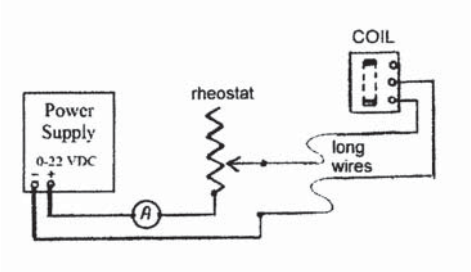



$$\tan\theta = \frac{B_C}{B_E} \tag{11.2}$$

where $B_C$ is given by equation (11.1).

## Procedure

1. Connect the 10-turn coil, rheostat, and ammeter to the power supply as shown in the diagram at the right. The purpose of the rheostat is to insert some resistance into the circuit since the resistance of the




coil is essentially zero. Use long wires and position the coil very far from the power supply and the rheostat. *Allow your instructor to check the circuit before you turn it on.*

2. Make up a data table with a column for angle $\theta$ in *degrees*, and two columns for coil current in *amps*. You will do *two* sets of measurements using the 10-turn coil: one set with forward current, and one set with the current direction reversed. Measure and record the diameter of the coil. Note that $2R$ in equation (11.1) is the diameter.

   (a) Place the compass on the table at the center of the coil and carefully orient the coil so that its plane is along a north-south line. The compass direction should be along the plane of the coil. Rotate the body of the compass until the compass points to 0°.

   (b) Turn on the power supply and increase the current until the compass rotates 10.0 degrees from its original position. Read and record the current. Continue to increase the current until you have measured and recorded the current at every 10.0 degree position between 20.0° to 70.0°.

   (c) Reverse the current through the coil (reverse the wires at the coil) and repeat the above measurements.

# Analysis

1. Set up an analysis table with columns for $\theta$ in degrees, forward current in A, $B_C$ in $\mu$T (microtesla), $B_E$ in $\mu$T, reverse current in A, $B_C$ in $\mu$T, and $B_E$ in $\mu$T.

2. Use equations (11.1) and (11.2) to carry out the analysis for $B_E$. Examine your results for $B_E$.

   (a) Comment on the amount of variability you observe in the results for each current direction. Does the variability in the results for each current direction show any pattern? Comment.

   (b) Do your results show any systematic difference between forward and reverse currents? If so, can you explain why?

3. Use your results to determine an average value for $B_E$. If you wish to exclude some values from your average, note what values were excluded and why.

4. The magnitude of the horizontal component of the Earth's magnetic field in the Washington DC area has been measured to be 18.4 $\mu$T. Compare your value to this expected value.

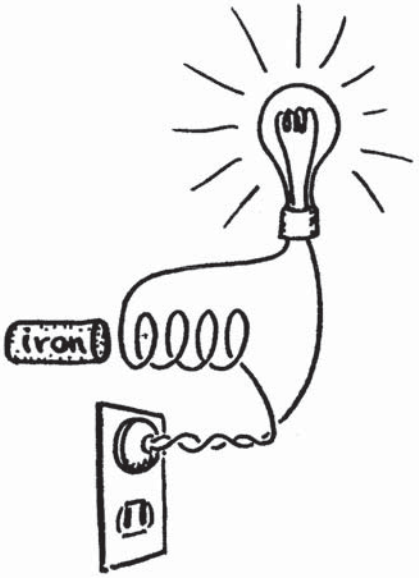
## FIGURING PHYSICS

### SHOVE IT IN

A light bulb is connected by a thick wire to an AC source as shown in the sketch.

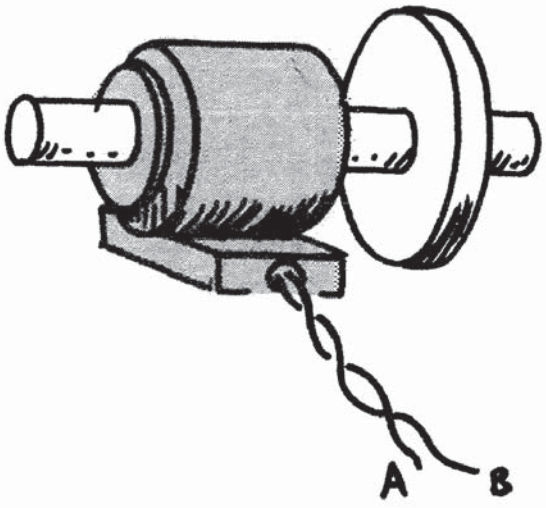
After a piece of iron is shoved into the coil of wire, the light

a) brightens
b) dims
c) is not affected



# REVERSIBLE MOTOR?

A direct current motor turns clockwise when wire A is connected to the plus (+) and B to the minus (−) side of a battery (the motor contains no permanent magnets). Now if we interchange A and B so that B is plus and A is minus, then



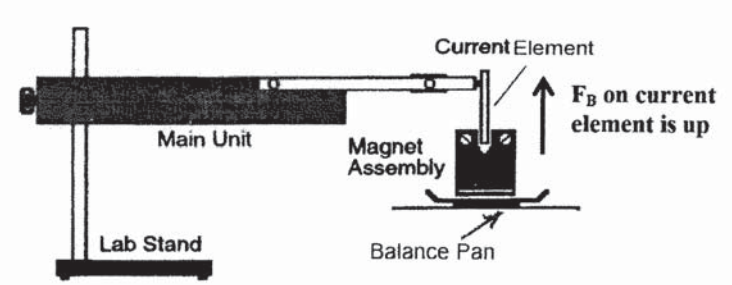

a) the motor will turn anticlockwise
b) the motor will continue to turn clockwise

# Experiment 12

# Magnetic Force on a Current Element

**Objective:** To investigate the relationship between the magnitude of the magnetic force on a current element and the electric current flowing through the current element.

**Method:** A special apparatus, designed to hold a current element in the magnetic field of a permanent magnet is shown in the diagram at the right. The current element is on a card that plugs into the end of the Main Unit as shown.




A permanent magnet, called the Magnet Assembly, is the source of the magnetic field that pushes on the current element. The Magnet Assembly is placed on the pan of a balance. The direction of the current that flows through the current element is chosen so that the magnetic force *on the current element is directed upward*. This causes an equal but opposite force, acting down on the Magnet Assembly, which, in turn, pushes down on the balance pan. Thus, the *total force* acting on the balance pan is equal to the weight of the Magnetic Assembly plus the magnetic force. This *total force* will be measured as a function of the current through the current element in the range of 0 amperes to 5 amperes and a plot of total force vs. current will be obtained. The relationship between total force and current will be investigated using a linear regression analysis of the data.

**Apparatus:**

| | | |
|---|---|---|
| Current Balance Main Unit | Two current elements, #37 and #38 | Pasco Ammeter |
| Magnetic Assembly | Beam balance, sensitive to 0.01 g | 3 long wires |
| 0–22 VDC Power Supply | Al lab stand | |

**Theory:** Two forces act downward on the balance pan, the constant weight of the Magnet Assembly and the reaction force to the upward magnetic force. When the current is zero, let $F_0$ be the weight of the Magnetic Assembly. When electric current flows through the current element, the downward reaction force on the balance pan is equal in magnitude to the upward magnetic force on the current element which is given by the expression $F_B = ILB$, where $I$ is the current throught the current element, $L$ is the length of the current element, and $B$ is the magnetic field due to the Magnet Assembly. Combining the two forces yields the

following formula for the total downward force $F$ acting on the balance pan

$$F = F_0 + ILB = F_0 + (LB)I. \tag{12.1}$$

This formula predicts that the total force is a linear function of the current-element current with slope $LB$ and $y$-intercept $F_0$.

# Procedure

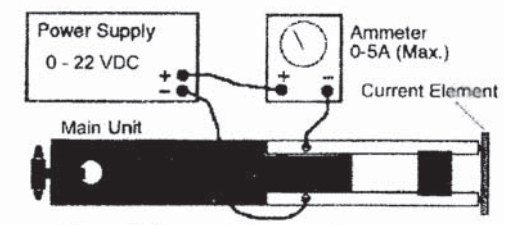
Good results in this experiment require *careful alignment* of the apparatus and *precise measurements* using the balance. Because the magnetic force is very small, to achieve meaningful results, the balance must be read to at least 0.01 g, which means at least 5 significant figures. The dial balance just achieves this precision while the beam balance can be read to 6 significant figures. Since a balance reads mass in grams, you must convert the measured mass to force using the expression $F = mg$, where $g = 9.80052$ m/s$^2$ to 6 significant figures. With mass measured and recorded in grams, force will have units of millinewtons (mN).

1. Measure and record the length of each of the current elements (#37 and #38). The length of the horizontal current element on each card is the distance between the centers of the vertical foil conductors that carry current into and out of the current element.

2. **Setup.** Mount the Main Unit on the lab stand so that its arms swing upward. Select one of the current elements (#37 or #38) and plug it into the end of the Main Unit. Ask your instructor for help if there seems to be a danger of breaking the card as you try to plug it into the Main Unit.

