Physics 202 Lab Manual
Electricity and Magnetism, Sound/Waves, Light

R. Rollefson, H.T. Richards, M.J. Winokur

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NOTE: E=Electricity and Magnetism, S=Sound and Waves, L-Light

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NOTE: E=Electricity and Magnetism, S=Sound and Waves, L-Light
Forward

Spring, 2005

This version is only modestly changed from the previous versions. We are gradually revising the manual to improve the clarity and interest of the activities. In particular the dynamic nature of web materials and the change of venue (from Sterling to Chamberlin Hall) has required a number of cosmetic and operational changes. In particular the PASCO computer interface and software have been upgraded from Scientific Workshop to DataStudio.

M.J. Winokur

In reference to the 1997 edition

Much has changed since the implementation of the first edition and a major overhaul was very much in need. In particular, the rapid introduction of the computer into the educational arena has drastically and irreversibly changed the way in which information is acquired, analyzed and recorded. To reflect these changes in the introductory laboratory we have endeavored to create a educational tool which utilizes this technology; hopefully while enhancing the learning process and the understanding of physics principles. Thus, when fully deployed, this new edition will be available not only in hard copy but also as a fully integrated web document so that the manual itself has become an interactive tool in the laboratory environment.

As always we are indebted to the hard work and efforts by Joe Sylvester to maintain the laboratory equipment in excellent working condition.

M.J. Winokur
M. Thompson

From the original edition

The experiments in this manual evolved from many years of use at the University of Wisconsin. Past manuals have included “cookbooks” with directions so complete and detailed that you can perform an experiment without knowing what you are doing or why, and manuals in which theory is so complete that no reference to text or lecture was necessary.

This manual avoids the “cookbook” approach and assumes that correlation between lecture and lab is sufficiently close that explanations (and theory) can be brief: in many cases merely a list of suggestions and precautions. Generally you will need at least an elementary understanding of the material in order to perform the experiment expeditiously and well. We hope that by the time you have completed an experiment, your understanding will have deepened in a manner not achievable by reading books or by working ”paper problems”. If the lab should get ahead of the lecture, please read the pertinent material, as recommended by the instructor, before doing the experiment.

The manual does not describe equipment in detail. We find it more efficient to have the apparatus out on a table and take a few minutes at the start to name the pieces and give suggestions for use. Also in this way changes in equipment, (sometimes necessary), need not cause confusion.
Many faculty members have contributed to this manual. Professors Barschall, Blanchard, Camerini, Erwin, Haeberli, Miller, Olsson, Visiting Professor Wickliffe and former Professor Moran have been especially helpful. However, any deficiencies or errors are our responsibility. We welcome suggestions for improvements.

Our lab support staff, Joe Sylvester and Harley Nelson (now retired), have made important contributions not only in maintaining the equipment in good working order, but also in improving the mechanical and aesthetic design of the apparatus.

Likewise our electronic support staff not only maintain the electronic equipment, but also have contributed excellent original circuits and component design for many of the experiments.

R. Rollefson
H. T. Richards
Introduction

General Instructions and Helpful Hints

Physics is an experimental science. In this laboratory, we hope you gain a realistic feeling for the experimental origins, and limitations, of physical concepts; an awareness of experimental errors, of ways to minimize them and how to estimate the reliability of the result in an experiment; and an appreciation of the need for keeping clear and accurate records of experimental investigations.

Maintaining a clearly written laboratory notebook is crucial. This lab notebook, at a minimum, should contain the following:

1. Heading of the Experiment: Copy from the manual the number and name of the experiment.
   Include both the current date and the name(s) of your partner(s).

2. Original data: Original data must always be recorded directly into your notebook as they are gathered. “Original data” are the actual readings you have taken. All partners should record all data, so that in case of doubt, the partners’ lab notebooks can be compared to each other. Arrange data in tabular form when appropriate. A phrase or sentence introducing each table is essential for making sense out of the notebook record after the passage of time.

3. Housekeeping deletions: You may think that a notebook combining all work would soon become quite a mess and have a proliferation of erroneous and superseded material. Indeed it might, but you can improve matters greatly with a little housekeeping work every hour or so. Just draw a box around any erroneous or unnecessary material and hatch three or four parallel diagonal lines across this box. (This way you can come back and rescue the deleted calculations later if you should discover that the first idea was right after all. It occasionally happens.) Append a note to the margin of box explaining to yourself what was wrong.

   We expect you to keep up your notes as you go along. Don’t take your notebook home to “write it up” – you probably have more important things to do than making a beautiful notebook. (Instructors may permit occasional exceptions if they are satisfied that you have a good enough reason.)

4. Remarks and sketches: When possible, make simple, diagrammatic sketches (rather than “pictorial” sketches) of apparatus. A phrase or sentence introducing each calculation is essential for making sense out of the notebook record after the passage of time. When a useful result occurs at any stage, describe it with at least a word or phrase.

5. Graphs: There are three appropriate methods:

   A. Affix furnished graph paper in your notebook with transparent tape.
   B. Affix a computer generated graph paper in your notebook with transparent tape.
   C. Mark out and plot a simple graph directly in your notebook.
Show points as dots, circles, or crosses, i.e., ·, o, or ×. Instead of connecting points by straight lines, draw a smooth curve which may actually miss most of the points but which shows the functional relationship between the plotted quantities. Fasten directly into the notebook any original data in graphic form (such as the spark tapes of Experiment M4).

6. *Units, coordinate labels:* Physical quantities always require a number and a dimensional unit to have meaning. Likewise, graphs have abscissas and ordinates which always need labeling.

7. *Final data, results and conclusions:* At the end of an experiment some written comments and a neat summary of data and results will make your notebook more meaningful to both you and your instructor. The conclusions must be faithful to the data. It is often helpful to formulate conclusion using phrases such as “the discrepancy between our measurements and the theoretical prediction was larger than the uncertainty in our measurements.”

**PARTNERS**

Discussing your work with someone as you go along is often stimulating and of educational value. If possible all partners should perform completely independent calculations. Mistakes in calculation are inevitable, and the more complete the independence of the calculations, the better is the check against these mistakes. Poor results on experiments sometimes arise from computational errors.

**CHOICE OF NOTEBOOK**

We recommend a large bound or spiral notebook with paper of good enough quality to stand occasional erasures (needed most commonly in improving pencil sketches or graphs). To correct a wrong number always cross it out instead of erasing: thus $\frac{\sqrt{1401}}{2} = 3.1416$ since occasionally the correction turns out to be a mistake, and the original number was right. Coarse (1/4 inch) cross-ruled pages are more versatile than blank or line pages. They are useful for tables, crude graphs and sketches while still providing the horizontal lines needed for plain writing. Put everything that you commit to paper right into your notebook. Avoid scribbling notes on loose paper; such scraps often get lost. A good plan is to write initially only on the right-hand pages, leaving the left page for afterthoughts and for the kind of exploratory calculations that you might do on scratch paper.

**COMPLETION OF WORK**

Plan your work so that you can complete calculations, graphing and miscellaneous discussions before you leave the laboratory. Your instructor will check each completed lab report and will usually write down some comments, suggestions or questions in your notebook.

Your instructor can help deepen your understanding and “feel” for the subject. Feel free to talk over your work with him or her.
Expt. M1 Systematic and Random Errors, Significant Figures, Density of a Solid

NAME: Jane.O. Student
Partner: John Q. Student

Date: 2/29/00

Purpose: To develop a basic understanding of systematic and random errors in a physical measurement by obtaining the density of a metal cylinder.

Equipment: Vernier caliper, micrometer, precision gauge block, precision balance

Theory: \[
\rho = \frac{\text{mass}}{\pi r^2 h}
\]

\[
\Delta \rho = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta h}{h}\right)^2 + \left(2 \frac{\Delta r}{r}\right)^2}
\]

DATA:
1. Calibration of micrometer
   Reading with jaws fully closed:
   
   - 1. 0.000013 mm ± 0.000001 mm
   - 2. 0.000014 mm
   - 3. 0.000012 mm
   - 4. 0.000014 mm
   - 5. 0.000015 mm

   Ave. ± Standard Deviation

   Measure four calibration gauge blocks

   Micrometer exhibits a systematic zero offset

   Plot of micrometer error vs. gauge block length

   Measure of cylinder diameter:
   Measure of cylinder height:
   Measure of cylinder mass

   CALCULATIONS:
   Density = ???
   Uncertainty from propagation of error.

RESULTS and CONCLUSIONS:
Errors and Uncertainties

Reliability estimates of measurements greatly enhance their value. Thus, saying that the average diameter of a cylinder is 10.00±0.02 mm tells much more than the statement that the cylinder is a centimeter in diameter. The reliability of a single measurement (such as the diameter of a cylinder) depends on many factors:

FIRST, are actual variations of the quantity being measured, e.g. the diameter of a cylinder may actually be different in different places. You must then specify where the measurement was made; or if one wants the diameter in order to calculate the volume, first find the average diameter by means of a number of measurements at carefully selected places. Then the scatter of the measurements will give a first estimate of the reliability of the average diameter.

SECOND, the micrometer caliper used may itself be in error. The errors thus introduced will of course not lie equally on both sides of the true value so that averaging a large number of readings is no help. To eliminate (or at least reduce) such errors, we calibrate the measuring instrument: in the case of the micrometer caliper by taking the zero error (the reading when the jaws are closed) and the readings on selected precision gauges of dimensions approximately equal to those of the cylinder to be measured. We call such errors systematic, and these cause errors in accuracy.

THIRD, Another type of systematic error can occur in the measurement of a cylinder: The micrometer will always measure the largest diameter between its jaws; hence if there are small bumps or depressions on the cylinder, the average of a large number of measurements will not give the true average diameter but a quantity somewhat larger. (This error can of course be reduced by making the jaws of the caliper smaller in cross section.)

FINALLY, if one measures something of definite size with a calibrated instrument, one’s measurements will vary. For example, the reading of the micrometer caliper may vary because one can’t close it with the same force every time. Also the observer’s estimate of the fraction of the smallest division varies from trial to trial. Hence the average of a number of these measurements should be closer to the true value than any one measurement. Also the deviations of the individual measurements from the average give an indication of the reliability of that average value. The typical value of this deviation is a measure of the precision. This average deviation has to be calculated from the absolute values of the deviations, since otherwise the fact that there are both positive and negative deviations means that they will cancel. If one finds the average of the absolute values of the deviations, this “average deviation from the mean” may serve as a measure of reliability. For example, let column 1 represent 10 readings of the diameter of a cylinder taken at one place so that variations in the cylinder do not come into consideration, then column 2 gives the magnitude (absolute) of each reading’s deviation from the mean.
Measurements | Deviation from Ave.
-------------|------------------
9.943 mm     | 0.000            
9.942        | 0.001            
9.944        | 0.001            
9.941        | 0.002            
9.943        | 0.000            
9.943        | 0.000            
9.945        | 0.002            
9.943        | 0.000            
9.943        | 0.000            
9.942        | 0.001            

Diameter = 9.943 ± 0.001 mm

Ave = 9.943 mm    Ave = 0.0009 mm≈0.001 mm

Expressed algebraically, the average deviation from the mean is $\bar{x} = (\sum |x_i - \bar{x}|)/n$, where $x_i$ is the $i^{th}$ measurement of $n$ taken, and $\bar{x}$ is the mean or arithmetic average of the readings.

**Standard Deviation and Normal Distribution:**

The average deviation shown above is a measure of the spread in a set of measurements. A more easily calculated version of this is the standard deviation $\sigma$ (or root mean square deviation). You calculate $\sigma$ by evaluating

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

where $\bar{x}$ is the mean or arithmetical average of the set of $n$ measurements and $x_i$ is the $i^{th}$ measurement.

Because of the square, the standard deviation $\sigma$ weights large deviations more heavily than the average deviation and thus gives a less optimistic estimate of the reliability. In fact, for subtle reasons involving degrees of freedom, $\sigma$ is really

$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

$\sigma$ tells you the typical deviation from the mean you will find for an individual measurement. The mean $\bar{x}$ itself should be more reliable. That is, if you did several sets of $n$ measurements, the typical means from different sets will be closer to each other than the individual measurements within a set. In other words, the uncertainty in the mean should be less than $\sigma$. It turns out to reduce like $1/\sqrt{n}$, and is called the error in the mean $\sigma_\mu$:

$$\sigma_\mu = \text{error in mean} = \frac{\sigma}{\sqrt{n}} = \frac{1}{\sqrt{n}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

For an explanation of the $(n-1)$ factor and a clear discussion of errors, see P.R. Bevington and D.K Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, McGraw Hill 1992, p. 11.

If the error distribution is “normal” (i.e. the errors, $\epsilon$ have a Gaussian distribution, $e^{-\epsilon^2}$, about zero), then on average 68% of a large number of measurements will lie closer...
than $\sigma$ to the true value. While few measurement sets have precisely a “normal” distribution, the main differences tend to be in the tails of the distributions. If the set of trial measurements are generally bell shaped in the central regions, the “normal” approximation generally suffices.

**How big should the error bars be?**
The purpose of the error bars shown on a graph in a technical report is as follows: if the reader attempts to reproduce the results in the graph using the procedure described in the report, the reader should expect his or her results to have a 50% chance of falling with the range indicated by the error bars.

If the error distribution is normal, the error bars should be of length $\pm 0.68\sigma$.

**Relative error and percentage error:**
Let $\epsilon$ be the error in a measurement whose value is $a$. Then $\left(\frac{\epsilon}{a}\right)$ is the relative error of the measurement, and $100 \left(\frac{\epsilon}{a}\right)\%$ is the percentage error. These terms are useful in laboratory work.