   (a) Place the Magnet Assembly (the permanent magnet) on the center of the balance pan of the balance. Then carefully adjust the height of the Main Unit so that when the balance is in equilibrium, the *current element is positioned at the center of the poles* of the Magnet Assembly.

   (b) The red side of the Magnet Assembly is the north pole of the magnet. Connect the power supply and ammeter to the Main Unit as shown in the diagram at the right so that the magnetic force *on the current element* will be directed vertically *upward*.



Top View of the Main Unit

   (c) *Critical adjustment*. Carefully adjust the current element so that it is in the center of the pole region of the permanent magnet and is parallel to the pole faces. The current element should not touch the magnet and the balance pan and balance indicator should be free to move up and down.

3. **Measurements.**

   (a) Set up two data tables (or a combined table) of six rows with columns for current in amperes, balance reading in g, and net force in mN. Identify each table by the current element number (#37 or #38) associated with the data.

(b) With current at 0.00, carefully balance the scale and record its mass measurement in your data table. Determine the force associated with this mass and record. Note that if you set currents to an exact value, they will have 3 significant figures and that your forces will have either 5 or 6 significant figures.

(c) Turn on the power supply and set the current to exactly 1.00 A. Record the current, balance the scale, and record the measured mass. Again determine the force associated with this mass and record. Repeat for currents of 2.00, 3.00, 4.00, and 4.50 A. Turn the current to zero and turn off the power supply.

(d) Slide the current element out of the Magnet Assembly, remove it from the Main Unit, and plug in the other current element. Again if you feel that there is some danger in breaking the card holding the current element, ask your instructor for assistance. Slide the new current element into the Magnet Assembly, make the adjustments described above and repeat the above measurements for this current element.

## Analysis

1. Enter your first set of data into a graphing calculator or computer and make a plot of force vs. current.

   (a) Draw and label a sketch of the graph you observe on your calculator/computer. Do the data plot as expected? Comment.

   (b) Do a linear regression on your data and report the slope and $y$-intercept with proper units (and pay attention to significant figures) and then write the explicit function.

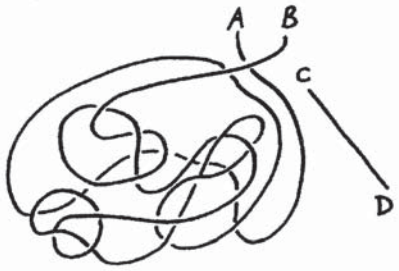
   (c) Use the slope of your function to determine an experimental value $B$, the magnetic field of the Magnet Assembly.

2. Repeat the above for the second data set.

3. You determined an experimental value for the magnetic field of the Magnet Assembly from each of your data sets. Compare the two experimental values and comment on how well they agree or disagree with one another. Can you think of a reason or reasons why the two experimental values of $B$ might disagree even though the same permanent magnet was used in both trials? Comment.

4. What is the best answer to the *Figuring Physics* question below? Explain.

## Figuring Physics




The sketch at the left shows a long wire running from A to B that is all tangled into a "rats nest". If a current flows from A to B, it produces a complex magnetic field at the position of the current element CD. Also, if a current flows from C to D, there will be a force on element CD. Now suppose that the direction of each current is reversed so that now current flows from B to A in the "rats nest" and from D to C in the element. The force on the current element will

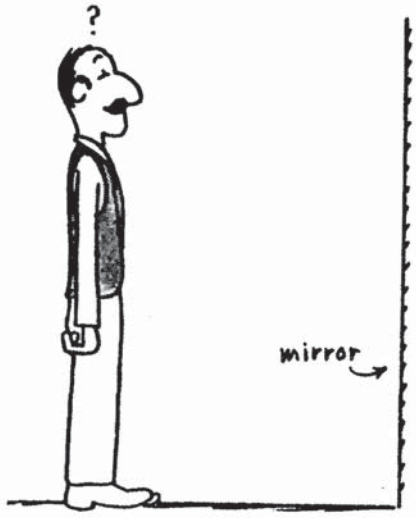
a) also be reversed.
b) be as it was before the current was reversed.
c) vanish.
d) be in a direction perpendicular to the way it was before the current was reversed.
e) be in a direction not mentioned above.

## FIGURING PHYSICS

### PLANE MIRROR

What must be the minimum length of a plane mirror in order for you to see a full view of yourself?

a) One-quarter your height
b) One-half your height
c) Three-quarters your height
d) Your full height
e) The answer depends on your distance.




Hewitt Drew it!

# Experiment 13

# Ray Tracing — Reflection and Refraction

**Objective:** To observe the reflection and refracton of light rays by mirrors and transparent optical shapes and to draw the paths of selected rays using the ray-tracing techinque described below.

**Method:** A light box will be used to produce light rays that will be directed toward various optical shapes. The behavior of the rays can be observed and the rays can be marked with a pencil and then drawn to show their path.

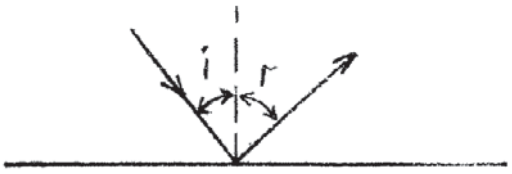
**Apparatus:** Light Box Power Supply, Light Box, Ray Slits, cm ruler, wood block, Front surface plane mirror, Optical shapes, Protractor, White paper, masking tape

**NOTES:** The light box will get hot. Use care when touching it. This experiment does not have a separate analysis section. All your pages will be data/observation pages. Do each procedure on a *different sheet* of paper. There are 5 procedures which will require 5 sheets of paper. *Read each procedure carefully before starting so that you can plan ahead and include all the drawing, calculations, and comments on the one paper.* If your calculations and comments require more room, use the back of the sheet. Let each person in your group be in charge of at least one procedure. You will submit one report for your group.

**Ray Tracing Technique.** Finding the paths followed by light rays as they reflect and refract at optical surfaces is called *ray tracing*. When asked to draw a ray, use the old maxim "*two points determine a straight line*". To draw the path of a light ray, mark a small dot at the center of the ray at a point near the optical surface and mark a small dot at the center of the ray at a point farther away. Then use the two points and a *straight edge* to draw the ray.

**Theory:** When a ray of light strikes a shiny smooth surface, it reflects as illustrated at the right. The law of reflection states that the angle of incidence $i$ is equal to the angle of refraction $r$, or

$$i = r. \tag{13.1}$$

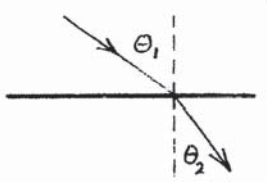



Both angles are measured with respect to the *normal to the surface*. When a light ray hits the surface of a transparent material, part of the ray will reflect, but most of the ray will refract as illustrated at the right. The

law of refraction, often called Snell's law, is given by the expression

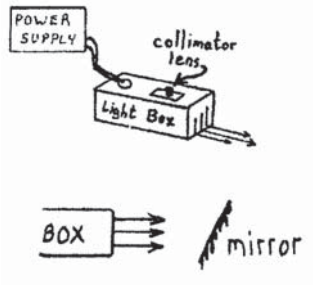
$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{13.2}$$

where $n_1$ is the *index of refraction* of the incident material, $n_2$ is the *index of refraction* of the refracting material, and angles $\theta_1$ and $\theta_2$ are the angles of incidence and refraction, respectively. Reflection and refraction of light rays by optical surfaces (mirrors, prisms, lenses, etc.) is used to control the path of light as it travels from objects to images.




# Procedure 1

**Observation and Measurements with a Plane Mirror.** Use a *front surface* mirror for this procedure. Tape the mirror to a wood block for support. Connect the power supply to the light box as shown in the sketch at the right. Insert the three-ray plastic slit pattern into the slot on the ray box and adjust the collimating lens to obtain three parallel rays. *Plan ahead* so that you can place your ray-tracing drawing on the paper without part of the drawing falling off the paper.




1. Project the rays toward the mirror as shown at the right and then rotate the mirror and observe the reflection of the rays.

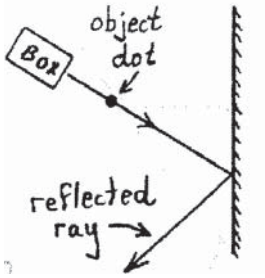
   (a) Orient the mirror so that the rays hit the mirror and bounce back on themselves. Then rotate the mirror until the reflected rays make a right angle at the mirror. *Through what approximate angle did you rotate the mirror in order to make the light rays reflect 90°?*

   (b) Insert the single-ray plastic slit pattern into the slot on the ray box. Then place the mirror near the left edge of the paper and direct the light ray so that light rays reflect through a total angle of less than 90° (i.e. $i + r < 90°$). Carefully mark the path of the incident ray and the reflected ray. Then carefully trace the position of the surface of the mirror. Remove the mirror and use a straightedge to draw the incident ray and the reflected ray. mark the rays with arrows so that their direction is specified. Use a protractor to measure the angle between the *incoming ray and the mirror's surface* and the angle between the *reflected ray and the mirror's surface*. Record the angles on your diagram. Then use these angles to determine the angle of incidence and the angle of reflection, and write the results under your diagram. *Comment on how well these results support the law of reflecton.*

2. Move the front surface plane mirror to the right half of your paper, placing it near the *center of that side* so that you have about equal areas in front and behind the mirror. Mark a small solid dot on the paper about 3 to 4 cm in front of the center of the mirror. This dot will serve as an *object point* for the mirror. Label it **O**.

   (a) Look into the mirror and view the *image* of the object point. *As you view the image of the object, does the image appear to be in front of the mirror's surface, on the mirror's surface, or behind the mirror's surface? Comment, stating how you determined your answer.*

   (b) Carefully trace the surface of the mirror on the paper. Then send a ray *through the object point* toward the mirror as shown. This ray acts as if it were an *object ray* that leaves the object and is reflected from the mirror. *Mark and draw the reflected ray.* Repeat this process of marking the reflected rays for four other rays from the object, using rays that hit the mirror on both sides of the direct line between object and mirror.




   (c) Remove the mirror and carefully draw all five *reflected rays from the mirror* using solid lines. Then carefully extend each line back into and behind the mirror using *dotted lines*. These dotted lines show the paths of the rays as perceived by an eye that looks into the mirror. *Comment on whether or not the dotted lines appear to come from a single point behind the surface of the mirror.*

   (d) The single point (or almost single point) from which the reflected rays emerge from the mirror is called the *image point* of the object point. Label this point **I** for image point. Then join the image point and object point by a straight line and measure the distance between the object point and the mirror. This is the *object distance*. Then measure the distance between the image point and the mirror. This is the *image distance*. Record both distances. *Is the image distance approximately equal to the object distance?* Comment.

## Procedure 2

**Focal Length of a Concave Mirror.** Select the concave mirror with the *smaller* radius (i.e. the greater amount of curvature) and direct three parallel rays into the center of the *concave* surface. Notice that the reflected rays intersect at a point. This point is the **focal point** of the concave mirror.

1. Trace the reflecting surface of the mirror on the paper and mark the *incident* and *reflected* rays. Remove the mirror and draw the incident and reflected rays. Measure and record the distance along the axis between the focal point and the mirror. This is the **focal length** of the mirror.

2. Since the mirror is essentially a hemisphere, estimate and record its diameter. Determine and record its radius of curvature. In theory, the focal length of a circular mirror is ½ its radius of curvature. Comment on how well your measurement of focal length agrees with theory.

# Procedure 3

**Image Position for a Concave Mirror.**

1. Place the concave mirror near the center of your paper and trace the reflecting surface of the mirror. Place a dot along the axis of the mirror about 8 cm in front of the mirror and imagine this dot to be an *object point*. Label it as **O**. Then direct a light ray through this point toward the mirror and *mark the reflected ray*. Repeat for two other rays, but keep the rays fairly near the axis of the mirror (i.e. paraxial rays).

2. Draw all three reflected rays and note where they meet. This is the *image point* of the object point. Label it as **I**. *Is this image behind the mirror, on the mirror, or in front of the mirror? Comment.*

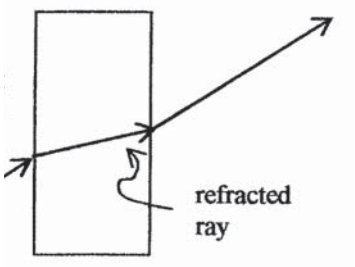
3. Measure and record the distance of the object **O** from the mirror (along the axis of the mirror) and do the same thing for the image **I**. Theory predicts that

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

where $d_o$ is the object distance, $d_i$ is the image distance, and $f$ is the focal length. Use your measured image and object distances in this expression to obtain a value for the focal length of the mirror. Compare this value to the focal length measureed above. *Comment on how well the two values agree or disagree.*

# Procedure 4.

**Refraction at the the Surface of a Transparent Rectangular Block.** Send a single ray at an angle toward one face of the rectangular block as shown and adjust the angle of incidence to be greater than 45°.



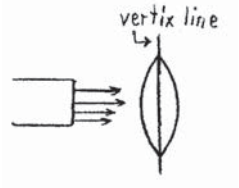

1. Trace the perimeter of the block and mark the incoming and outgoing rays. Remove the block and draw the incoming and outgoing rays. Then draw the *refracted* ray that passed through the block. Use a protractor to measure the angle between the *incident ray and the face of the block* and the angle between the *refracted ray (inside the block) and the face of the block.* Record these angles on your diagram.

2. Use these angles to determine the angle of incidence and the angle of refraction for the ray and write their values under your diagram. Use equation (13.2) to obtain a value for the index of refraction of the block.

# Procedure 5

**Refraction by Lenses.** You should be able to do both of the ray diagrams below on the same paper. Plan carefully.

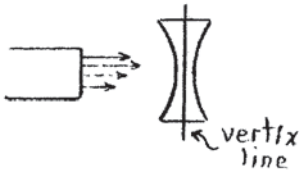
1. Converging Lens. Place the *thin* converging lens on the top half of a sheet of paper and send three parallel rays along its axis as shown. The parallel rays represent rays from an object at infinity. The point of convergence of these three rays is called the **focal point** of the lens.




   (a) Trace the outline of the lens, mark the incoming and outgoing rays, remove the lens, and draw the rays. Draw the vertex line. Mark the focal point as **F**.

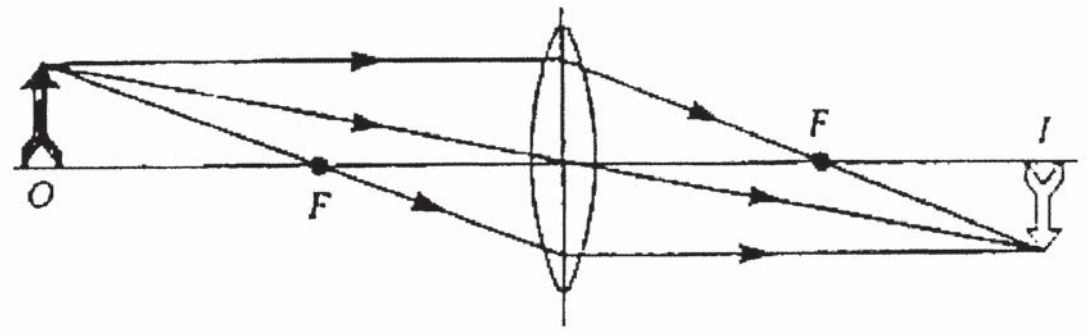
   (b) Measure and record the distance from the vertex line to the focal point. This distance is the **focal length** of the lens.

2. Diverging lens. Place the diverging lens on the lower half of a sheet of paper and send three parallel rays along the axis of the lens as shown. Notice that the refracted rays seem to diverge from a point in front of the lens (a virtual image point). this point is the **focal point** of the diverging lens.




   (a) Trace the outline of the lens, mark the incoming and outgoing rays, remove the lens, and draw the rays. Draw the vertex line. Mark the focal point as $F$.

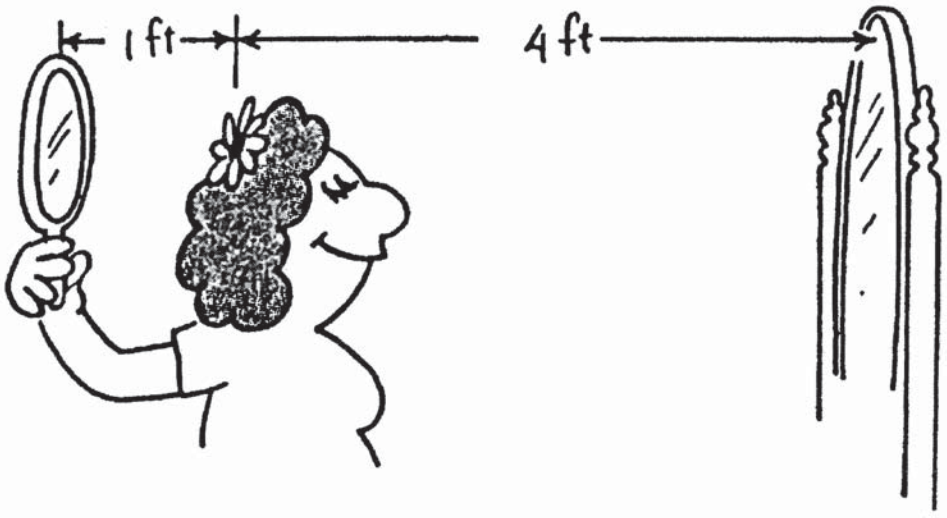
   (b) Measure and record the distance from the vertex line to the focal point. This distance is the **focal length** of the lens (note that this distance is negative).