**UNCERTAINTY ESTIMATE FOR A RESULT INVOLVING MEASUREMENTS OF SEVERAL INDEPENDENT QUANTITIES**

Let $R = f(x, y, z)$ be a result $R$ which depends on measurements of three different quantities $x$, $y$, and $z$. The uncertainty $\Delta R$ in $R$ which results from an uncertainty $\Delta x$ in the measurement of $x$ is then

$$\Delta R = \frac{\partial f}{\partial x} \Delta x,$$

and the fractional uncertainty in $R$ is

$$\frac{\Delta R}{R} = \frac{\partial f}{f} \Delta x.$$

In most experimental situations, the errors are uncorrelated and have a normal distribution. In this case the uncertainties add in quadrature (the square root of the sum of the squares):

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\partial f}{f} \Delta x\right)^2 + \left(\frac{\partial f}{f} \Delta y\right)^2 + \left(\frac{\partial f}{f} \Delta z\right)^2}.$$

**Some examples:**

A.) $R = x + y$. If errors have a normal or Gaussian distribution and are independent, they combine in quadrature:

$$\Delta R = \sqrt{\Delta x^2 + \Delta y^2}.$$

Note that if $R = x - y$, then $\Delta R / R$ can become very large if $x$ is nearly equal to $y$. Hence avoid, if possible, designing an experiment where one measures two large quantities and takes their difference to obtain the desired quantity.

B.) $R = xy$. Again, if the measurement errors are independent and have a Gaussian distribution, the relative errors will add in quadrature:

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}.$$
Note the same result occurs for $R = x/y$.

C.) Consider the density of a solid (Exp. M1, Physics 201):

$$\rho = \frac{m}{\pi r^2 L}$$

where $m =$ mass, $r =$ radius, $L =$ length, are the three measured quantities and $\rho =$ density. Hence

$$\frac{\partial \rho}{\partial m} = \frac{1}{\pi r^2 L} \quad \frac{\partial \rho}{\partial r} = \frac{-2m}{\pi r^3 L} \quad \frac{\partial \rho}{\partial L} = \frac{-m}{\pi r^2 L^2}.$$  

Again if the errors have normal distribution, then

$$\frac{\Delta \rho}{\rho} = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(2\frac{\Delta r}{r}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}.$$  

**SIGNIFICANT FIGURES**

Suppose you have measured the diameter of a circular disc and wish to compute its area $A = \pi d^2/4 = \pi r^2$. Let the average value of the diameter be $24.326 \pm 0.003$ mm; dividing $d$ by 2 to get $r$ we obtain $12.163 \pm 0.0015$ mm with a relative error $\Delta r/r = 0.0012$. Squaring $r$ (using a calculator) we have $r^2 = 147.938569$, with a relative error $2\Delta r/r = 0.00024$, or an absolute error in $r^2$ of $0.00024 \times 147.93 = 0.036 \approx 0.04$. Thus we can write $r^2 = 147.94 \pm 0.04$, any additional places in $r^2$ being unreliable. Hence for this example the first five figures are called *significant*.

Now in computing the area $A = \pi r^2$ how many digits of $\pi$ must be used? A pocket calculator with $\pi = 3.141592654$ gives

$$A = \pi r^2 = \pi \times (147.94 \pm 0.04) = 464.77 \pm 0.11 \text{ mm}^2$$

Note that $\frac{\Delta A}{A} = 2\frac{\Delta r}{r} = 0.00024$. Note also that the same answer results from $\pi = 3.1416$, but that $\pi = 3.142$ gives $A = 464.83 \pm 0.11 \text{ mm}^2$ which differs from the correct value by 0.06 mm², an amount comparable to the estimated uncertainty.

A good rule is to use one more digit in constants than is available in your measurements, and to save one more digit in computations than the number of significant figures in the data. When you use a calculator you usually get many more digits than you need. Therefore at the end, be sure to round off the final answer to display the correct number of significant figures.

**SAMPLE QUESTIONS**

1. How many significant figures are there in the following numbers?
   
   (a) 976.45
   
   (b) 4.000
   
   (c) 10

2. Round off each of the following numbers to three significant figures.
   
   (a) 4.455
(b) 4.6675
(c) 2.045

3. A function has the relationship $Z(A, B) = A + B^3$ where A and B are found to have uncertainties of $\pm \Delta A$ and $\pm \Delta B$ respectively. Find $\Delta Z$ in terms of $A$, $B$ and the respective uncertainties assuming the errors are uncorrelated.

4. What happens to $\sigma$, the standard deviation, as you make more and more measurements? What happens to $\bar{\sigma}$, the standard deviation of the mean?

   (a) They both remain same
   (b) They both decrease
   (c) $\sigma$ increases and $\bar{\sigma}$ decreases
   (d) $\sigma$ approaches a constant and $\bar{\sigma}$ decreases
Part I
Electricity and Magnetism

E-1 Electrostatics

LEARNING OBJECTIVES:

Content goals:
(1) To use an electroscope to study electrostatic phenomena. (2) To measure potential (voltage) differences (i.e. the work per unit charge to move a small test charge between two conductors) and thus, in an indirect fashion, charges.

Scientific Inquiry Skills:
(1) Making qualitative observations. (2) Generating explanations that connect those observations to a conceptual model.

PART I: THE ELECTROSCOPE

Apparatus:
1. aluminum-leaf electroscope
2. insulated hollow conducting sphere
3. proofball
4. two rods: lucite and hard rubber
5. two cloths: rabbit fur and silk cloth.

Introduction:
In this part of the lab you will use a deceptively simple device, an electroscope, to study the nature of charge. The electroscope’s primary working parts are two connected conducting foil leaves that are free to move at one end. Figure 1 show a schematic of the electroscope when it is (a) discharged (or neutral) and (b) charged with a net charge. (For reference, on the electroscope, a 1kV potential results in the foil leaves fully deflecting.) Recall that charge appears in two forms (positive and negative) and like charges repel. The electroscope also has a case that must be grounded during the experiment in order to protect the foil leaves from unwanted stray charge. A conductor allows charge to flow whereas insulators do not.

Preliminary Questions:
1. Draw a picture of how the charges are distributed on the electroscope before you start your experiment.
2. Draw a picture predicting what the charge distributions and electroscope will look like if a charged object is brought close to (but does not touch) the conducting knob? Will the net charge on the knob be of the same or opposite sign? What will be the sign of the charge on the foil leaves be?
3. Draw a picture predicting what the electroscope will look like if a charged object touches the conducting knob. Will the net charge on the knob be of the same or opposite sign? What will be the sign of the charge on the foil leaves?

4. How will you know if your predictions are correct?

Experiments:

For each experiment you should record everything in your note book: briefly explain what you did and how, as well as all you observed. Use pictures and diagrams as necessary. The questions included below can be used as a guide, but should not be considered a sufficiently complete record of what you did and observed. If you find you are having difficulty getting reliable results, check the troubleshooting guide for solutions or ask your TA.

1. Charge the rubber rod by rubbing with fur, and transfer some of the charge to the electroscope leaves by touching the rod to the electroscope knob. This is known as charging by conduction. Note what happens when said charged rod approaches the knob in your notebook. (For reference, the rubber rod when rubbed with rabbit fur acquires a negative charge, although there is no way to determine this with the electroscope.) How does this compare to your prediction?

2. Touch the electroscope knob with your hand. Record your observations. How can you explain your observations in terms of the movement of electric charge?

3. Again, transfer some charge to the electroscope using the rubber rod and fur. Without grounding the electroscope, observe and diagram what happens when a lucite rod rubbed with silk approaches the knob. Can you make any inferences about the sign of charge acquired by the two rods?
4. (First discharge the electroscope by touching the knob and case simultaneously.) Charge one of the rods. Make the leaves diverge by bringing the charged rod close to the knob, but do not touch the electroscope with the rod. While keeping the rod at a fixed location, ground the knob to the case, break the ground and then remove the rod. This is known as \textit{charging by induction}. Explain what happens when the same rod is brought near the knob, and what happens when the other rod is brought near the knob (after charging the rods). Explain each step in this process using diagrams and a brief description.

5. In the following give the proofball a charge by contact with a charged lucite or rubber rod. Keep in mind that the lucite and rubber rods acquire opposite charges, and use diagrams to explain and record results.

   a. Connect the hollow conductor to the electroscope knob by fine wire. Discharge them. Charge proofball by touching (avoid rubbing) it to a charged rubber or lucite rod, then introduce the proofball into the hollow conductor but without contacting the conductor. Ground the hollow conductor by touching it. Note behavior of electroscope. Break the ground and remove the proofball. Test the relative sign of charge on the electroscope (note whether it matches the sign of the rod you chose or the other one).

   b. Repeat part a, but now ground the hollow conductor by touching it \textbf{only on the inside} with your finger or a short conductor.

   Record and explain your observations in terms of the movement of charge, using diagrams to aid you.

**PART II: THE ELECTROMETER**

**Apparatus:**
1. PASCO electrometer
2. two hollow conducting spheres and one open hollow sphere
3. two charge producing paddles (white & blue) and one aluminum paddle
4. proofball
5. insulated cup and Faraday Cage. (\textbf{Do not} carry the cup and Faraday Cage by the top cover. It may separate causing the cup to drop and become damaged.)
6. heat gun
7. alcohol lamp.

**Introduction:**
In this part of the lab, you will use an electrometer, a very sensitive voltmeter, to explore charge distributions and the sign of charge. Connect the insulated cup and Faraday Cage to the electrometer using a shielded coaxial cable. The electrometer will now measure the potential difference between the cup and grounded Faraday cage. This potential is proportional to the quantity of charge on the cup as long as the Faraday Cage furnishes a perfect shield from external charged objects. Be sure to zero the electrometer before
making your measurement. Choose a voltage range on the electrometer that gives a large
but less than full scale deflection.

Figure 2: Schematic diagram of electrometer and relevant connections.

Preliminary Questions:

1. Will the electrometer allow you to discern the absolute sign of a charge? Explain.

2. If you are given a charged spherical conductor where does the excess charge reside?
   Draw a picture of your prediction. Does it matter if the spherical conductor is hollow
   or solid? Explain.

3. How might you determine whether your results are trustworthy?

Experiments:

Explain the following experiments with diagrams showing charge distributions. Some
sample diagrams appropriate for this experiment are shown in Figure 3. Again, if you find
you are having difficulty getting reliable or accurate results, check the troubleshooting
guide for solutions or ask your TA.

1. Discharge both the blue and the white paddles. Gently rub the white and the blue
   surfaces of the paddles together. Then:

   a) Hold one of them near the bottom of the cup, but don’t let it touch.
   b) Take the paddle out.
   c) Put it back in, touching the cup this time.
   d) Remove the paddle.

   Record the electrometer reading after each step. Explain the results and draw the
   diagrams (as shown above). Was there any charge left on the paddle at the end?
   Which paddle has a positive charge? Which paddle has a negative charge?
2. Momentarily ground the cup. Charge one of the paddles, then:
   a) Place paddle in cup without touching.
   b) Again momentarily ground the cup.
   c) Remove the paddle.

   Note the reading after each step. Explain what happened at each step and draw the diagrams (as shown above).

3. Start with both paddles discharged. Then rub them together. Measure the charge on each using the electrometer. Explain. Compare the amount of charge produced by rubbing two paddles of the \textit{same} kind (borrow one from another group), or by rubbing a metal paddle on a metal paddle, etc. (Surface “dirt” on one paddle may mean you are rubbing dissimilar paddles. Sometimes cleaning the paddles with alcohol makes a big difference.) Record your observations and draw the diagrams to explain what you observed.

4. Discharge the cup and the blue and white paddles. What happens if you place the paddles inside the cup (without touching the cup) and,
   a) you charge them by rubbing while they both are inside the cup?
   b) Take out one paddle?
   c) Put it back in?
   d) Take out the other?
   e) Take them both out?

   Observe electrometer reading after each step. Explain using diagrams as necessary.

5. Rub the aluminum paddle on the white (or blue) paddle. Do only insulators acquire charge by rubbing? If there is a charge acquired, determine the sign. Arrange the white, blue and aluminum paddles in a series of acquired charge from most positive to most negative. (This is called a “triboelectric” series. Tribology is the study of friction.)
6. Ask your TA to charge up your open sphere using a Fun Fly Stick. Discharge the proofball and test that it (and the handle) have zero charge, then touch it to the outside of the hollow sphere and measure its charge. Do the same experiment but touch inside the sphere. Record your observations. What can you conclude about the distribution of charge in this system?

7. Ask your TA to charge an isolated solid metal sphere using the Fun Fly Stick. Measure the relative charge density $\sigma$ at various points of the sphere. Charge density $\sigma$ is $\Delta Q/\Delta A$ where $\Delta Q$ is the charge on a small element $\Delta A$ of the surface. Since it is not practical to remove a piece of the surface, we place the aluminum paddle flat against the surface and measure the charge on the paddle after it is removed. This measurement gives a number only approximately proportional to the charge density (Why?) but does give a good idea of the relative charge distribution.

OPTIONAL: Repeat step 7 but with the paddle perpendicular to the surface instead of flat. Can you explain the differences?

8. Discharge the second solid sphere when it is far from the charged sphere. Then move it within a few centimeters of the charged sphere. Explore the charge distribution on both spheres with the paddle and record your observations. What do you observe about the sign of the charge on different parts of the second sphere? Is it the same everywhere? Explain your observations.

9. Does a grounded conductor necessarily have no net charge? Momentarily ground the second sphere when it is near the first one, then move it away and see whether it is charged. What is the sign of the charge? Explain.

PART III: CONCLUSION QUESTIONS

1. What is the difference between charging by induction and charging by conduction? What is the net charge on the electroscope in each case?

2. Why does touching the electroscope with your hand ground it? Do you end up with a net charge? If so, how can we see the effects of this?

3. Can the electroscope differentiate between positive and negative charges? Explain based on your observations.

4. What is the relationship between the potential difference measured by the electrometer and the quantity of charge on the cup?

5. Why is it necessary to discharge the paddles and cup before starting an experiment? How would your observations be different if you skipped this step?

6. Do only insulators acquire charge by rubbing? Explain.

7. You measured the charge density $\sigma$ of the solid sphere using the paddle. Why does this method only give us an approximate measure of the relative charge density? What would you have to do to get a more exact measurement?

8. Electrostatics experiments often do not work well in humid weather. Explain why this might be so.
9. In very dry or cold weather, objects such as clothing, table tops, etc. that somehow acquire a charge tend to hold that charge for a long time, i.e. they are slow to discharge. How might this affect the observations in these experiments?

10. Where might you observe the effects of a net charge in your everyday life?

**TROUBLESHOOTING**

1. In humid air insulators may adsorb enough moisture that charges leak off rapidly. If so, dry all insulators with a heat gun. Their large surface charges may influence nearby unshielded instruments. If so, ask your instructor for help; e.g. use grounded foil to shield against them. Also remove any clinging loose bits of fiber (e.g. silk or rabbit fur) that may disturb results.

2. The fragile leaves of the electroscope may tear if charged too heavily. **Do not disassemble electroscope** to attempt repair: see your instructor.

3. To remove charges on the glass windows of the electroscope, lightly rub your hands over the windows while grounding your body.

4. When instructed to touch the hollow sphere with the proofball, avoid rubbing which may result in inaccurate results. (Remember that rubbing is how you created the charge separation on the lucite or rubber rods. Here, we want to charge by conduction.)

5. In humid weather or if there is excess charge on the handle, your proofball may not hold charge. If this happens you can try cleaning or heating the handle (as described in the next item), or putting the lucite rod into the hollow conductor directly.

6. Charges on the insulating handle of a proofball can cause serious measuring errors. Test the handle by grasping the ball with one hand (while the other hand touches the electroscope ground), and then bring parts of the insulating handle close to the electroscope knob. If the leaves move, the handle is charged. To discharge it, hold the handle in a source of ionized air. The charged insulator will attract ions of the opposite sign until it is neutral. An open flame is a simple source of both positive and negative ions. The heated air convects these ions upward such that the handle will attract the correct sign to make it neutral. **Hold the insulator at least 10 cm above open flame to avoid heat damage to the handle.**

7. Avoid unnecessary handling of insulators because handling may impair their insulating capability. (Perspiration is a salt solution which is a conductor.)

8. If your clothing or hair has a net charge, the electrometer reading may change if you move around. Hence, during a given measurement, change position as little as possible and ground yourself.

9. To remove all charge from the cup, press the ‘Zero’ button. (This connects the electrometer terminals to each other so that any charge flows from/to ground). If the meter does not read within a few percent of zero, notify your instructor.
10. Cleaning your paddles before beginning may produce better results. Dirt on the paddles will affect how much charge is transferred (and how actually the same two paddles of the same type are).

11. Always discharge paddles and cup before starting an experiment. To test if an object is charged, put it into the cup and see whether the electrometer deflects. Conductors discharge easily by touching them to a grounded conductor. To discharge an insulator, you must create sufficient ions in the surrounding air. The insulator will then attract ions of the opposite charge until all charge is neutralized. An open flame is a simple source of ionized air; the ions in the flame convect upward with the hot gas. **To avoid damage to the insulator, keep it at least 10 cm above the flame!**

12. You may measure charge and still avoid spurious effects from charges on the insulating handles if you will touch the charged proofball (or paddle) to the bottom of the cup and then remove it from the cup before reading the electrometer. But remember to discharge the cup (by momentarily grounding) before taking the next reading! However, if the potential of the insulating handle is too large (e.g. way off the least sensitive scale), one can still get spurious effects from leakages.
E-2 Electric Fields

INTRODUCTION:

In this lab you will map equipotential lines and electric field lines between charged conductors. Mapping is done by applying a potential difference between two conducting electrodes and probing the potential in the region between them with a Digital Multimeter (DMM). Once you have mapped the equipotentials, you can use your knowledge from class to determine the characteristics of the electric field lines.

LEARNING OBJECTIVES:

Content goals: (1) To develop an intuitive understanding of relationship between electric fields and equipotential contours and (2) physically map both in two dimensions. Inquiry goals: To make and interpret graphical (visual) representations of data.

PRELIMINARY QUESTIONS:

1. Do electric fields extend through a vacuum?
2. Do electric fields extend through the interior of an insulator?
3. Do electric fields extend through the interior of a conductor?
4. What is the relationship between electric field lines and equipotential lines?
5. Draw what you expect the equipotential and electric field lines to look like for a point charge. What do you expect them to look like for a dipole? A conducting plate?

APPARATUS:

1. Power supply (18V, 3A Max)
2. Fluke 115 Digital Multimeter (DMM) & test probes
3. Conductive paper with various conducting electrode configurations
4. Field plotting board
5. Carbon paper
6. White paper
7. Red and Black Banana Cables
**Fluke DMM**

To use the Fluke DMM, choose the DC voltage indicator, $\vec{V}$, from the dial of measurements. Place one probe on the electrode that is grounded and place the other at a different location on the conductive paper. The Fluke will now read the difference in electric potential between those two locations. **Pressing harder will not improve your measurement!** Note that although the DMM will measure the potential difference between arbitrary points, one probe should always be referenced to ground for the purposes of this lab.

**EXPERIMENTS:**

1. Place white paper on the field plotting board, then a piece of carbon paper. On top of those, place the conductive paper with a dipole electrode configuration.

2. Record the shape of the electrodes on the white paper by tracing them with a hard pencil or a ball point pen.

3. Using the power supply, place 18 volts across the terminals of the plotting board (as in Fig. 1). Check the quality of the electrodes you are using with the DMM to make sure there are no appreciable potential differences between various locations within the electrodes. If you find any, ask your TA to find you a new one or fix the silver paint quality.
4. Map the equipotential line which corresponds to +3 volts by exploring the region of the grounded electrode with one probe while keeping your other probe on your reference. Make several dark marks where you find a potential of +3V, and make those recorded points are close enough together that you can later draw a smooth line through the points. Note: the points only need to be close together when the direction of the equipotential changes rapidly.

5. Map another 8 other equipotential lines. Chose voltages that are spread out evenly to 18V. Remove the white paper when completed.

6. On the white paper, connect the dots representing individual equipotentials with smooth lines.

7. Repeat steps 1-7 for the two configurations shown in Fig. 2. In each case map about ten equipotentials.

![Figure 2: Electrode configurations for (a) parallel plates and (b) a lightning rod.](image)

**QUESTIONS:**

1. Explain in a sentence or two how you mapped the equipotential lines.

2. For two different electrode configurations, calculate the mean magnitude of the electric field strength in the region where the field is largest. This can be done by picking adjacent equipotential contours and measuring the distance between them.

3. What is the relationship between electric potential lines and electric field lines? Hint: Consider the relationship between electric potential and electric field:

   \[ V_b - V_a = -\int_a^b \vec{E} \cdot d\vec{l} \]

   and note that \( V_b = V_a \) for any points \( b \) and \( a \) on the equipotential.

4. Using your answer in the previous questions, draw about 5 electric field lines on each of the equipotential maps. Do they look like what you might expect?

5. Where in Fig. 2(b) is the electric field strength the highest? Lowest? Why do experts recommend that if you are caught outside during a thunder shower and cannot obtain shelter that you find a low spot, and curl up your body, while standing
on one foot if possible? Note: there are three effects here, two from shape and the other from size, arising from the fact that lightning is caused by excessive electric fields (> 5000 V/cm), and that currents flow through the paths of least resistance.

6. For the sketch below see if you can sketch out the electric field lines. Afterwards check your answer at http://badger.physics.wisc.edu/lab/java/E2-2.html.

7. Using the applet at http://badger.physics.wisc.edu/lab/java/E2-3.html, randomly place five unknown charges in a small region of space. Use any information available to determine the relative strength and sign of these five charges.
E-3 Capacitance

LEARNING OBJECTIVES:

Content goals: (1) Understand the parallel-plate model of capacitance. (2) Understand the differences between capacitors in series and parallel. Inquiry goals: (1) Comparison of models to data. (2) Estimations of error.

PART I: Parallel Plate Capacitors

INTRODUCTION:

We will explore the most common model of the capacitor: the parallel plate. This device allows us to experiment with aspects of capacitance that are not normally available to us in commercially produced electronics. We will use the parallel plates to test our model of capacitance and find the limitations of this technique.

PRELIMINARY QUESTIONS:

1. If the charge on a capacitor is doubled, what is the change in the voltage on that capacitor?
2. If the separation between the plates is doubled, what happens to the capacitance?
3. The parallel-plate model only holds when the separation between plates is small compared to the size of the plates. Using what you learned in last week’s lab, draw a set of electric field lines for a capacitor with a separation comparable to the plate size. How does this help you understand the limits of the model?

APPARATUS:

1. Pasco parallel-plate capacitor
2. Electrometer and Cable
3. Power supply

EXPERIMENTS:

1. Draw a schematic of your experimental setup as outlined in the next four steps.
2. Connect the two plates of the capacitor to the electrometer as shown in figure 1.
3. Separate the plates by half a centimeter. This gap keeps the charge from leaking between the plates on dry days.
4. Charge the plates to 15V by momentarily connecting the positive lead of the power supply to the input plate and the other lead to the grounded plate.
5. With the supply leads disconnected, slowly change the plate spacing. Be sure to span at least 5cm. Observe the changes in voltage as you move the plates farther apart.

**NOTE:** Stray static charge will affect your results. Remove "Static-y" clothing and move as little as possible while performing the experiment.

6. Describe qualitatively what you observe. Address the functional dependence of the data (linearly increasing, exponentially decreasing, etc.). Be sure to mention any deviation from that dependence.

7. Return the plates to a half-centimeter spacing and recharge them to 15V

8. Record a table of voltage vs separation out to 5cm in 0.5cm increments. Make a scatter plot of your result in Excel. Be sure to add error bars to your voltage measurements.

**QUESTIONS:**

1. Based on the extent of the error bars, which parts of the plot are most consistent with the parallel plate model: $C = \epsilon_0 A/d$? Which parts are inconsistent and why?
2. Calculate the charge on the non-grounded plate of the capacitor in its initial configuration (assume a dielectric constant of 1). Based on your data, calculate the charge at a separation of 2.5cm and 5cm. Be sure to propagate your errors due to uncertainties in your measurements (see the error analysis section at the beginning of your lab manual). Are these values consistent?

3. What is the energy stored in the capacitor, \( U = \frac{1}{2}CV^2 \), in its initial configuration? How does that change as a function of separation?

PART II: Capacitor circuits

INTRODUCTION:

Now we will use commercially manufactured capacitors identical to what you find in modern circuitry. The construction of these devices is quite complicated and is designed to largely mitigate the inconsistencies that you saw with the parallel plate. The capacitances of these devices are fixed and usually very reliable. Here we will look at how capacitors behave in series and parallel configurations.

PRELIMINARY QUESTIONS:

1. When adding two capacitors in series, do you expect the resulting capacitance to be higher or lower than the capacitance of the components? What if they are in parallel?

2. What is the relative charge of two capacitors in series if one is double the capacitance of the other? What if they are in parallel?

APPARATUS:

1. Plug Board
2. Circuit element kit
3. Power Supply
4. Electrometer
5. Voltage Probes and BNC cables

EXPERIMENTS:

Use the electrometer and probes to measure voltages. Connect the red probe to the electrometer input connection, and the black probe to the electrometer ground input with black coaxial cables (not the banana plug cables).

Series capacitors:

1. Temporarily short out each capacitor, by plugging it into the metal holder. This ensures that there is no residual charge on the capacitors.

2. Build the circuit in Figure 2 (note that the voltage source is not connected).
3. Touch the black and red voltage source leads across the series circuit, then disconnect the leads.

4. Measure the voltage drops across each capacitor individually. Be sure to include estimates of error. Compare these to the predicted value.

**Parallel capacitors:**

1. As in the previous experiment, temporarily short out each capacitor.

2. Build the new circuit in Figure 3 (again, the voltage source is not initially connected). **Do not place the second capacitor!**

3. Charge up the 0.47 $\mu$F capacitor to 12V and disconnect the supply leads.

4. Add the 1.0 $\mu$F capacitor to the circuit in parallel

5. Measure the voltage drop across each capacitor. Be sure to include estimates of error. Compare these to the values predicted by the model.
Plug 1 μF capacitor in after making sure it is discharged, and after disconnecting the voltage source.
E-4 Electron Charge to Mass Ratio

OBJECTIVES:

To observe magnetic deflection of electrons, at fixed energy, in a uniform magnetic field and then use this information to obtain $e/m$, the electron charge/mass ratio.

APPARATUS:

Figure 1: Foreground: dip-needle magnetic-field sensor sitting on power supplies with built-in digital meters; Background: Sargent-Welch $e/m$ equipment and black cardboard.

INTRODUCTION

Your $e/m$ vacuum tube contains a number of features for producing and visualizing a thin uniform electron beam. Refer to Figs. 2 & 3 for schematic details. Passing current through a wire filament (F) causes it to become hot. If the filament becomes hot enough, electrons spontaneously leave the surface (a process called thermionic emission). The filament is in close proximity to a higher-potential electrical element (the anode C), and so some of the electrons accelerate through the vacuum towards the anode. The current between the filament and anode is called the “anode current”. To allow a narrow beam of electrons to leave the vicinity of the anode a thin slit, S, has been cut in the anode cylinder.