# Figuring Physics

## MIRROR IMAGE

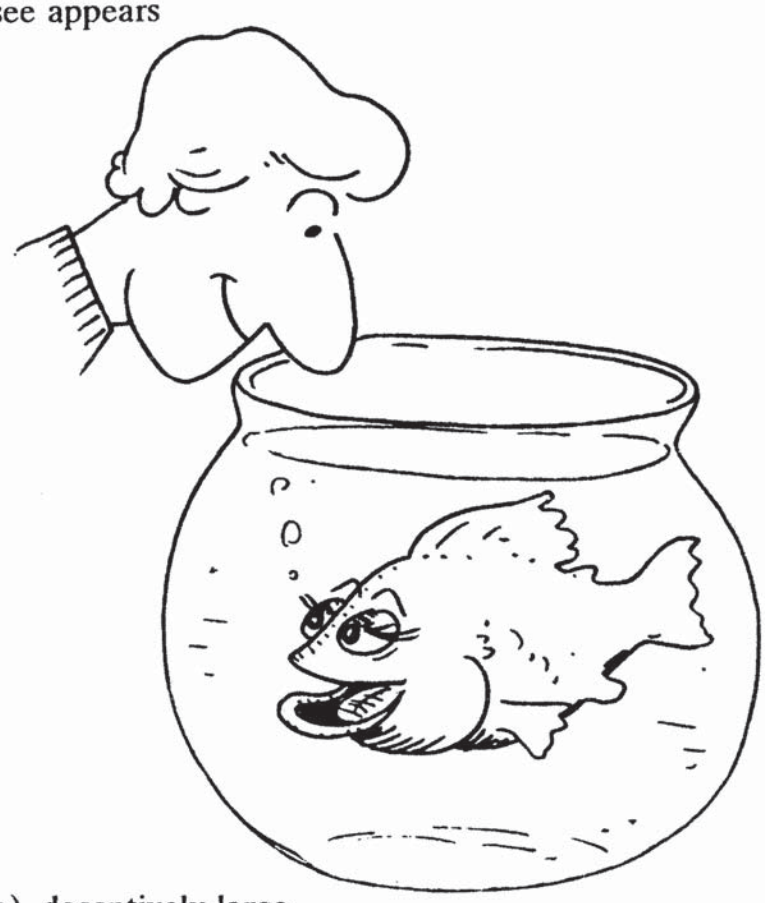
A lovely lady holds a hand mirror one foot behind her head while standing 4 feet from a dresser mirror as shown. How far in back of the dresser mirror is the image of the flower in her hair?



## FIGURING PHYSICS

### HOW BIG?

When you look down into a fishbowl, the fish you see appears



a) deceptively large
b) deceptively small
c) the size it would appear if there were no water

# Experiment 14

# Geometrical Optics

**Objective:** To observe images formed by a mirror and a lens and to determine the focal length of the mirror and the lens. You will also observe a real image formed by the mirror.

**Method:** A lighted object, mounted on an optical bench, will be used to send light toward an optical surface (a mirror or a lens). The real image formed by the optical surface will be focused onto a screen. Th object position and image position, easily read from a meter scale on the optical bench, will be recorded and used to compute object distance and image distance. The focal length of the mirror or lens will be computed using your measured distances and the mirror/lens formula.

**Apparatus:**

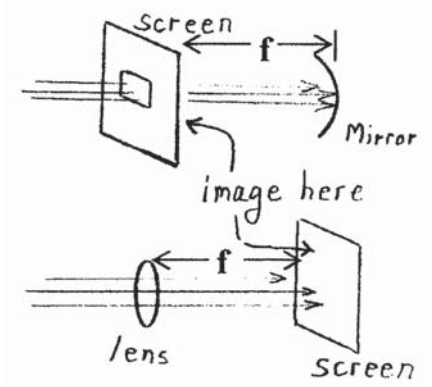
| | | | |
|---|---|---|---|
| Optical bench | Lens holder | Concave mirror | Night light |
| Lighted object | Screens and holder | Lens (+15 cm) | |
| cm ruler | Meter stick | level | |

**Note:** When you mount the components on the bench, be sure that they all have the same horizontal axis. The axis of each component must have the *same height* above the bench. There is not a separate analysis section for this experiment. Set up an Observation/Data sheet (or sheets) and record all observations, measurements, and calculations on the observation sheets as requested. Work together on this experiment and submit a single report from your group.

**Theory:**

## Procedure 1

**Quick Determination of Focal Length.** *The optical bench is not needed for this part of the experiment.* With the room lights OFF, the shade of an outside window will be opened so that the bright window can be used as an object. The object distance from window to lens or mirror is practically infinitely when you stand far from the window and the image of the bright window will occur in the focal plane of the mirror or lens. By focusing the image of the window on a portable screen as shown below, a quick estimate of the focal length (distance from screen to optical surface) can be measured.




1. Standing far from the window, hold the mirror by hand and focus the image of the window onto the screen as shown in the diagram at the right. Use the screen with the hole so that the rays from the window can reach the mirror and reflect back onto the screen to form the image.

2. While holding the mirror and screen steady with the image focused sharply onto the screen, let your partners use a meter stick to make an *approximate measurement* of the focal length. Record the result.

3. Place the $+15$ cm lens in a lens holder and repeat the above procedure to determine the focal length of the lens. Record your result.

   **Theory:** The lens/mirror equation is expressed as

   $$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

   where $d_o$ is the object distance, $d_i$ is the image distance, and $f$ is the focal length of the lens or mirror. If $d_o$ and $d_i$ are measured, the focal length can be computed from this equation. The *expected* magnification $M$ of the mirror or lens is given by the expression $M = -d_i/d_o$. The *experimental* magnification of either surface is determined by the ratio $M = h_i/h_o$ where both $h_i$ and $h_o$ obey the sign convention rules for geometrci optics.

## Procedure 2

**Image Formation by a Concave Mirror.** The optical bench is used in this part of the experiment. Place the bench on your table with the metric scale going from left to right with the left end (the 0.0 cm end) close to an electric outlet. Use the level to level the bench. Good experimental practice requires that you record the *positions* of the optical components on your data sheet and later use these positions to compute the object and image *distances*.

1. Set Up. Mount the concave mirror at $x = 100.0$ cm at the right end of the optical benc and mount the lighted object at approximately 15 cm. The rays from the lighted object will travel to your right toward the mirror, reflect from the mirror, and then travel to your left. Place the screen with the hole in front of the mirror and move it to obtain a sharp image (on the mirror side) of the lighted object.

2. Investigate Image Position and Image Height. To observe how the *image position* and *image height* change as a distant object is moved closer to the mirror, smoothly move the object closer and closer to the mirror. As you do so, move the screen to maintain a sharp image of the object. *You can do this quickly by holding the screen in your hand.* Also note how the size of the image changes. At some point, the image will move behind the object and you will have to move the screen to a position behind

the object. Continue until the image position is near $x = 0$ cm. Comment on the orientation (upright or inverted) of the image.

(a) Record your observations of how the *image position* changes as the object moves from a distant point toward the mirror. Also record how the *image size* changes as the object moves from a distant point toward the mirror.

(b) *When the image was about the same height as the object, how did the approximate image distance compare to the approximate object distance?*

3. Real Image. The mirror provides an excellent opportunity to view a *real image*. Place the lighted object near the position where the image and object are about the same size. (You cannot exactly obtain this position because the two mounts collide with each other.) Obtain a good image on the screen and then go behind the screen and place your eye about 2 to 3 meters *behind the screen on the axis*, looking toward the *back* of the screen along the path that the rays take to form the image. While in this position, have a partner remove the screen so you can view directly the real image that had been focused on the screen. Examine this real image (you may try to touch it). *Comment on how this image differs from images that you see in plane mirrors.*

4. Focal Length. Set up a data table of two rows with columns for *object position* in cm, *image position* in cm, *image height* in cm, and *experimental magnification* ($h_i / h_o$). Measure the object height $h_o$ (to the nearest 0.1 cm) and record this height and the mirror position above your data table.

(a) Move the object to a position where the image height is *smaller* than the object height. Record the object position, image position, and image height (recall that $h_i$ is negative if inverted). Compute and record a value for experimental magnification.

(b) Move the object to a position that results in an image *height larger* than the object height and repeat the above measurements.

(c) Using your data, compute the object distance and image distance for the first trial. Show the computation and results under your table. Use these distances to determine an experimental value for the focal length of the mirror. Then determine a value for the expected magnification from the image and object distances.

(d) Repeat the above computations for the second trial.

(e) Comment on how well your two experimental results for focal length agree with each other. How well do your experimental results agree with the quick result for focal length? Comment on how well your experimental magnifications agree with your expected magnifications.