Normally the electron beam is invisible to your eye. However the $e/m$ tube also contains Mercury (Hg) vapor. When electrons with energies in excess of 10.4 eV collide with Hg atoms, some atoms become ionized or excited, and then quickly recombine and/or de-excite to emit a bluish light. Hence the bluish light marks the path taken by the electron beam (the electrons which collide with atoms are permanently lost from the beam).

The potential difference $V$ between the filament and anode (Fig. 2 and 3) accelerates electrons thermionically emitted by the filament. Those electrons traveling toward
the slit $S$ emerge with a velocity $v$ given by

$$V_e = \frac{1}{2}mv^2$$

provided that the thermal energy at emission is small compared to $V_e$.

**Preliminary Questions:**

1. What is purpose of the Helmholtz coil? (read through the appropriate section first)
2. If you double the filament voltage, what would you expect to happen: A. beam gets brighter; B. radius of electron trajectory gets bigger.
3. If you double the filament current, what would you expect to happen: A. beam gets brighter; B. radius of electron trajectory gets bigger.

![Figure 2: The e/m tube viewed along the earth’s magnetic field (i.e., $B_{\text{earth}}$ is perpendicular to the page).](image)

![Figure 3: Side view of Figure 2.](image)
If the tube is properly oriented, the velocity of the emerging electrons is perpendicular to the magnetic field. Hence the magnetic force vector \( \vec{F} \), which is described as a cross product \( \vec{F} = e (\vec{v} \times \vec{B}) \), supplies the centripetal force \( \frac{mv^2}{r} \) for a circular path of radius \( r \). Since \( \vec{v} \) is perpendicular to \( \vec{B} \)

\[
evB = \frac{mv^2}{r}
\]

Eliminating \( v \) between (1) and (2) gives

\[
e/m = \frac{2V}{B^2r^2}
\]

Our digital voltmeter measures accurately the accelerating voltage \( V \). The radius of curvature, \( r \) or \( D/2 \), is half the distance between the filament \( F \) and one of the cross bars attached to rod \( A \). The cross bar positions are as follows:

<table>
<thead>
<tr>
<th>Crossbar No.</th>
<th>Distance to Filament</th>
<th>Radius of Beam Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.065 meter</td>
<td>0.0325 m</td>
</tr>
<tr>
<td>2</td>
<td>0.078 meter</td>
<td>0.039 m</td>
</tr>
<tr>
<td>3</td>
<td>0.090 meter</td>
<td>0.045 m</td>
</tr>
<tr>
<td>4</td>
<td>0.103 meter</td>
<td>0.0515 m</td>
</tr>
<tr>
<td>5</td>
<td>0.115 meter</td>
<td>0.0575 m</td>
</tr>
</tbody>
</table>

To find \( e/m \) we still need to know the magnetic field strength \( B \). Instead of measuring \( B \), we calculate it from the dimensions of the Helmholtz coils and the measured coil current, \( I \), needed to bend the beam so that it hits a given cross bar.

Helmholtz coils consist of two identical coaxial coils which are separated as in Fig. 4 by a distance \( R \) equal to the radius of either coil. They are useful because near the center \( (X = R/2) \) the field is nearly uniform over a large volume. (Most textbooks assign this proof as a problem. Hint: Find how \( dB/dX \) changes with \( X \) for a single coil at \( X = R/2 \), etc.)

The field at \( X = R/2 \) is in fact:

\[
B = \frac{8}{\sqrt{125}} \left( \frac{N\mu_0 I}{R} \right) \text{ teslas}
\]

as one sees by adding the axial fields \( B(x) \) from each of the single coils:

\[
B(X) = \frac{N\mu_0 IR^2}{2[R^2 + X^2]^{3/2}}
\]

\(^1\)The actual \( B \) at the maximum electron orbit is only \( \sim 0.5\% \) less. See Price, “Electron trajectory in an \( e/m \) experiment”, Am. J. Phys. 55, 18, (1987)
Thus when \( X = R/2 \), then

\[
B = 2B(X) = \frac{N\mu_0 I^2 R^2}{[R^2 + R^2/4]^{3/2}} = \frac{N\mu_0 I}{R \left[ \frac{5}{4} \right]^{3/2}} = \frac{8}{\sqrt{125}} \left( \frac{N\mu_0 I}{R} \right).
\]

In Eq. 4,

\[
N = \text{number of turns on each coil (72 for these coils)}
\]

\[
I = \text{current through each coil in amperes}
\]

\[
R = \text{mean radius of the coils in meters (approximately 0.33 m but varies slightly from unit to unit)}
\]

\[
\mu_0 = 4\pi \times 10^{-7} \text{ tesla meter/ampere}.
\]

Finally if we substitute (4) into (3) we obtain

\[
e/m = \left( 2.47 \times 10^{12} \frac{R^2}{N^2} \right) \frac{V}{I^2 r^2} \text{ coulombs/kg}. \tag{5}
\]

CIRCUIT DIAGRAM: Fig. 5 should help you hook up the components. The current must have the same direction in both sets of Helmholtz coils.

Figure 4: Basic wiring layout.

SUGGESTED PROCEDURE:

1. Set the axis of the Helmholtz coils along the local direction of the earth’s field, \( B_e \), as determined with a compass and dip needle. The axis should point towards the geographic north but at an angle about 60 degrees from the horizontal. Thus the axis should point deep under Canada. Put the long axis of the e/m tube in the north-south direction and with the cross bars up.

CAUTION: Nearby ferromagnetic material (e.g. steel in the power supply, the table and in the walls) can alter the local direction of \( B_e \). As long as the field direction does not change during the experiment, there should be no problem.

2. Set the filament supply knob to zero before turning the power on.
3. Since $e/m$ depends on $V/I^2$, one needs high quality meters for $V$ and $I$. Our digital meters have an accuracy of $\pm$ one digit in the last displayed digit.

4. Start with $\sim 22$ V between filament and anode. The anode current is displayed on the “anode” display. With the room dark, gradually turn up the filament control until the beam is visible. The anode current should remain zero until the filament is sufficiently hot, perhaps hot enough that you can see the glowing filament. The filament dial will often be well beyond the halfway position before the anode current departs from zero. You should not expect to see the beam until the anode current is at least a few milliamps. To make the beam more visible, use black cloth and black cardboard to block out stray light: place the black cardboard inside the Helmholtz coils and view from the top. When the beam appears, adjust the filament control to give 5-10 mA of anode current. **Do not exceed 15 mA!** With no current through the Helmholtz coils, the earth’s magnetic field should slightly curve the beam (like the dotted line in Fig. 2).

5. **Correction for the earth’s magnetic field:** Increase $I$ through the Helmholtz coils until the beam deflects. If the sense of deflection is the same as that from the earth’s field (i.e. when $I = 0$), reverse the leads to the Helmholtz coils; the curvature should then be like B in Fig. 2. The field from the coils then opposes the earth’s field; hence adjust the coil current until the beam path is straight. Since light travels in straight lines, the beam should then hit the glass at the center of the area illuminated by light from the filament.

This field current which just cancels the earth’s field, we will call $I_e$. Clearly the $I$ for Eqn. 5 must have $I_e$ subtracted: Let the correct field current for crossbar $n$ be $I_n$, and let $I'_n$ be the measured current to bend the beam around so that the outside sharp edge of the beam hits the center of the $n^{th}$ crossbar. Hence $I_n = I'_n - I_e$ is the correct current to bend the beam to the appropriate radius, $r_n$.

**MORE ACCURATE METHODS TO ELIMINATE THE EFFECT OF THE EARTH’S FIELD:**

Uncertainty in $I_e$ can dominate the uncertainty in $e/m$, so consider using the following more accurate methods to eliminate the effect of the earth’s field:

i. Take two readings of coil currents at $n = 3$, $I'_3$ and $I''_3$: one with the earth’s field opposing that of the Helmholtz coils, the other with it aiding. To accomplish this, first (with the cross bars up) measure $I'_3$ (as described above); then rotate just the e/m tube $180^\circ$ about its long axis. CAUTION: Always rotate the tube in the sense to REDUCE the TWIST in the filament and anode leads. Otherwise one can twist the leads off.

Next reverse the current in the Helmholtz coil and adjust it so that the beam again hits the same cross bar. Call this reading $I''_3$. Then

$$I'_3 - I''_3 = 2I_e.$$
ii. Or better yet, for each cross bar record an \( I'_{n} \) and \( I''_{n} \) reading. The average

\[
\frac{I'_{n} + I''_{n}}{2} = I_{n}
\]

is the current required if the earth’s field were absent. You may find it easier to measure \( I'_{n} \) for \( n = 1 \) to \( 5 \) and then rotate the e/m tube just once to measure \( I''_{n} \).

**MEASUREMENTS AND ANALYSIS:** (If time is short, measure only two cross bars at each voltage.)

1. Make two determinations of \( e/m \) for each cross bar.

2. Repeat for an accelerating voltage of \( \sim 44 \) volts. (Note \( I_{e} \) should remain the same and one can measure it more precisely at the lower accelerating voltage.)

**SUGGESTED DATA TABULATION:** {If you use the alternative method (ii. above), replace \( I_{e} \) by \( I''_{n} \) and \( I_{n} = I'_{n} - I_{e} \) by \( I_{n} = \frac{1}{2}(I'_{n} + I''_{n}) \).

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Volts} & \text{bar} & \text{radius} & I_{e} & I'_{n} & I_{n} = I'_{n} - I_{e} & e/m \\
\hline
\hline
\hline
\end{array}
\]

3. Estimate the reliability of your value of \( e/m \) and compare to \( 1.76 \times 10^{11} \) C/kg.

**OPTIONAL:**

Note that the electron beam expands in a fan shape after leaving the slit. Interchange the filament leads and note how the fan shape flips to the other side of the beam.

**Explanation:** The fan shape deflection arises from the filament current’s magnetic field acting on the beam. Our filament supply purposely uses unfiltered half wave rectification of 60 Hz AC so that for half of the cycle no current flows thru the filament but which is still hot enough to emit sufficient electrons. The electrons emitted in this half cycle constitute the sharp beam edge which we use for measurement purposes. This trick not only avoids deflection effects for this part of the beam, but also avoids the uncertainty in electron energy arising from electrons being emitted from points of different potential along the filament. (During this half cycle of no filament current the filament is \( \sim \) an equipotential.) The fan shape deflection relates to electrons emitted during the other half cycle when filament current flows. [See: F.C. Peterson, *Am. J. Phys.* 51, 320, (1983)]
E-5 Magnetism

E-5a Lenz’s Law

OBJECTIVES:
1. To observe the eddy currents induced by the magnetic field in a moving conductor.
2. To follow how the eddy current intensity depends on the shape of the conductor.

YOU NEED TO KNOW: You must understand and be able to use the Right Hand Rule in order to determine the direction and sense of the forces involved.

APPARATUS:
A Permanent Magnet; four different paddle pendulums; two small red and green magnets. (There is only a single one of these set-ups per room and so, if it is in use, proceed to the next section first.)

PROCEDURE I: (10 min)
1. Using one of the small magnets determine the direction of the magnetic field between the jaws of the permanent magnet.
2. Observe and describe the behavior of the four pendulums when dropped between the jaws of the permanent magnet.
3. Reverse the magnet. Observe and describe the behavior of two pendulums when dropped between the jaws of the permanent magnet.
4. Set pendulum #1 between the jaws of the magnet. Move the magnet rapidly in a direction parallel to the pendulum plate (i.e. without touching jaws). Describe what happens.

Figure 1: The magnet and the paddle pendulum.

Figure 2: Paddle moves in the +y direction
QUESTIONS:
Q1: Use the right hand rule to determine the motion of electrons at the moment when pendulum # 4 enters the magnetic field region. Is it from A to B? Or from B to A?
Q2: What is the direction of the current flowing in the pendulum? Is it from A to B? Or from B to A?
Q3: Use the right hand rule to determine the direction of the force exerted on the current that flows in the arm of the pendulum by the magnetic field. Is it along the positive or the negative y axis?

**E-5b Induction - Dropping Magnet**

**OBJECTIVE:**
To show that a moving magnet induces an *emf* within a coil of wire.

**INTRODUCTION:**
After discovering the phenomenon of induction using two coils wrapped around an iron ring, Faraday was able to show that plunging a magnet into a coil of wire also generated a momentary induced current. Faraday did not use the concept of Changing Flux instead he thought of the ‘lines of force’, and concluded that when these lines move across a wire an *emf* is induced. Can you see the correspondence of this concept with the concept of flux? Think about this.

![Figure 3: A moving magnet - lines move across a wire](image)

**EXPERIMENT:**
You will be repeating Faraday’s experiment by observing the *emf* induced in a coil by a fast moving magnet, and you will check that the *emf* you observe obeys the ‘right hand rule’. If you have the time you can see the effect of changing the speed and the polarity of the magnet.

**YOU NEED TO KNOW:** Lenz’s Law and the use of the right hand rule. A varying magnetic field induces a current that opposes the magnetic field change.

**EQUIPMENT:**
PC, PASCO interface and power amplifier module.

A voltage sensor is connected to the coil and to port A of the interface. Be sure the red wire is connected to the top of the coil. In this way a positive voltage corresponds to a current in the direction of the arrow on the top of the coil.

A stand holding a plastic tube and a coil.

A long bar magnet, this magnet has a small cut at one end, that is the North pole.

A pair of red and green bar magnets

PRECAUTIONS:

The bar magnet is very fragile. DO NOT DROP IT!

The bar magnet is easily depolarized. KEEP OTHER MAGNETS AWAY!

When dropping the magnet, hold the tube and stopper together.

PROCEDURE I: (15 min)

1. Click on the Launch E-5b icon below (web version) to initiate the PASCO software window. Click “setup” (brings up “Experiment Setup” window); click appropriate channel; set sensitivity to “Low (1x)”. Make sure sampling rate is no less than 500Hz.

2. Set the distance \(d_1 \sim 15\ cm\) between the top of the plastic tube and the top of the coil. Record this in your lab notebook. Be sure that the red terminal of the voltage sensor is plugged on the top plug of the coil.

3. The long bar magnet has a narrow cut at one end, this is the North pole of the magnet.

4. Hold the long bar magnet at the top of the tube; the end with the cut should be down, and just one centimeter or so inside the tube.

5. CLICK on the START icon and drop the magnet immediately afterwards.

6. to see the whole graph, and measure the heights \(h_1\) and \(h_2\) of the two peaks using the cursor cross-hairs [see PASCO Interface and Computer Primer section (Appendix E.)].

7. Slide the tube upwards, remove the rubber stopper and the magnet, replace the rubber stopper at the bottom of the plastic tube, and slide the tube down again.

8. Print the graph on printer.

QUESTIONS: (10 min)
Q1: The graph you obtained has a fall, a rise, a diminished slope, then a rise and finally a fall. Explain what is happening at these various times.

Q2: Explain why the two voltage peaks you measured in 1.6 are not the same size. Can you give an approximately quantitative justification for the ratio $h_1/h_2$? HINT: remember Newtonian mechanics formula for free fall $v = \sqrt{2gh}$ where $g$ is the acceleration due to gravity.

Q3: Examine the direction of the winding in the coil; verify that the directions of the peaks is what you would expect using the right hand rule (curled fingers = current; thumb = magnetic field).

PROCEDURE II: (10 min)

Repeat procedure I with the magnet inverted (the South Pole at the bottom).

QUESTION:

Q1 Explain in what way(s) and why the new graph is different.

PROCEDURE III: (20 min)

1. Move the coil further down on the tube making the new distance $d_2$ at least about two and a half times larger than $d_1$. Record this new distance $d_2$.
2. Repeat procedure I. Measure and record the heights $h'_1$ and $h'_2$ of the new peaks.

QUESTIONS:

Q1 Explain the reason for the difference between this graph, and the one obtained in procedure I.
Q2 Can you give an approximate quantitative explanation for the ratio $h'_1/h_1$?

E-5c Induction - Test Coil

OBJECTIVES:

1. To observe the emf induced in a small detecting coil by the varying magnetic field produced by the varying current in a separate large coil.
2. To follow how this emf depends on the shape, and the frequency of the inducing current. The computer will produce a voltage varying with time in the form of a triangular waveform with amplitude $V_{max} = 3$ V and a frequency $f = 10$ Hz.

![Figure 5: The triangular waveform](image)

INTRODUCTION:
1. The applied voltage varies linearly from $V_{\text{min}} = -3 \, V$ to $V_{\text{max}} = 3 \, V$ in $50 \, ms$. The slope of the voltage curve is therefore $\Delta V/\Delta t = 120 \, V/s$.

The resistance of the large coil is $R \simeq 7 \, \Omega$ so current flowing in the large coil will vary linearly from $I_{\text{min}} = -3/7 = -0.43 \, A$ to $I_{\text{max}} = 3/7 = +0.43 \, A$ in $50 \, ms$. Correspondingly $\Delta I/\Delta t = 17.2 \, A/s$. The strength of the magnetic field produced by the large coil is proportional to the voltage applied on it, and therefore the rate of change $\Delta B/\Delta t$ is proportional to the slope of the curve that shows the voltage versus time.

\[ \text{YOU NEED TO KNOW: The emf induced in a coil is then }\mathcal{E} = -N\mathcal{A}\Delta B/\Delta t \text{ where } N \text{ is the number of turns in the small coil and } \mathcal{A} \text{ its cross-sectional area.} \]

\section*{EQUIPMENT:}
- PC and PASCO CI-750 interface.
- Power amplifier module.
- A stand holding a small detecting coil.
- Two large back-to-back coils with an ohmic resistance $R = 7 \, \Omega$. The radius of the coil pair is $r = 0.105 \, m$. The output signal from the PASCO goes to the input of the Power Amp and then the output from the Power Amp goes to the large coil (using the RED and BLACK banana jacks).

\section*{PROCEDURE I: (10 min)}
1. Click on the Launch E-5c icon below (web version) to initiate PASCO software window. The monitor should now show a scope window and a window for the control of the signal generator. If necessary set the frequency to 10 Hz and the pull down menu to choose the triangular (or sawtooth) waveform. In the oscilloscope window set the trigger level to 1 V.

2. If necessary adjust the signal generator amplitude to 3 V.

3. Analog channels A and B are used to sense the voltage drop across the large coil (A) and the voltage induced in the small coil (B). For both coils, connect RED to 1 and BLACK to 2 (see Fig. 6).

4. Turn on the signal generator and initiate data acquisition by CLICKing on the START icon. You should now see the voltage induced in the small coil together with the one applied to the large coil.

5. Adjust the size of the waves you see in the scope window using the size controls on the side of the scope window, then measure the height $h_1$ of the square wave using the cursor [see PASCO Interface and Computer Primer section (Appendix E.)]. Record this height.

\section*{QUESTIONS}
(a) Explain why the induced voltage is a square wave.
(b) Observe the direction of the winding in the large coil. What is the direction of the magnetic field during the rising part of the triangular wave? Explain your thoughts.
Figure 6: The layout with the Pasco CI and back-to-back coil assembly.

(c) Observe the direction of the winding in the small coil. What is the direction of the induced \textit{emf} during the rising part of the triangular wave? Explain your thoughts.

**PROCEDURE II:**

Move the small detecting coil 5 centimeters away from the large coil, measure the amplitude of the induced voltage. Repeat at distances of 10 and 15 centimeters. Make a simple graph using Microsoft Excel or any other suitable application.

**QUESTION**

How does the strength of the magnetic field depend on distance? $\sim 1/r$? $\sim 1/r^2$? $\sim 1/r^3$? Or something else?

**PROCEDURE III:**

1. Replace the detecting coil to its original position at the center of the large coil. Decrease the amplitude of the triangular wave to 2 V.

2. Measure the height of the square wave and record this value.

**QUESTIONS**

Q1: Did the slope of the triangular wave change? By how much?

Q2: Is the change in amplitude of the square wave what you would expect? Why?

**PROCEDURE IV:**

1. Repeat procedure III with a frequency of 15 Hz.

2. Compare the result with those of procedure I and III

**PROCEDURE V:**
1. Return the voltage and frequency to the values used in procedure III. Rotate the
detecting coil 90° so that it is in the horizontal plane. Observe the resulting induced
voltage.

2. Rotate the coil another 90° so that it is in the vertical plane again. Observe the
resulting induced voltage. Compare the result with procedure III.

E-5d Induction - Faraday Discovery

INTRODUCTION:

Michael Faraday (1791-1867) was a bookbinder journeyman (English for appren-
tice). He read some of the books he was supposed to bind, and became interested
in ‘natural philosophy’ (the term science did not exist in the XVIIIth century).
In 1813 he applied for a job as a technician in the laboratories of the Royal Labora-
tories to professor Davy, he got the job. Some people say that this was the greatest
discovery Davy ever made! He worked all his life in the laboratories, starting as a
technician, became Director of the Laboratories, was elected to The Royal Society
of London, and became a Professor at the Royal Institution. Some of you will be
pleased to know that he knew no math, and never used math in his researches.

Faraday performed many kinds of experiments, in chemistry, optics, and metallurgy,
but perhaps the most important experiments were on electricity and magnetism.
Having learned of Oersted’s experiments on the magnetic fields produced by an
electric current, he wondered if the reverse could be true: perhaps magnetic fields
could in turn produce an electric current. His first experiments were unsuccessful,
until he realized that it was the change in magnetic field that produced a
momentary current.

His first experiments were similar to the one you will be doing today: two separate
coils were wound on an iron ring, the current in the primary coil was interrupted,
and the momentary current in the secondary was observed.

The explanation of this effect is, as you know, that the change in current in the pri-
mary circuit produces a change in the magnetic field that exists inside the secondary
coil, the electromotive force in the induced secondary is then

\[ \mathcal{E} = -AN \cdot \left( \frac{\Delta B}{\Delta t} \right) \]

where \( N \) is the number of turns, and \( A \) is the cross-sectional area of the secondary
coil.

OBJECTIVES:

To observe the induced momentary emf that appears in a secondary circuit when
the current in the primary circuit is turned on, or interrupted. This is the original
Faraday discovery: induction of a current by a varying magnetic field.

In procedure II you will observe that induced momentary emf appears also in the
primary circuit itself when the current is turned on, or interrupted; you will be
observing the self induction of a coil. Faraday used a switch to interrupt or start
the current as shown in Fig. 7; you will use the computer to do the same job: the
computer will produce a square wave, the voltage will change abruptly from 0 volts
Figure 7: Faraday’s experiment

Figure 8: The square wave

(current off = switch open) to a value of about 3 Volts (current on = switch closed) as shown in Fig. 8.

EQUIPMENT:
- PC and PASCO CI-750 interface, again with Output connected to the power amplifier input.
- Two voltage sensors are plugged in the interface. The voltage sensor plugged in the A port measures the voltage across the external resistor; the voltage sensor plugged in the B port measures the voltage across the coil (see Figs. 9 and 10).
- Computer controlled Power Amplifier Module.
- A pair of nested coils. The outer one is the ‘primary’. It has about 2600 turns of fine wire and has a resistance of \( \sim 95 \, \Omega \). The primary coil is insulated from the inner secondary coil, an iron bar fits inside the inner coil.
- A plug board and a 100 \( \Omega \) resistor.

PROCEDURE I:
1. Click on the Launch E-5d icon below (web version) to initiate the PASCO DataStudio software window. Set sensitivity setting (in Experiment Setup window) for Channel A to “Low (1x)” and for Channel B to “High (100x)”. Make sure the iron bar is inserted in the inner coil.
2. Check that the power amplifier is on, (the yellow pilot light labeled ‘Power’ should be on and the red pilot light labeled ‘Distorting’ on the power amplifier should off).
3. Check that the amplitude is \( \sim 4 \) Volts, and the frequency is \( \sim 10 \) Hz. CLICK on the ON button of the Signal Generator, then CLICK on START icon.
4. The computer monitor should now display two curves:
   - one curve (curve A) looks like a square wave, but not quite; it shows the voltage across the external 100 \( \Omega \) resistor, and therefore tells you the current flowing in the coil.
   - the other curve (curve B) shows the induced voltage across the secondary coil.
5. Then print the graph for one of the peaks [instructions are in the PASCO Interface and Computer Primer section (see Appendix E.)].

QUESTIONS:
Q1: The shape of curve A is not quite a ‘square wave’. Why not? HINT: this is an LR circuit with a time constant \( \tau = \frac{L}{R} \)
Q2: Are the peaks of voltage across the secondary coil, (curve B) that correspond to current on vs. current off about the same size? Explain.
Q3: Are the peaks of voltage across the secondary coil, that correspond to current on vs. current off of the same polarity? Explain.

PROCEDURE II: (15 min)

1. Remove the voltage sensor banana pins from the terminals R and S of the secondary coil and insert them into the terminals P and Q of the primary coil, without disconnecting these terminals from the power supply.
2. Change the sensitivity of Channel B to “Low (1x)” and change the scale of scope 2 to 1 V/div.
3. CLICK on the ON button of the Signal Generator, next CLICK on START and then, after a second or so, CLICK on STOP.

4. The Monitor now displays two curves:
   - one curve (curve A) looks like a square wave, but not quite; it shows the voltage across the external 100 Ω resistor, and therefore tells you how the current flowing through the primary coil varies with time.
   - the other curve (curve B) shows the voltage across the primary coil.
   The two curves look very similar: they should have about the same height, and should rise and fall at the same times.

   If curve B is inverted relative to curve A, exchange the banana pins in terminals P and Q and repeat item 1.2 of this procedure.

5. Adjust the graph axes so that just one full cycle may be seen and then print out copies for your lab manual [instructions in PASCO Interface and Computer Primer section (refer to Appendix E.)].

QUESTIONS
Q1: The shape of curve A is not quite a ‘square wave’, why not? HINT: this is an LR circuit with a time constant $\tau = L/R$
Q2: The curve that describes the voltage across the primary coil, (curve B) is similar to curve A. Why? HINT: think of two approximately equal resistors in series.
Q3: The curve that describes the voltage across the primary coil, (curve B) is similar to curve A, but it shows ‘spikes’. Why? HINT: the voltage across this coil is due to two factors, R and L.
E-6 Oscilloscopes and RC Decay

LEARNING OBJECTIVES

Content goals: (1) Learn the basic operation of an oscilloscope. (2) Use the oscilloscope to understand RC Decay. Inquiry goals: (1) Comparison of models to data.

PART I: THE OSCILLOSCOPE

Introduction:

The oscilloscope is basically a high-speed graph-displaying device – it draws a graph of an electrical signal called a waveform. In most applications the graph shows how signals change over time: the vertical (Y) axis represents voltage and the horizontal (X) axis represents time. This simple graph can tell you many things about a signal. Here are just a few, you can ...

- determine the amplitude and frequency
- tell how often a particular portion of the signal is occurring relative to other portions.
- find out how much of a signal is direct current (DC) or alternating current (AC).
- tell how much of the signal is noise and whether the noise is changing with time.

Basic Functions:

In this section, you’ll set up the oscilloscope to display a waveform as shown in figure 1. Power on the scope and press the “Default Setup” button on the second row of buttons at the top of the panel. If you ever get lost, you can press Default Setup and start from scratch. Connect the Channel 1 probe to the gold contacts. These contacts output a continuous 5V@1kHz square wave. The probe itself should be clipped to the top contact and the alligator clip ground should connect to the bottom contact. You should initially see a very unsteady display that is not scaled properly.