# Procedure 3

**Image Formation by a Converging Lens.** Carefully place the lens in the lens holder and mount it at $x = 50.0$ cm and mount the lighted object at the left end of the bench at approximately $x = 0$ cm. The rays from the lighted object will travel to your right toward the lens, refract through the lens, and continue to travel to your right. Place the screen just behind the lens and move it until you obtain a sharp image of the lighted object.

1. Investigate Image Position and Image Height. To observe how the *image position* and *image height* change as a distant object is moved closer to the lens, smoothly move the object closer and closer to the lens. As you do so, move the screen and maintain a sharp image of the object on the screen. At some point, the image will be about the same height as the object. Continue until the image position is near $x = 100$ cm. Comment on the orientation (upright or inverted) of the image.

(a) Record your observations of how the *image position* changes as the object moves from a distant point toward the lens. Also record how the *image size* changes as the distant object moves toward the lens.

(b) *When the image was about the same height as the object, how did the approximate image distance compare to the approximate object distance?*

2. Focal Length. Set up a data table of two rows with columns for *object position* in cm, *image position* in cm, *image height* in cm, and *experimental magnification* ($h_i / h_o$). Record the object height and lens position above your table.

(a) Move the object to a position where the image height is *smaller* than the object height. Record the object position, image position, and image height. Compute and record a value for experimental magnification.

(b) Move the object to a position where the image height is *larger* than the object height and repeat the above measurements.

(c) Using your data, compute the object distance and image distance for the first trial. Show the computations and results under your table. Use these distances to find an experimental value for the focal length of the lens. Then determine a value for the expected magnification from the image and object distances.

(d) Repeat the above computations for the second trial.

(e) Comment on how well your two experimental results for focal length agree with each other. How well do your experimental results agree with the quick result for focal length? Comment on how well your experimental magnifications agree with your expected magnifications.

3. Consider the *Figuring Physics* question on page 87. What is the best answer? Explain.

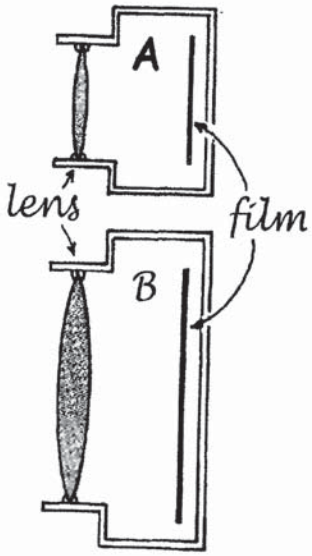
4. Consider the *Figuring Physics* question on page 88. What is the best answer? Explain.

# Figuring Physics

## BIG CAMERA

Both cameras shown at the right are the same in every way except for the diameter of the lenses. If they are used to photograph a distant object, which camera produced the biggest image of the object?

a) Camera A.
b) Camera B.
c) Both cameras produce the same size image.



# Figuring Physics

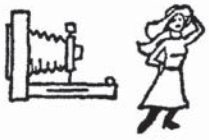
## CLOSE-UP

The first sketch shows a camera properly focused on the DISTANT MOUNTAINS. When the camera is re-focused on a very NEAR subject it will be set as shown in

a) the second sketch
b) the third sketch
c) the fourth sketch

a)

b)



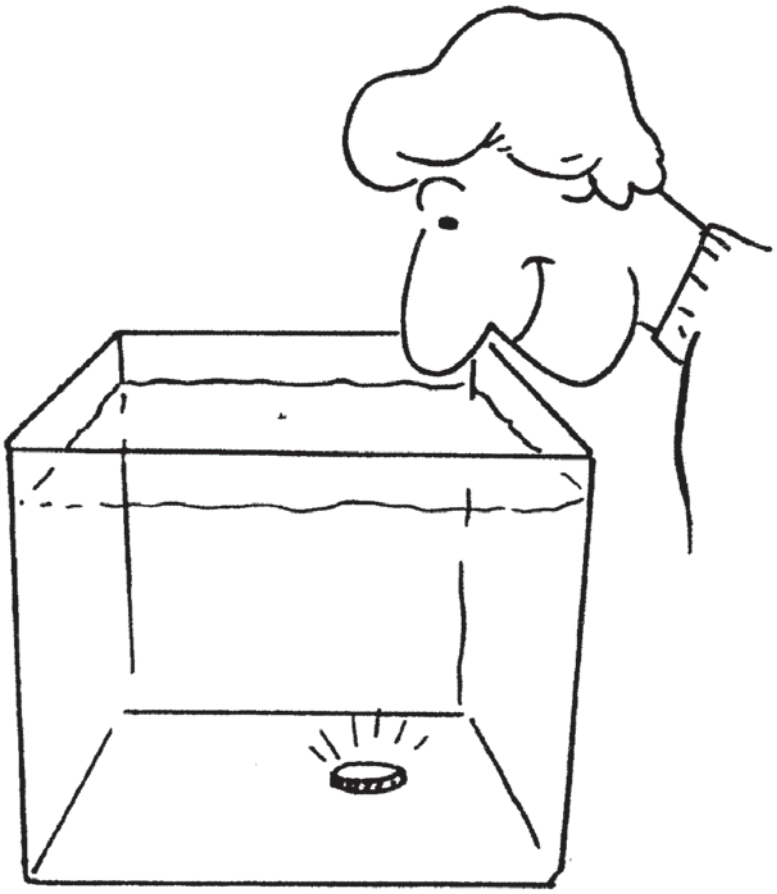
c)

FIGURING PHYSICS

## I COULD ALMOST TOUCH IT

A coin is under water. It appears to be

a) nearer the surface than it really is
b) farther from the surface than it really is
c) as deep as it really is



# Experiment 15

# Wave Properties of Light

**Objective:** To observe and investigate the properties of diffraction patterns due to single slits and interference patterns due to double slits and gratings.

**Method:** Coherent light from a helium-neon laser will be used to produce diffraction and interference patterns from a number of slit patterns and several gratings. The results from measurements will be compared to the expected theoretical predictions.

**Apparatus:**

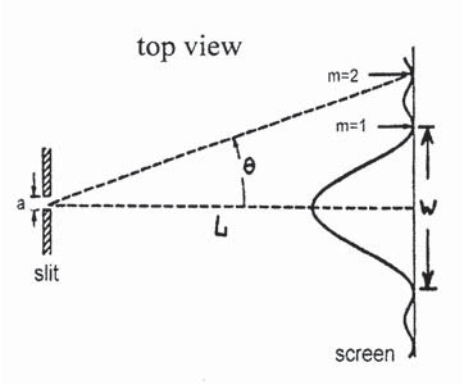
| | | |
|---|---|---|
| helium-neon laser | laser slide set* | masking tape |
| magnetic optical bench | meter stick | metric tape |
| white paper screen | component holders | night light |

*See page 96 for a list of the contents in the *laser slide set* and the dimensions of the various slit patterns and gratings.

**Comment:** Before the invention of the laser, it was very difficult to study the wave properties of light because existing sources of *coherent monochromatic* light were of very low intensity. Diffraction and interference patterns had to be captured on photographic film using long exposures. *The laser is a very intense source of coherent monochromatic light*. Diffraction and interference patterns are easily observed on a paper screen in a darkened room. The laser used in this experiment is a 0.5 milliwatt helium-neon (He-Ne) laser, operating at 632.8 nm.

**Please Note:** *Direct light from a laser is very dangerous to your eyes.* **Never look directly into the laser beam or its reflection from a shiny surface.** While working with the laser, keep it pointed away from other groups. The slit patterns used in this experiment are fabricated from metal foils and can produce intense reflections. Be careful while working with the slit patterns. There is not a separate analysis section for this experiment. Set up an Observation/Data sheet (or sheets) and record all observations, measurements, and calculations on the observation sheets as required.

**Theory — Diffraction.** Diffraction is the bending of light around an edge. A common way to show diffraction is to allow coherent monochromatic light to illuminate a narrow aperture or slit, as illustrated in the diagram at the right. Shown as a *top view*, the light bends around the two edges of the slit and produces a characteristic interferenceparterne on the distant screen called a *diffraction pattern*.




The single slit diffraction pattern consists of a broad central region (the *central diffraction maximum*) at the center of the screen with a set of alternating bright and dark regions on either side of the central region. These alternating bright and dark regions are called *diffraction maxima and diffraction minima*. If a slit of width $a$ is illuminated with light of wavelength $\lambda$, then the *angular position* $\theta$ of the $m^{\text{th}}$ *dark diffraction minimum* is given by the expression

$$a \sin \theta_m = m\lambda \tag{15.1}$$

where $m$ is a positive integer, $m = 1, 2, 3, \ldots$. The width $w$ of the central diffraction pattern on the screen, from the *center* of the 1st minimum on one side to the *center* of the 1st minimum on the other side is given by the expression

$$w = 2L \tan \theta \tag{15.2}$$

where $L$ is the distance from the slit to the screen.