To stabilize the graph, adjust the “Trigger Level” knob. The trigger level is indicated graphically by an arrow on the right side of the display. It is also displayed numerically on the bottom right. You should now see a stable plot that is clipped at the top.

Use the Channel 1 “Vertical” scale knob to display the entire waveform. The numerical value for this scale is displayed in Volts on the bottom left corner of the display. You may have to readjust the trigger level after scaling.

Use the “Horizontal” scale knob to scale the waveform horizontally to match the figure. This scale is displayed in μ-seconds on the bottom center of the display above the date.

Play around with all three knobs until you understand what they are doing. What is the function of each knob and how do they relate to the numbers displayed? What is the relationship between the scales and the grid that the waveform is plotted against? How does the trigger level need to relate to the amplitude of the waveform to display a stable graph?
Measurement

While the display grid will allow you to make crude measurements of amplitude and period, our oscilloscopes offer more sophisticated measurement tools in the form of cursors.

Press the “Cursor” button on the second row of buttons on the top of the panel. Change the Type to Amplitude. Using the knob at the top left, adjust the cursor position to line up with the maximum amplitude of the square wave. Note that the position of this cursor is displayed on the right side under Cursor 1. Now highlight Cursor 2 and adjust the position to the minimum amplitude of the square wave. The difference between the two cursor positions is displayed at $\Delta V$ and should be 5V in this case.

Change the Type to Time. Using the same mechanics as above, measure the period and frequency of the displayed waveform. Estimate the error on this measurement and the amplitude measurement above.

Probe the gold contacts with the Fluke Multimeter set to measure AC Volts and record the result. Why is this number different from the amplitude measured with the cursors? Are the two measurements consistent?

External Signals

Disconnect the probe from the gold contacts and connect them to the output of the function generator using the BNC to micro-grabber adapter. **Always use the oscilloscope probes to connect to the inputs. Never use a BNC cable.** Turn the function generator on. Its default output 5V@1kHz sine wave should be displayed on your oscilloscope. The amplitude given by the function generator is the Peak amplitude, or the maximum absolute value of the signal. Measure the Peak-to-Peak amplitude and the Frequency of
the waveform. Do they agree with the function generator to within your measurement uncertainties?

Now connect the Fluke Multimeter to the function generator output and record the RMS amplitude. Is this measurement consistent with the oscilloscope?

Experiment with several different types, amplitudes and frequencies of waveforms created using the function generator. What is the difference between the 5V@1kHz square wave you first observed and the 5V@1kHz square wave generated by the function generator? Be sure you are confident in your abilities to accurately display several types of waveform on the oscilloscope before moving on.

**PART II: RC DECAY**

Now we will use the scope to characterize an RC Circuit. Build the series RC circuit with the plug board kit as shown figure 2. **Be sure to match the raised bump indicating ground with the figure.** Drive the circuit with a 5V@1kHz square wave. Monitor the function generator output with the oscilloscope as you’ve done in previous sections. Plug a second probe into Channel 2 of the oscilloscope and use that probe to measure the voltage drop across the capacitor. You’ll need to press the blue “2” button. You should see something similar to figure 3.

![Figure 2: RC Circuit Schematic](image)

Using the cursor feature, measure the time constant for this circuit. Does it agree with the calculated value to within your measurement precision? For five different combinations of resistors and capacitors, measure the time constants and compare them to the calculated values. You will need to change the driving frequency of the function generator and the horizontal scale of the oscilloscope accordingly.

**PART III: DIFFERENTIAL AMPLIFIERS**

Amplifiers are devices which usually increase the amplitude of the output signal compared to the input signal. The customary symbol for an amplifier is a triangular shape:
In the sine wave example above, the gain is 10 and the input signal is between an input terminal and ground. The internal oscilloscope amplifiers for channels 1 and 2 are of this type and have a common ground. Because of this common ground, one has problems in using a scope to examine simultaneously voltages across individual circuit elements that are in series.

We can avoid these problems by interposing “differential amplifiers” which have two inputs $V'$ and $V''$, (neither at ground), and which amplify only the voltage difference $(V' - V'')$. 
See figure 5. Note now that the ground of the output signal is independent of any input ground.

Connect the resistor and capacitor signal to the differential amplifiers as shown in the figure below. Connect the outputs of the differential amplifiers to the scope inputs, and set both gains to 1. You should see something similar to figure 7. Describe what is happening to the voltage drop across the resistor when the capacitor is charging and discharging. What is the relative phase of the two components? Now press the pink “Math” button to bring up a selection of mathematical operators. Change the operation to “+”. Describe the significance of what is now displayed. How is it consistent or inconsistent with Kirchoff’s laws?

Figure 6: Inputs to differential amplifiers

Figure 7: Differential Amplifier Outputs
LEARNING OBJECTIVES:

Content goals: (1) Study voltage and phase relationships in LRC circuits. (2) Explore concepts of impedance and resonance. Inquiry goals: (1) Comparison of models to data.

INTRODUCTION:

In the previous oscilloscope lab, we learned the basic functionality of the oscilloscope and used it to characterize several RC circuits. In this lab we’ll add inductors to the experiments and use more sophisticated concepts to aid with the analysis. We’ll need to introduce the concepts of impedance and resonance before we get to the experiments.

We define the impedance $Z$ of any part of a circuit is the ratio of the voltage across that part and the current though that part. Because impedance is defined as a ratio of voltage/current, impedance is measured in Ohms.

Recall that:

- The impedance $X_R$ of an resistor $R$ is $X_R$
- The impedance $X_L$ of an inductor $L$ is $X_L = 2\pi fL$
- The impedance $X_C$ of a capacitor $C$ is $X_C = \frac{1}{2\pi fC}$
- The impedance of the entire circuit (shown in Fig. 1) is

$$Z = \sqrt{X_R^2 + (X_L - X_C)^2}$$

Note that the impedance $Z$ of the RLC series circuit is a minimum for $X_L = X_C$. The frequency for which this occurs is the resonant frequency. Derive an expression for this frequency in terms of the inductance and capacitance of the circuit.

At resonance, the current through $R$ is maximum, but the voltage $V_{LC}$ across the LC series combination is a minimum and in fact would be zero if the inductor had no resistance.

LRC Circuits

Create the circuit in figure 1 using the plug board kit. The function generator supplies $V_{AC}$. By default it generates a sine wave at a displayed amplitude of 5V (10V Peak-to-Peak) and displayed frequency of 1 kHz.

Voltage relationships

Use the DMM to measure the RMS voltage drop across the resistor, capacitor, inductor and all three together (Yes, you should be writing this down). Recall that the current through all of these components is identical as they are in series. Are these measurements consistent with your expectations? Explain this in terms of the measured voltage drops in terms of the impedances of each component.
Repeat these measurements at 700 and 400 Hz. How and why do the voltage drops of each component change as a function of frequency? How and why does the voltage drop of the entire circuit change?

Use the oscilloscope to carefully search for the resonant frequency. Be sure to use the differential amplifier (as in lab E-6) for each of your signals. Measure the voltage drop across the resistor with Channel 1. Adjust the frequency until the signal is maximized. Is your measurement of the resonant frequency consistent with the calculated resonance? Measure the resonances for the 0.47 and 1 μF capacitors (Sorry, we only have the one inductor!) and note the differences.

For several different frequencies on either side of resonance, create a table of the voltage drop across the resistor. Add a third column to the table and calculate the power dissipated at each frequency. Use this table to create a plot of power vs frequency. Fit a Gaussian to this plot and record the width of the distribution and the maximum amplitude. Replace the 1KΩ resistor with a 100Ω resistor and repeat the above experiment. What is the difference? Radio and mobile phone transmitters are designed to transmit as much power in as narrow a frequency band as possible. Which of these circuits would make a better transmitter?

Phase Relationships

Switch back to the 1KΩ resistor and use channel 2 of the scope to look at the voltage drop across the combination of the inductor and capacitor. Use the Math feature to add the two waveforms. As you change the frequency, note the phase change between the different waveforms. Figure 2 shows this relationship. Set the signal generator near resonance. What is the phase relationship between the resistor part and the capacitor-inductor part of the circuit? Try to make a more accurate determination of the resonance frequency using the relative phase.

With $f = f_r$, short out the capacitor by a jumper, (e.g. with metal bridge connector). Note what happens. Un-short capacitor and then short the inductor. Explain results in terms of Fig. 2. Does current lead or lag the applied voltage in each case?
Remove the shorts and try $f < f_r$ and $f > f_r$. Explain the phase behavior.
**E-8: Transistors**

**OBJECTIVE:**
To experiment with a transistor and demonstrate its basic operation.

**APPARATUS:**
An npn power transistor; dual trace oscilloscope & manual; signal generator &
frequency counter; power supply (±15 V fixed/±9 V variable); circuit plug board &
component kit; two digital multimeters (DMM); differential amplifiers.

**INTRODUCTION:**
Our junction transistor (Fig. 1) is like two back to back np diodes (see E-8 Part
C, #3). Hence there are two possibilities, an npn transistor and a pnp transistor.
Our npn transistor has a central p-type layer (the Base) between two n-type layers
(the Emitter and Collector). There are other type transistors which we will not
discuss, (e.g. a MOSFET: Metal-Oxide Semiconductor-Field-Effect-Transistor).

![Figure 1](image1)

For an npn transistor the collector is positive relative to the emitter. The base-
emitter circuit acts like a diode and is normally conducting (i.e. forward-biased). The
base-collector circuit also acts as a diode but is normally non-conducting (reverse
biased) if no current flows in the base-emitter circuit. However when current flows
in the base-emitter circuit, the high concentration gradient of carriers in the very
thin base gives an appreciable diffusion current to the reverse biased collector. The
resulting collector current $I_c$ depends on the base current $I_b$. We write $I_c = \beta I_b$
where $\beta$ is the current amplification factor.

**PRECAUTIONS:** Although our power transistor is fairly indestructible, its
characteristics are temperature sensitive. Hence avoid exceeding the voltages
suggested; also leave the power supply off when not making measurements;
read currents and voltages to two significant figures only.

**SUGGESTED EXPERIMENTS:**

1. **CURRENT Amplification:**
   Measure $\beta$ for various emitter to collector voltages, $V_{ec}$. Set
   up the circuit as in Fig. 2.

![Figure 2](image2)
Start with the voltage divider completely counter-clockwise so that the emitter-base voltage $V_{eb}$ is a minimum. With the variable power supply set to 3 V, record the $I_b$ measured on DMM1 and the $I_c$ on DMM2.

Repeat the readings for ten reasonably spaced (higher) settings of the voltage divider (i.e. higher $V_{eb}$ and hence higher $I_b$).

Calculate $\beta (= I_c/I_b)$ and plot it against $I_b$. Over what range of $I_b$ is $\beta$ reasonably constant? Repeat the above but with emitter to collector voltage $V_{cc}$ now at 7 V.

2. (Optional) MEASUREMENT OF $I_c$ vs $V_{eb}$: Remove the multimeter DMM1 (used as a microammeter) from the circuit of Fig. 2 and use it instead as a voltmeter to measure the emitter to base voltage $V_{eb}$. With the variable power supply set to give 7 V for $V_{cc}$, use the voltage divider to vary $V_{eb}$. Read and record both $V_{eb}$ and $I_c$ for 10 reasonably spaced values of $V_{eb}$. Plot $I_c$ vs $V_{eb}$. The results are very similar to a diode curve (as expected since $I_c$ is proportional to $I_b$ over the region where $\beta$ is a constant).

3. VOLTAGE Amplification: By adding a large load resistor in series with the collector, one can convert the current amplification $\beta$ observed earlier into a voltage amplification. Hook up the circuit plug board as in Fig. 3.

The input voltage to the transistor $V_{in}$ includes the drop across the 4.7 kΩ protective resistor. The voltage gain is $G = \Delta V_{out}/\Delta V_{in}$. Record input voltages $V_{in}$ and output voltages $V_{out} (= V_{cc})$ for ten reasonably spaced values of $V_{in}$ from 0 to 5 volts.

Graph $V_{out}$ vs $V_{in}$ and calculate the voltage gain $G$ at the steeply changing part of your graph. The value of $V_{in}$ at the center of this region we call the “operating voltage” of the amplifier. How would the gain change if the load resistance was 2.2 kΩ instead of 10 kΩ?

4. Distortion effects when amplifier is overdriven: Set up the circuit plug board as in Fig. 4. Connect Y1 and Y2 to the scope. To connect the signal generator to the board, use the BNC to banana plug adapter and remember that the side with the bump goes to ground.
Adjust the voltage divider until the $V_{in}$ is close to the “operating voltage” found in #3.

Vary (and record) the amplitude of the input signal from small values to those which overdrive the amplifier and produce considerable distortion in the output $Y_2$.

Observe and record the effect of changing $V_{in}$ to values outside of the operating range (where $\beta$ is constant).
Part II  
Sound and Waves  

S-1 Transverse Standing Waves on a String  

OBJECTIVE: To study propagation of transverse waves in a stretched string.

INTRODUCTION:
A standing wave in a string stretched between two points separated by a distance \( L \) is equivalent to superposing two traveling waves on the string of equal frequency and amplitude, but opposite directions. The distance between nodes (points of minimum motion) is one half wavelength, \((\lambda/2)\). Since the ends of the string are fixed, the only allowed values of \( \lambda \) are \( \lambda_n = 2L/n \), \( n = 1, 2, 3 \ldots \).

The wave velocity, \( v \), for a stretched string is \( v = \sqrt{F/\mu} \) where \( F = \text{tension in the string} \) and \( \mu = \text{mass per unit length} \). But \( v = f\lambda \) and hence only certain frequencies are allowed,  
\[
 f_n = \frac{\sqrt{F/\mu}}{\lambda_n}. \tag{1}
\]

![Figure 1: The Modes of a String](image1)

![Figure 2: A close-up](image2)

PART A: Waves from a mechanical driver (i.e. a speaker)

APPARATUS:

*Basic equipment:* Electrically driven speaker; pulley & table clamp assembly; weight holder & selection of slotted masses; black Dacron string; electronic balance; stroboscope.