# Procedure 1 — Diffraction

Set up a white screen about 1.5 to 2.5 meters away from the laser. Mount the single slit slide on a magnetic holder and place the holder fairly close to the front of the laser. Adjust the slide so that the laser beam goes through the *widest* slit. Project the diffraction pattern onto the screen.

1. **General Observations.**

   (a) Observe the nature of the diffraction pattern. Identify the central diffraction maximum and note the diffraction minima on each side of the central region. Consult with your instructor if you can't identify these features of the diffraction pattern.

   (b) At the top of your data sheet record the wavelength of the laser. Then observe, in turn, the diffraction pattern due to each slit of smaller width. Comment on the change you observed in the *width of the diffraction maximum* as the width of the slit is *decreased*.

2. **Measurements.** Project the diffraction pattern from the 0.04 mm wide slit onto the screen. Carefully measure and record the distance $L$ from the slide to the screen.

   (a) Record the slit width. Then measure and record the width $w$ of the central diffraction pattern (from the middle of the *1st dark region* on one side to the middle of the *1st dark region* on the other side of the central bright region). Repeat for the 0.08 mm pattern.

   (b) For each slit width, use the known slit width and distance $L$ to compute a value for the *expected* theoretical width of the central diffraction maximum.

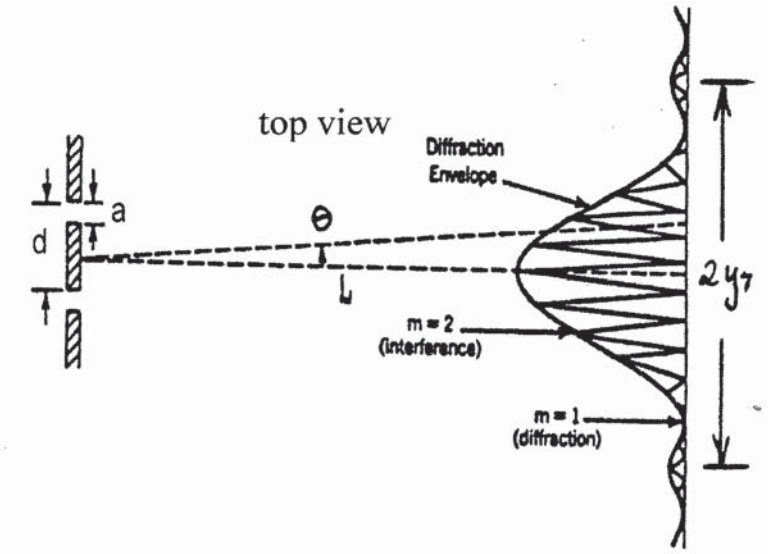
   (c) For each trial, compare your measured width for the central diffraction maximum to the expected width. *Comment on how well your measurements agree with the expected values.*

3. A fine thread or wire of diameter $d$ will produce the same diffraction pattern as a slit of width $a$, where $d$ replaces $a$ in the above formulas. Obtain a hair from the head of one of your group and tape it vertically across the opening of the blank mount. Place the hair in the center of the laser beam and observe the resulting diffraction pattern. *Comment on whether or not its shape is similar to the single-slit diffraction pattern.*

   (a) Measure and record the distance $L$ from the hair to the center of the screen. Then measure and record the width of the central diffraction pattern.

   (b) Use your measurements to compute a value for the diameter $d$ of the hair.

**Theory — Double-Slit Interference.** Interference is the effect produced when two or more waves are superimposed together at the same place. A common way to show interference with light is to allow coherent monochromatic light to illuminate two narrow slits as shown in the top view in the diagram below.




The width of each slit is $a$ and the distance between the centers of the two slits is $d$. Interference occurs as the light from each slit spreads out into the space behind the slits. When light falls onto a distant screen, a characteristic pattern of *equally spaced* bright and dark regions, called an *interference pattern*, is produced. Each dark or bright region, called a *fringe*, is labeled by its position from the center of the screen. The bright region at the center of the screen is the $0^{\text{th}}$ bright fringe, the first dark fringes on either side of the $0^{\text{th}}$ bright fringe are called the $1^{\text{st}}$ dark fringes, the next bright fringes are called the $1^{\text{st}}$ bright fringes, and so on. In addition to the interference pattern, a diffraction pattern is also produced on the screen (due to the width of each slit) as shown in the diagram. As you view the pattern on the screen, you must distinguish carefully between the interference pattern and the diffraction pattern. The interference pattern consists of *equally spaced* bright and dark fringes, but some of the fringes will be very dim or missing because they fall very near or exactly on the diffraction minima.

The angular position of the $m^{\text{th}}$ *bright* fringe is given by the expression

$$d \sin\theta_m = m\lambda \tag{15.3}$$

where $d$ is the distance between the two slits, $\lambda$ is the wavelength of the light, and $m$ is a non-negative integer, $m = 0, 1, 2, \ldots$ corresponding to the *order* or number of the bright fringe. The distance on the screen between two occurrences of the same order bright fringe (on opposite sides of the $m = 0$ bright fringe) is

given by the expression

$$2y_m = 2L \tan \theta_m \tag{15.4}$$

where $L$ is the distance between the slit pattern and the screen and angle $\theta$ is the angular position of the $m^{\text{th}}$ bright fringe.

# Procedure 2 — Double-Slit Interference

Mount the double-slit slide on a magnetic holder and place the ($a = 0.04$ mm, $d = 0.500$ mm) double slit into the laser beam. Observe the interference pattern. As you view the pattern, distinguish between *interference effects* and *diffraction effects* because both are present simultaneously. Consult with your instructor if in doubt.

1. **General Observations.**

   (a) Now observe the interference pattern due to the larger slit spacing and the same slit widths ($a = 0.04$ mm, $d = 0.250$ mm). Comment on what changes, if any, you observed in the positions of the interference fringes and the position of the central diffraction minima. Do your observations agree with the predictions of the theory?

   (b) Return to the original interference pattern ($a = 0.04$ mm, $d = 0.500$ mm). Now observe the interference pattern due to the other slit of the *same spacing*, but with *wider* slits ($a = 0.08$ mm, $d = 0.500$ mm). Comment on what changes, if any, you observed in the positions of the interference fringes and the position of the central diffraction minima. Do your observations agree with the predictions of theory?

2. **Measurements.** Project the interference pattern from a double slit of your choice onto the screen. Record the slit spacing that you chose. Measure and record the distance $L$ from the double slit slide to the screen.

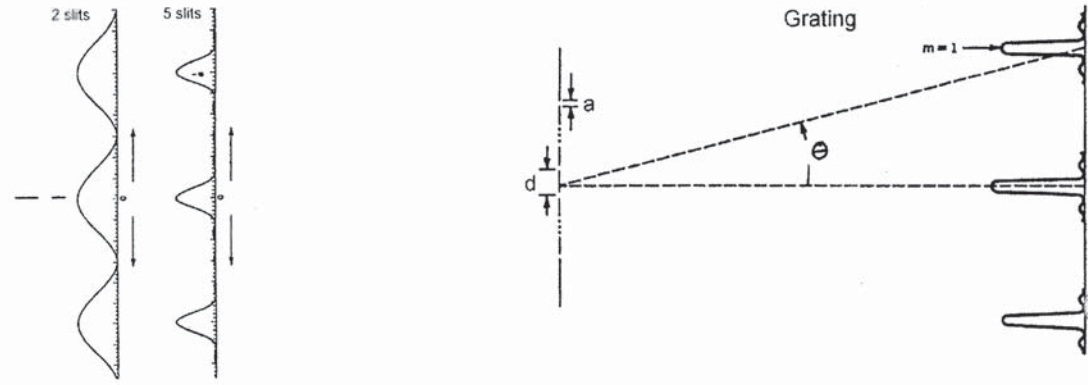
   (a) Then measure and record the distance $2y_8$ (or $2y_{10}$) between that bright fringe on one side of the screen to the same bright fringe on the other side of the screen. Repeat the measurements for a double slit with a *different slit spacing*.

   (b) For each set of measurements, use the known slit spacing and your measured distance $L$ to compute an *expected* value for the distance $2y_8$ (or $2y_{10}$).