*Computer equipment:* Personal computer; PASCO\(^\text{©}\) interface module; power amplifier module; various electrical connectors.

The set-up consists of an electrically driven speaker which sets up a standing wave in a string stretched between the speaker driver stem and a pulley. Hanging weights on the end of the string past the pulley provides the tension.
The computer generates a digitally synthesized sine wave with adjustable frequency and amplitude (max: \( \sim 10 \, V \)). The PASCO interface transforms the digital signal into a smooth analog signal. This is fed into the power amplifier, which puts out the same signal, but with a current large enough to drive the loudspeaker.

**Precautions:** Decrease the amplitude of the signal if the speaker makes a rattling sound, or if the red pilot light on the amplifier is lit. The generator is set to produce sine waves; **do not change the waveform.**

**Note:** Although the speaker is intended to excite string vibrations only in a plane, the resultant motion often includes a rotation of this plane. This arises from nonlinear effects since the string tension cannot remain constant under the finite amplitude of displacement. [See Elliot, *Am. J Phys.* 50, 1148, (1982)]. Other oscillatory effects arise from coupling to resonant vibrations of the string between pulley and the weight holder; hence keep this length short.

![Figure 3: The apparatus](image)

**SUGGESTED EXPERIMENTS:**

**PROCEDURE I:** Checking Equation (1)

1. Place the sheet of paper provided on the table; this will make it easier to see the vibration of the string. Measure accurately the distance, \( L \), between the bridge and the pin of the speaker using the two meter ruler; record this in your lab notebook. Click on the LAUNCH EXPERIMENT icon (i.e., the telescope), from the on-line lab manual. The computer monitor will appear as shown in Fig. 4.

2. You will see that the computer is set to produce a 60 Hz sine wave with an amplitude of 2 V. To start the string vibrating **CLICK** the “ON” button.

3. **CLICK** on the up/down arrow in order to change the amplitude or the frequency of the signal although this produces rather large steps. **NOTE:** The nominal step sizes for adjusting the amplifier frequency and voltage may be much too large. To alter the step size use the \( \text{◀} \) or \( \text{▶} \) buttons. To alter the current or voltage (which of these depends on configuration) use the \( + \) or \( - \) buttons. You can also change the value directly by **CLICK**ing the mouse cursor in the numeric window and entering a new value with keyboard number entry.
4. At 60 Hz check Eq. 1 by first calculating the necessary string tension to produce a standing wave in the third or fourth mode. Weigh the string to get μ. Your instructor will provide you with a one meter length of string. (Dacron 30# has ≈ 0.283 g/m.) Note that the hanger itself has a 50 g mass so it may not be easy to access the fourth mode (depending on L).

Check your results by adjusting the string tension by increasing/decreasing the weight to find the tension which results in the largest amplitude vibrations. How do the two values (calculated and measured) compare?

5. Now put a 200 g mass on the mass hanger and restart the signal generator. Record the total mass and tension in your lab book.

6. Adjust the frequency so that the amplitude of the oscillation is at its maximum by changing the frequency in 1 Hz steps. This is best done as follows: First decrease the frequency until the amplitude of the string is very small. Then increase the frequency in 1 Hz steps, observe that the amplitude first increases and then decreases. Record the best frequency \( f_2 \) in your table.

7. Change the frequency to observe the third mode. Find and record the best frequency (using 10 Hz steps at first may be faster).

8. Find and record the frequency of the higher modes.

9. OPTIONAL: Check the frequency \( f \) of the string in its 2nd mode with the stroboscope. Note that the stroboscope is calibrated in RPM or cycles per minute, NOT Hz (cycles per second). You should find a value close to 70 Hz.

ANALYSIS:

1. Divide the various frequencies \( f_n \) by \( n \) and enter the values in a table. Calculate the average value of \( f_n/n \); this is the expected value of the frequency of the first mode.

2. Calculate the velocity of propagation on the string using the appropriate equation.

3. Calculate the mass per unit length of the string. How do the two values for the string mass per unit length compare?
PROCEDURE II: \( f_n \) vs string tension

In this section you will investigate the dependence of the resonant frequency of a string as a function of the applied tension.

1. Choose six masses between 100 gm and 1 kg and enter the values in the data table.
2. Determine the resonant frequency of the second mode of the string under these different tensions and record your results. (Hint: increasing the mass by a factor of two increases \( f_n \) by nominally a factor of \( \sqrt{2} \).)
3. Plot a graph of frequency versus mass, \( m \), and include the zero value.
4. Plot a graph of frequency versus \( \sqrt{m} \) and again include the zero value.

QUESTIONS:

1. Which of the two graphs can be fitted with a straight line? A parabola? Why?
2. From the slope of the graph having the linear relationship obtain the mass per unit length of the string and compare to your previous result.

PART B: “Virtual” waves on a drum head

PROCEDURE III: (If time permits)

Vibrations of a circular drum head. In this section you will examine, via a virtual demonstration, the vibrational modes of a two dimensional drum head.

1. Click on the icon at left to download and initiate the MPEG movie viewer to observe the “first” mode.
2. Use the replay and step frame functions to view the motion.
3. Where is the displacement at a maximum? Always at a minimum?

The [0,1] mode.

1. Click on the icon at left to download and initiate the MPEG movie viewer to observe the first of the two “second” modes.
2. Use the replay and step frame functions to view the motion.
3. Where is the displacement at a maximum? Always at a minimum?

The [0,2] mode.

1. Click on the icon at left to download and initiate the MPEG movie viewer to observe the second of the two “second” modes.
2. Use the replay and step frame functions to view the motion.
3. Where is the displacement at a maximum? Always at a minimum?

The [1,1] mode.

JAVA APPLET:

If time permits and you are interested the web version of the lab has a link to an applet ../java/ph14e/stwave_refl.htm which animates transverse 1D motion for a propagating wave incident on a fixed or a free boundary.
S-2 Velocity of Sound in Air

OBJECTIVE:
To calculate the velocity of sound from measurement of the wavelength in air for sound of a certain frequency.

APPARATUS:
Resonance tube with arrangement for varying water level (use only distilled water); rubber tipped hammer; tuning fork; Hg thermometer.

INTRODUCTION:
For a closed tube, resonance occurs at tube lengths of an odd multiple of one-fourth wavelength, i.e. at $\lambda/4$, $3\lambda/4$, $5\lambda/4$ etc.

SUGGESTIONS:
1. Find the positions of the water level in the tube for the first three of these resonances. Use these readings to calculate the speed of sound, $v = |\vec{v}|$. Initially have enough water that you can raise the level above the first resonance position. The tuning fork frequency is on the fork.

Since the effective end of the resonance tube is not at the tube’s end, do not use the position of the tube’s top in your calculations, but rather take differences between the other readings.

2. Sound waves in gases have a speed $v = \sqrt{\gamma RT/M}$. (Recall the formula for the speed of sound on a string, $v = \sqrt{T/\mu}$ (e.g., Lab S-1)). Correct your value of $v$ to 0°C ($T = 273.16$ K) and compare with that accepted for dry air at 0°C: 331.29 ± 0.07 m/s, [Wong, J. Acoust. Soc. Am., 79, 1559, (1986)]. For humid air see 3. below.

3. We quantify proportions in gas mixtures by the pressure each gas contributes to the total pressure. This is called the “partial” or “vapor” pressure. Think of the speed as resulting from an average $<\gamma/M>$,

$$<\gamma/M> = [(\gamma_a/M_a)P_a + (\gamma_w/M_w)P_w]/(P_a + P_w),$$

so that

$$v_{dry} \cong v_{humid}\sqrt{(\gamma_a/M_a)/<\gamma/M>},$$

where $\gamma_{air} = 1.40, \gamma_w = 1.33, P_a$ is the partial pressure of air, $P_w$ is the vapor pressure of water, $M_a \sim 29$ kg and $M_w = 18$ kg.

How should the v.p. of water, $P_w$, in the tube affect the speed?

OPTIONAL: Humidity changes will affect tuning of what musical instruments?

4. What effect does atmospheric pressure have on the velocity of sound in dry air? (Assume air at these pressures is an ideal gas.)

5. Viscosity and heat conduction in the tube may reduce $v$ by $\sim0.1\%$. See N. Feather, “The Physics of Vibrations and Waves”, Edinburgh Univ. Press, (1961), p. 110-120; this reference also has a delightful historical account (including Newton’s famous goof).
Part III
Light

L-1: Diffraction and Interference

OBJECTIVES:
To observe diffraction and interference and to measure the wavelength, $\lambda$, of laser light.

APPARATUS:
Optical bench; Diode laser assembly; two Pasco accessory disks; short focal length lens; screen; Pasco Interface with light and rotation sensors, mounting bracket, light aperture module
Interference demonstrations: optical flats (2), Newton’s rings, 18 mm gauge blocks (2), interferometer & Na lamp.

INTRODUCTION:
The diode laser provides plane light waves of wavelength 650 ($\pm 10$) nm. The waves in a perpendicular cross section of the beam are in phase (i.e. the light is said to be “coherent”). Any finite plane wave will spread by diffraction. The spreading is rapid if the beam is narrow, e.g. after passing the narrow slit in Part I below. If we illuminate two closely spaced narrow slits (narrow relative to the slit to slit spacing) by the same laser beam, the two spreading beams will overlap and interfere: Part II.

CAUTION:
The laser is a very bright source. Do not allow the laser beam to enter the eye and do not point the beam at anyone!

Experiment I: Single Slit Diffraction:

![Figure 1: Schematic of single slit diffraction](image)

Diffraction minima at $\theta = m \lambda / a$

Figure 1: Schematic of single slit diffraction
THEORY:

The angular separation in radians of the first minimum from the center of the pattern is

\[ \theta = \frac{\lambda}{a} \]

where \( a \) is the width of the slit. (For your derivation you may refer to the text and remember that for small \( \theta \), \( \sin \theta \approx \theta \).

SUGGESTED PROCEDURE:

1. Mount the laser and variable width slit on the optical bench as shown in Fig. 1. The laser light should fully illuminate the wheel pattern. Observe the pattern on the supplied white screen and qualitatively explain why in your lab book that the first minimum occurs as shown in Fig. 1 at \( m = 1 \).

QUESTIONS:

Q1. Qualitatively, how does the pattern vary as the slit width narrows (i.e., rotate the wheel)?

Q2. Qualitatively, how do you expect the pattern vary if the wavelength, \( \lambda \), could decrease from red to blue-violet?

Click on the Single Slit Diffraction link immediately below (web-version only) to test your prediction.

2. To enable more quantitative observations the PASCO interface module has been configured to provide an Intensity (0 to 100%) vs. Linear position of the light sensor plot and table. Launch the experiment by CLICKing on the telescope icon below (web-version only). After the PASCO experiment window pops up, start the data acquisition by CLICKing on the START icon. Move the combined light and rotary motion sensor in the lateral direction gently and smoothly by hand. Practice starting on one side of the diffraction pattern and move smoothly towards the other.

3. There are two aspects for configuring the light sensor: aperture size and detector gain. Using a larger aperture lets more light reach the detector. A larger gain increases the sensor output but can more easily saturate the output at maximum and increase the noise. To set the gain: 1) CLICK on the SETUP icon 2) DCLICK on the yellow light bulb icon (or Light Sensor) 3) In the Sensor Properties window click on the “Calibration” tab and 4) CLICK on Sensitivity pull-down menu. Ask your instructor for a brief demonstration if you are at all uncertain. Adjust and record the gain setting which give you reasonably good results.

4. Turn the PASCO wheel to a single slit width of \( a = 0.08 \) mm.

5. Let \( y \) be defined as the linear distance between the detector position and the location of the central maximum. Using the cross-hair feature of the PASCO graph display, measure \( \theta = y/D \) for \( m = 1 \) and -1. Plot \( m \) vs \( \theta \). From the slope and known value of \( a \), calculate \( \lambda \). Is your value of \( \lambda \) comparable with the stated value of the diode laser?
Experiment II: Two-Slit Interference

For double slit interference, shown in Fig. 2, the distance $y$ to the $n^{th}$ bright fringe from the midpoint, $y = 0$, is

$$y = D \tan \theta \approx D \theta \quad \text{and} \quad \theta \approx n \lambda/d$$

Hence

$$\lambda = \frac{y d}{n D},$$

(For more information refer to the text and recall that for small $\theta$, $\theta \approx \sin \theta \approx \tan \theta$.)

Interference maxima at $\theta = n \lambda/d$

Figure 2: Schematic of double (or multiple) slit interference.

SUGGESTED PROCEDURE:

1. Mount the slide containing the four electroformed slits in the slit holder (or rotate the PASCO wheel) and illuminate one of the slit pairs with the diode laser.

2. Note the difference in pattern and spacing of the resulting interference fringes on the screen. From Experiment I you know that individually these slits exhibit diffraction effects. Thus you will observe both (i.e., a combination of single and double slit diffraction) interference effects in all patterns. Observe the interference pattern for four slit pairs.

3. Choose one pattern for careful measurement and measure the separations between a number of adjacent maxima ($n = -1, 0, 1, \text{etc.}$) and calculate $\lambda$ using the same general procedure as experiment I.