   (c) For each measurement, compare your measured distance $2y_8$ (or $2y_{10}$) to the expected theoretical value. *Comment on how well your measurements agree with the expected values?*

**Theory — Diffraction Gratings.** A diffraction grating is a multi-slit array consisting of many thousands of narrow slits sitting side-by-side, all parallel to one another with the same slit spacing between adjacent slits. You can think of a grating as a double slit that has been repeated many thousands of times. As the number of slits increase in a multi-slit array, several changes occur in the interference pattern compared to the pattern due to the two slits. One change that occurs is that more slits pass much more light and the *interference fringes become much brighter*. However, the *major change* that occurs as the number of slits is increased is that the *bright fringes become very narrow—so narrow that for all practical purposes, they become lines (or spots if using a laser)*. This effect is illustrated in the sketch below *at the left* that shows the intensity pattern produced on a screen from *five slits* compared to the intensity pattern from *2 slits*. As the number of slits becomes *very large*, the bright interference fringes narrow into bright lines as illustrated in the sketch below *at the right. Also of importance is that no change occurs in the position of the bright fringes.* Thus, as the number of slits in a mult-slit array increases, the *positions* of the bright fringes remain exactly at the same places a sfor the double slits. This means that equations (15.3) and (15.4) are also valid for all multi-slit

arrays. Called *diffraction gratings*, these multiple-slit arrays are used to study the spectral distribution of light from a wide variety of sources including stars, chemical reactions, molecular vibrations, etc. Diffraction gratings are characterized by a property called their *grating constant* that specifies how many slits occur for each centimeter (or millimeter) or width. For example, a good grating would have a grating constant of 5000 lines/cm. Since the slits of a grating all have the same spacing, the *grating constant* $G$ is the *reciprocal of the slit spacing* (i.e., if $G =$ grating constant, then $G = 1/d$, where $d$ is the slit spacing of adjacent slits.)




## Procedure 3 — Interference from Diffraction Gratings.

1. **General Observations.** Mount the diffraction mosaic slide on a magnetic holder and project the interference pattern from *grating A* onto the screen. Observe the spacing of the bright fringes. Observe in turn the interference patterns from *grating B* and from *grating C*. Comment on the change that you observed in the fringe spacing as the grating constant was increased.

2. **Measurements.** Select a grating of your choice from the diffraction mosaic and record its grating constant. Project its interference pattern onto the screen.

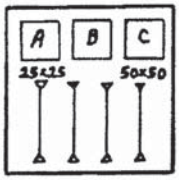
   (a) Measure and record distance $L$ from the grating to the screen. Select an order of interference and measure and record the distance $2y_m$ for this order.

   (b) Use your measurements to compute a value for the slit spacing and then compute an experimental value for the grating constant. Compare your experimental value for the grating constant to the manufacturer's value. *Comment on how well your measurement agrees with the manufacturer's value.*

# List of Contents in the Laser Slide Set

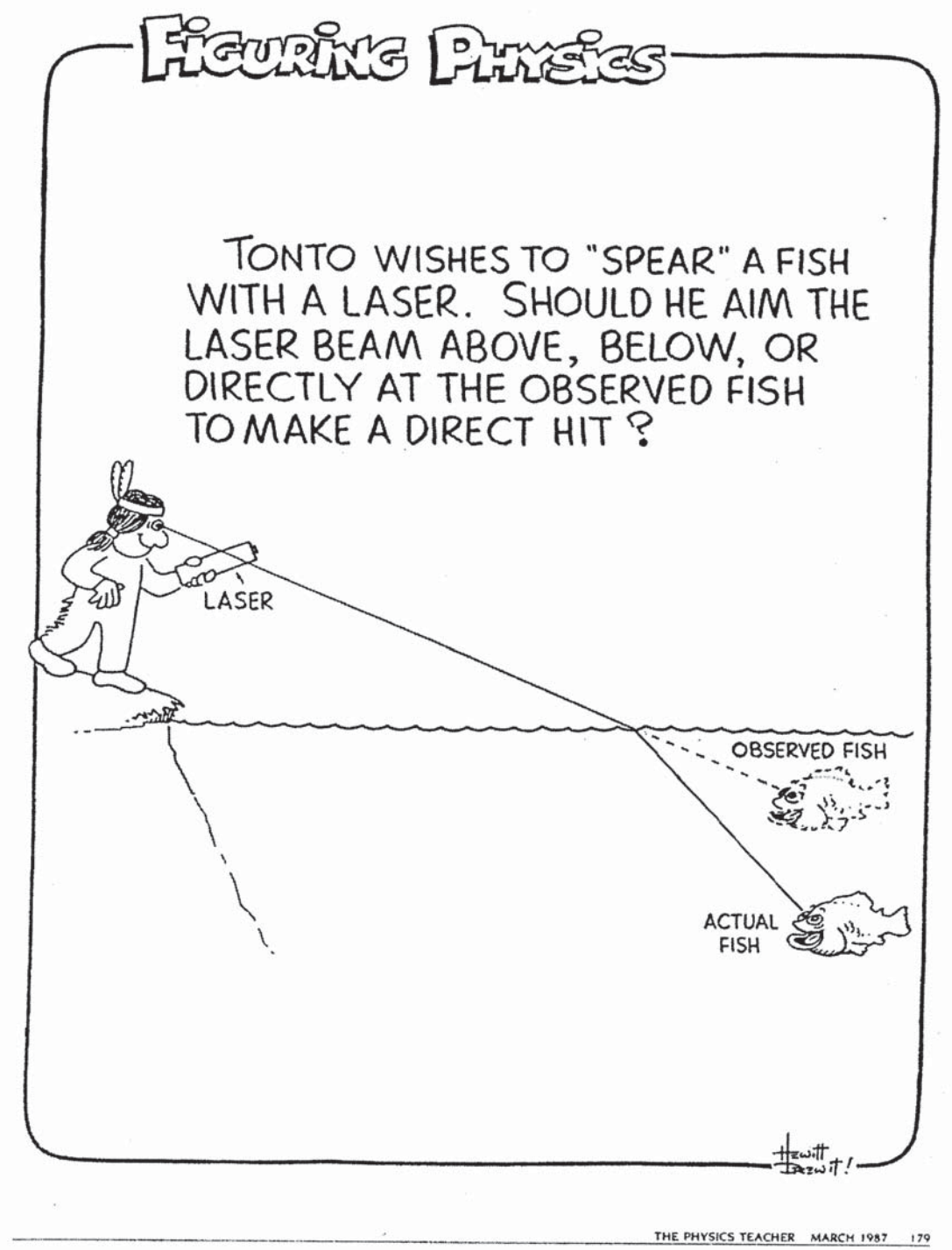
Each Laser Slide Set consists of a small plastic box containing the following items:

1) Single slit slide 4 widths [(a=0.02mm, 0.04 mm, 0.08 mm, & 0.16 mm)]
2) Double slit slide 4 sets [(a=0.04mm, d=0.250 mm), (a=0.04mm, d=0.500 mm)],
   ..... [(a=0.08mm,d=0.250 mm), (a=0.08mm, d=0.500 mm)]
3) Circular apertures 2 diameters [(0.04 mm & 0.125 mm)]
4) Multiple slit slide 2 slits, 3 slits, 4 slits, & 5 slits [(a=0.04 mm, d=0.125 mm)]
5) Diffraction mosaic slide (see sketch below)
6) Transmission grating 5276 lines/cm
7) Transmission hologram
8) 2 polarizer slides
9) 1 blank holder
10) lens f = + 18 mm lens
11) lens f = + 48 mm lens
12) lens f = - 22 mm lens



Diffraction Mosaic

| gratings | double slits | a, μm | d, μm |
|---|---|---|---|
| A: 245 lines/cm | 25x25 | 25 | 50 |
| B: 490 lines/cm | 25x35: | 25 | 60 |
| C: 960 lines/cm | 25x50: | 25 | 75 |
| | 50x50: | 50 | 100 |


FIGURING PHYSICS
TONTO WISHES TO "SPEAR" A FISH WITH A LASER. SHOULD HE AIM THE LASER BEAM ABOVE, BELOW, OR DIRECTLY AT THE OBSERVED FISH TO MAKE A DIRECT HIT ?
LASER
OBSERVED FISH
ACTUAL FISH
Hewitt Drew it!

# Experiment 16

# The Grating Spectrometer

**Objective:** To align a grating spectrometer and to use it to measure the wavelengths of the visible line spectra emitted from excited hydrogen ($H_2$) gas, from excited mercury (Hg) vapor, and to view the line spectra from excited neon.

**Comment:** Light emitted from excited low-pressure gases (i.e. neon lights or low-pressure mercury lamps) has a very different type of spectrum compared to the continuous rainbow-like spectrum emitted by hot solids and hot liquids such as lamp filaments or molten iron. The spectrum from excited gases is composed of a set of discrete wavelengths called a *line spectrum*. Such spectra occur when atomic electrons fall from higher orbits to lower orbits in the atom. The study of line spectra is one of the major techniques for learning about the orbit structure of atoms.

**Method:** A diffraction grating spectrometer will be aligned and then used to measure the angular position of each of the visible lines emitted by the excited gas. The wavelength of each line can be computed from Young's interference expression for bright fringes

$$d \sin\theta = m\lambda, \quad \text{where } m = 0, 1, 2, 3, \ldots \tag{16.1}$$

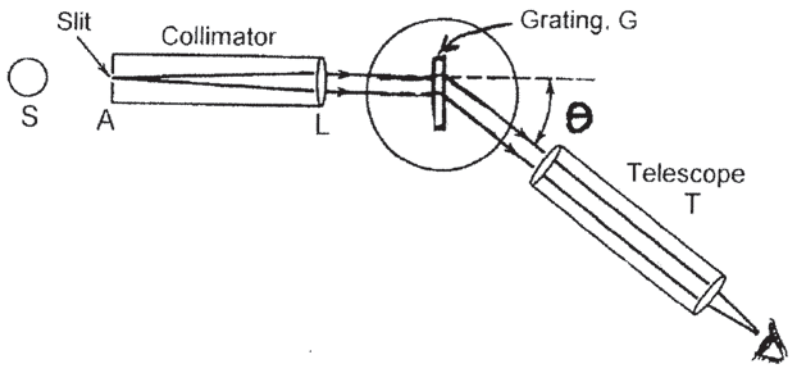
and $d$ is the spacing between adjacent slits in the grating $\theta$ is the angular position of the $m^{\text{th}}$ bright fringe, and $\lambda$ is the wavelength of the light. Research-grade diffraction gratings produce only two or three complete orders of interference. Gratings are usually specified by a *grating constant* which is the reciprocal of $d$. The grating constant of the grating used in this experiment is 600 lines per millimeter.

**Apparatus:**

| | | |
|---|---|---|
| Grating spectrometer | grating | spectrum tubes: H, Hg, Ne |
| night light | black tape | spectrum tube power supply |

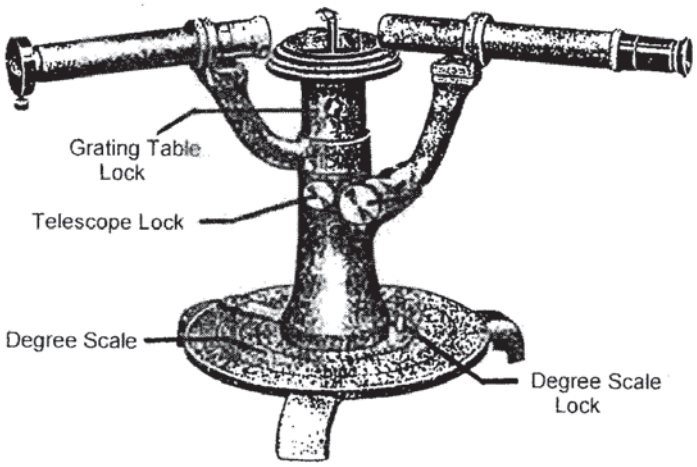
## Procedure 1 — Alignment of the Spectroscope

In order to accurately measure the wavelength of light, the spectometer must be carefully aligned and then calibrated. We will do a good alignment, but will not calibrate the spectroscope. We will assume that a careful alignment will leave the spectroscope in a state that is very near its calibrated condition. Take the time to do the alignment properly so that you can obtain good results.




The light path for a typical spectrometer is sketched at right. The light to be analyzed is represented by source $S$. Light from this source enters the spectroscope through slit $A$, travels through the collimator and falls upon grating $G$. A collimator is a lens or set of lenses that produces a light beam with parallel rays.

The first-order spectrum from the grating is observed using telescope $T$ that is connected to a degree scale so that the angle $\theta$ of a bright interference fringe can be measured. The light that falls upon the grating must be composed of plane waves (parallel rays), a task accomplished when slit $A$ is adjusted to be in the focal plane of the collimator lens $L$. Since equation (16.1) describes the positon of the bright fringes for parallel rays coming from the grating, the telescope must be adjusted to view only parallel rays. It is also important that the grating be positioned normal (perpendicular) to the path of the light from the collimator.




There are several locking screws on the vertical column of the spectrometer. The sketch at the right identifies these screws. The screw under the grating table locks the table to the spectrometer shaft. The screw near the base of the shaft locks the degree scale to the rotation of the telescope. The telescope lock screw locks the telescope from moving. In general, this screw can be left unlocked.

The alignment of the spectrometer consists of three parts. (1) You first adjust the telescope to view parallel light, (2) you adjust the collimator to make parallel light, and (3) you insert the grating onto the grating table. Note that the telescope has two adjustable tubes—the eyepiece and the focus tube. The three steps of the adjustment are described below.

Step 1. Adjust the telescope to view parallel light. Remove the grating from the grating table and set it aside.

Turn the telescope around so that it points at a distant object far across the room.

1. Focus the eyepiece of the telescope on the cross hairs by pulling the eyepiece out and slowly pushing it inward until the cross hairs appear in sharp focus.
2. Move the focus cylinder of the telescope in and out until the far object is in sharp focus.
3. Check for *parallax* between the vertical cross hair and the image of the distant object. If no parallax exists, the cross hair is in the image plane of the telescope. If parallax exists,carefully repeat the first two steps until parallax disappears. You may wish to wrap black tape around the telescope and eyepiece tubes so that the adjustments cannot be disturbed as you work with the apparatus.

Step 2. Adjust the collimator to produce parallel light. Open the collimator slit to mid-position and place a light just behind the collimator.

1. Swing the telescope so that it looks into the collimator tube. Move the collimator tube in and out until the aperture is in sharp focus. Rotate the collimator so that it is vertical as seen through the telescope. If the aperture is in sharp focus then the light rasy that leave the collimator and pass into the telescope are parallel rays. You may wish to wrap black tape around the collimator tube so that its adjustment cannot be disturbed as you work with the apparatus.
2. Move the telescope slightly sideways so that the vertical cross hair is over the non-movable (left) edge of the collimator slit as seen through the telescope. Now adjust the degree scale to 0.0 degrees and lock it.

The collimator and telescope are now aligned.

Step 3. Position the Grating. This is a critical step since we are not calibrating the spectrometer. The grating must be placed on the grating table so that its plane is perpendicular to the path of the light. An error in placement affects the angular position of the bright fringes.

- Place the side of the grating marked "down" on the grating table and carefully position it at the *exact center of the table* so that its plane is perpendicular to the path of the light coming from the collimator.
- This complete the alignment of the spectroscope.

## Procedure 2 – Wavelength Measurements

- Set up a data table with three columns for gas, color, and measured angle. All measured angles will be in the first order.
- Place the *hydrogen lamp* into the spectrum tube power supply and energize the tube. Place the thin neck of the hydrogen tube just beyond the collimator slit (you may have to raise the power supply by placing a book under the power supply). Leave the aperture at its mid-position opening and view the zeroth order. Move the entire spectroscope or the power supply to obtain maximum brightness as you look through the telescope. If you don't see the zeroth order or have a problem, consult with your instructor.
  - Now swing the telescope around to view the first order lines of the spectrum. You may have to reduce the opening of the aperture slit to see the separate lines. The best measurements are made with a fairly narrow aperture, but you need enough light to see the vertical cross hair. Since the spectrometer was aligned with 0.0 degrees at the *left edge* of the collimator slit, select a line in the spectrum and record its color. Then move the telescope so that the vertical cross hair is at the left edge of the line. Measure and record the angular position of the line to the nearest 0.1 degree.

  - Measure the angular position of all the visible lines of hydrogen.

- Replace the hydrogen tube with the *mercury tube*. Using the above method, measure the angle corresponding to any four lines of the mercury spectrum. Choose the four lines carefully so that you are fairly sure you know the color of each selected line.

- Replace the mercury tube with the *neon tube* and observe the spectrum of neon. What colors seem to dominate the spectrum? Do not attempt to measure the position of any of the lines, but determine the *approximate number* of lines in the visible spectrum of neon and record.

# Analysis

1. Set up an analysis table for the gas data. Make columns for gas, color, measured wavelength, expected wavelength, and percent difference.

2. For each measured line, compute a value for the measured wavelength using equation (16.1). Write in the expected wavelength from the table of spectra in the list below and compare each measured wavelength to its expected value.

3. Comment on how well you were able to measure the wavelengths using the spectroscope. Do you detect any pattern in the errors as a function of wavelength?

## Spectra for Selected Excited Gases

| Hydrogen | | Mercury | | Helium | |
|---|---|---|---|---|---|
| red | 656.3 nm | red | 690.7 nm | red | 706.5 nm |
| blue-green | 486.1 | yellow | 579.1 | red | 667.8 |
| blue | 434.0 | yellow | 577.0 | yellow | 587.6 |
| violet | 410.2 | green | 546.1 | green | 501.5 |
| | | blue-green | 491.6 | blue-green | 492.2 |
| | | blue | 435.8 | blue | 471.3 |
| | | violet | 407.8 | dark blue | 447.1 |
| | | violet | 404.7 | violet | 438.8 |
| | | | | violet | 412.1 |
| | | | | violet | 402.6 |
| | | | | violet | 396.5 |

# MURPHY'S LAW OF EXPERIMENTAL PHYSICS

In an experiment, if anything can go wrong, it will.

## COROLLARIES TO MURPHY'S LAW

1. When something goes wrong, it will do so at the worst possible time.
2. Left to themselves, things always go from bad to worse.
3. If everything seems to be going well, you have obviously overlooked something.