4. Compare your calculated result with the stated value.
Experiment III (optional): Fresnel Bright Spot and Other Interference Patterns

**Diffraction from a small circular object** The Fresnel bright spot (also called Poisson’s bright spot) is a bright spot in the center of the shadow cast by every circular obstacle in the path of a plane wave. The effect is implicit in Fresnel’s representation of a coherent plane wave by half-period zones (e.g. see Shortley and Williams, “Elements of Physics” 5th ed. p. 737 or, if this is the web-version, see this example at http://www.physics.ucla.edu/~dauger/fresnel/PoissonAragoStory.html ), but was first pointed out by Poisson (a disbeliever in the wave theory) in an attempt to ridicule Fresnel’s wave theory. Arago subsequently showed experimentally that the spot existed.

**Diffraction from a small circular opening:** By analogy with the Fresnel bright spot in a circular shadow, you might expect a dark spot centered in the image of a circular opening. In this case the situation is more complex: the on-axis Fresnel bright spot in the shadow results from superposition of a large number of higher Fresnel half-period zones whereas the light from a small circular aperture comes only from a few low Fresnel half-period zones whose superposition on axis may result in either a dark or bright spot: Dark for an even number of zones, bright for an odd.

Test this using the 2 circular apertures on the PASCO Slit Accessory wheel. Illuminate the hole with the diverged laser beam in the same manner as described above. By varying the hole size and/or distance from hole to screen you may change the small number of half-period zones contributing and hence see the central point on axis as either a bright or a dark spot, e.g. see Fig. 13, Shortley and Williams, p. 740. Again careful alignment is important to obtain a clean symmetric image.

If time permits you may find it interesting to view the four addition two-dimensional diffraction patterns.

**DEMONSTRATIONS ON THE DISPLAY TABLE:**

A. Interference between optical flats, gauge blocks, etc.
B. Newton’s rings
C. Michelson’s interferometer
LC-2: Mirrors and Lenses

OBJECTIVES:
To study image formation and focal lengths of mirrors and lenses.

APPARATUS:
PASCO Optical Rail; Lenses & mirrors, telescope, illuminated arrow light source & 12V power supply, sharply pointed rod, desk lamp, white screen.

INTRODUCTION:
We will design, test and then measure mirror and lens assemblies by several techniques. In all instances it will be possible to use a simple interactive Java applet to perform a virtual pre-lab exercise. For the physical set-ups it will require testing location of image by absence of parallax, and others require focusing a telescope for parallel rays. For both techniques see Appendix D. Please master this material: your instructor is available for help.

Experiment I. Radius of curvature and focal length of a concave mirror:
VIRTUAL PRE-LAB:
1. If using the web-lab manual launch the virtual application by clicking on the Concave Mirror Application button below.
2. After clicking on “Start Me” you should observe a concave mirror, an object and its image. On the lower left corner is a cursor position readout.
3. With respect to the figure below and the mirror equation, find the focal length.
4. Adjust the object to get $p = q$, and obtain the focal length again.
5. Move the object so that $p = f$. Do you see an image?
6. Move the object so that $p < f$. Is there an image? Is it real or virtual? Is the image height smaller or larger than the object?

The Mirror Equation is given by:
\[
\frac{1}{p} + \frac{1}{q} = \frac{2}{R} = \frac{1}{f}
\]

where $f$ is the focal length and $R$ is the mirror radius curvature.
Note that when the object and image are equally distant from the mirror, $p = q = R$. You can use this condition to get an approximate value for $R$ and $f$.

![Figure 1: Layout of concave lens experiment.](image)

NOTE: The mirror holder contains a concave and a convex mirror on opposite sides. Be sure you use the concave mirror!

NOTE: You will need to place the white screen off to the side of the track and slightly twist the mirror mount to image the arrow.

SUGGESTED PROCEDURE
I. By using object and image distances:
1. Resolve the image of the illuminated arrow formed by the concave mirror on
the white screen. Experiment with varying object distances, \( p \), until you able
to follow how the image distance, \( q \), varies with the object distance. You will
need to slightly twist the mirror mount to make the image appear on either
side of the light source.

2. Measure the image distance at several different positions of the illuminated
arrow object. From each pair of conjugate object and image positions calculate
\( f \) for the mirror. Make a table of the results in your lab book, but leave space
to compare with the results of II. and III. below.

II. Obtaining \( f = R/2 \) by imaging at
center of curvature \( (q = p = R) \): Re-
place the illuminated arrow and screen
with the rod and place the rod at \( R \). If
the tip of the rod is at the center of cur-
vature, a real inverted image will appear
just above it with the tip and its image
coinciding. An absence of parallax (see
Appendix D.) between the tip and im-
age is the most sensitive test for coinci-
dence. When the parallax vanishes, the
distance between the tip and the mir-
ror is the radius of curvature \( R \). From
several determinations of \( R \), (switching
roles with your lab partners estimate the
reliability of your results.)

III. By placing object at the principal
focus \( (p = f) \): If the tip of the rod is
at \( f \), rays from the tip will reflect from
the mirror as a parallel bundle and give
a sharp image of the tip in a telescope
focused for parallel rays (see appendix
D). Keep the distance between tip and
telescope small or the reflected light may
miss the telescope. The best test for lo-
cating the focal point is absence of paral-
lax between the tip’s image and the cross
hairs in the telescope, but the telescope
must already be focused for parallel rays
(e.g., focus on something out the win-
dow). From several settings estimate the
reliability of your \( f \) measurement.

**Experiment II: LENSES**

**VIRTUAL PRE-LAB:**

1. If using the web-lab manual launch the virtual application by clicking on the Con-
verging Lens Application button below.
2. After clicking on “Start Me” you should observe a convex lens, an object and its image. On the lower left corner is a cursor position readout.

3. With respect to the figure below and the lens equation. Find the focal length.

4. Move the object so that its inverted image has the same height. Find the focal length at this point.

5. Move the object so that $p = f$. Do you see an image?

6. Move the object so that $p < f$. Is there an image? Is it real or virtual? Is the image height smaller or larger than the object? What is the sign of $q$?

1. **Converging lens with short focal length:**

   From the thin lens formula
   
   $$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

   Measure $f$ using the two methods diagrammed below (by adjustments in the object distance). Compare the results from the various methods.

   **I.**
   
   ![Diagram of converging lens setup]
   
   **Note:** $p+q \geq 4f$

   **II.**
   
   ![Diagram of converging lens setup]

2. **Focal length of a diverging lens:**

   Since the image is always virtual it is necessary to combine it with a converging lens and configured so that the final image is real.

**VIRTUAL PRE-LAB:**

1. If using the web-lab manual launch the virtual application by clicking on the Diverging Lens Application button below.

2. After clicking on “Start Me” you should observe a concave lens, an object and its virtual image. On the lower left corner is a cursor position readout.

3. With respect to lens equation and starting positions, find the focal length. Can you find an object distance for which the image height and object height are the same?
4. Now restart the simulation with a combination of a convex and concave lens by clicking on the “Add 2nd lens” link.

5. This 2nd lens will render a final image which is real. The image with a “1” by it is that of just the convex lens while the image with a “2” next to it is that of the pair. Move the object and alter its height, if necessary, so that the first image has the relationship \( q_1 \approx 2p_2 \). (In this simulation \( |f_2| = 3|f_1| \) and qualitatively resembles the figure shown below.)

6. Now repeat the last step with \( |f_2| = |f_1| \) by clicking on the “Another 2nd lens” link. Finally reset to the “Another 2nd lens” and then click on the convex lens and drag it past the diverging lens.

I. Use the set-up sketched below. First adjust Lens_1 so that with Lens_2 removed, \( q_1 \sim 2p_1 \). Measure \( q_1 \), insert the diverging Lens_2 reasonably close to Lens_1 and then locate the new image distance \( q_2 \). From \( p_2 = d - q_1 \) (a virtual object) and \( q_2 \) calculate \( f_2 \).

II. OPTIONAL: Find \( f_2 \) by this more sensitive method: With the pointed rod as object now detect the image by a telescope focused for parallel rays. (As shown in the following figure.)

If using the web-lab manual, launch the virtual application by clicking on the Dual Lens Test Application button below to obverse a point source in action.

To align all the objects: tape a piece of paper with a lot of markings on it to the pointed rod. Look through the telescope and move the diverging lens forward and backward until you can see some markings clearly in the telescope. Then move the rod up or down, as necessary, and rotate the telescope from side to side, as necessary, until you can see the tip of the pointed rod. Then move the diverging lens a small amount until the tip is in focus.

As a last step you will move the pointed rod (i.e. vary \( p_1 \) and hence \( q_1 \)) until a sharp image appears in the telescope with \textit{no parallax} relative to the cross hairs. (This occurs only if parallel rays leave the diverging lens.) The image from the converging lens at \( q_1 \) serves as a virtual object for the concave lens, Lens_2. After properly adjusting \( p_1 \) this virtual object will be at the focal point of the diverging lens, Lens_2. Obtain \( q_1 \) by setting \( p_1 \) and using the known value of \( f_1 \). (Make sure
that $q_1$ is large enough to accommodate $d + |f_2|$. Now look for the image in the telescope and adjust $p_1$. Note that since $q_2 = \infty$, $f_2 = p_2$ and $p_2 = d - q_1$.

**OPTIONAL**

**Experiment III: Focal Length of a Convex Mirror**

Once again, since convex mirrors give virtually images it is necessary to study the mirror in combination with a converging lens.

Measure the focal length of the convex mirror by combining it with a converging lens. Set the pointed rod at twice the focal length of the lens ($p_1 = 2f_1$). Next adjust the mirror position until the inverted image position shows no parallax with the object. Then $R = d - 2f_1$ and

$$f_{\text{mirror}} = f_2 = R/2.$$  

Of course the lens must have $f_1 > f_2$, so use a long focal length lens.
L-3: Optical Instruments

OBJECTIVE:
To construct a number of optical instruments and measure magnification.

APPARATUS:
Identical to the of L-2 plus white board, achromatic doublets, Ramsden eyepiece.

SUGGESTION: In constructing an optical instrument catch the real image formed by the first lens on paper. This location can tell where the next lens goes; e.g. for a telescope or microscope place the next lens slightly less than its focal length beyond the first image.

EXPERIMENTS:
1. Inverting Telescope
A. First measure the $f$ of a weak converging lens ($25 \leq f \leq 50$ cm) and of a strong converging lens ($f \sim 5$ cm). The first lens ($f$ large) typically has the virtue of intercepting and focusing a fairly large area of light while the second lens can be positioned to give a large virtual image (and hence magnification.) Notice that if the first image, $q_1$ is at a point $p_2 > f_2$ with respect to the second lens you get a real, erect second image. If you are using the web-based lab manual and desire a demonstration, click on the Inverting Telescope Demo button immediately below.

Use you will use these two lenses to construct an astronomical (inverting) telescope. As an object, use the white board and scale while illuminated by a bright light. As a procedure for measuring the magnification, vary the space between the objective $L_1$ and the eyepiece $L_2$ until the virtual image $I_2$ of scale $S$ seen through $L_2$ lies in the plane of $S$ (i.e. $p_1 + d = |q_2|$). As a sensitive test of this there should be no parallax between the scale as seen directly by your eye 2 and the scale image seen by eye 1 thru the telescope as shown in Fig. 2. Generally a person will adjust the eyepiece so that the virtual image appears at the distance of most distinct vision ($\sim 25$ cm).

![Figure 1: The inverting telescope (not drawn to scale).](image)

![Figure 2: View scale with one eye, then the other.](image)
B. Adjust the telescope direction until these images superimpose (as in Fig. 3). The number of divisions on the scale as viewed directly (by eye 2) which fall in one division of the image as seen through the telescope (by eye 1) is clearly the magnifying power of the telescope.

Compare your measured magnification \( M \) with that calculated for an astronomical telescope, namely \( M = \frac{f_1}{f_2} \) where \( f_1 \) is the focal length of the objective and \( f_2 \) that of the eye piece. Why are the two different? Calculate the magnification from the actual measured object and image distances. Compare with the measured \( M \).

2. **Erecting telescope**

A. Measure the focal length, \( f \), of a second strong converging lens and use it as the inverting lens \( L_3 \) (Fig. 4) to form an erecting telescope. \( L_2 \) must be adjusted to give a real image, \( I_2 \). Notice that varying the space between \( I_1 \) and the inverting lens \( L_3 \) changes the magnification. If you are using the web-based lab manual and desire a demonstration, click on the Erecting Telescope Demo button immediately below. In this simulation your are now able to readjust both the positions and focal lengths!

B. What position of the inverting lens makes the shortest possible telescope, (i.e. it makes the distance between \( I_1 \) and \( I_2 \) a minimum)?

3. **Simple microscope or magnifier**: Experiment with one of the strong converging lenses as a magnifier until you can make the virtual image appear at any distance you choose: vary the object distance from zero to the focal length. The parallax test described in Part 1 will enable you to locate the virtual image. When the parallax between the object and the virtual image (seen through the lens) vanishes, the object and virtual image are in the same plane.

4. **Compound microscope**: Use the two strong converging lenses to form a compound microscope.
5. *Galilean telescope (or opera glass)*: Make use of the weak converging lens and a strong diverging lens.

**OPTIONAL:**

1. *Ramsden eyepiece*

   A. Ask the instructor for the holder containing a Ramsden eyepiece, a crosshair, a diaphragm, and an objective lens. See Fig. 6.

   ![Figure 6: Construction of a Ramsden eyepiece.](image)

   The Ramsden eyepiece consists of lenses 1 and 2, plano-convex lenses of $f = 85$ mm. Spherical aberration is less than for a single lens because the ray bending is spread over four surfaces. It is a minimum if the curved surfaces face one another as shown. (In addition if the two lenses were their focal length apart, chromatic aberration would be a minimum. But, since dirt specks on lens 1 then would be in focus, lenses 1 and 2 are usually set $2f/3$ apart). The tube also contains an objective lens to convert the tube into a telescope or microscope.

   B. Use the Ramsden eyepiece with $d = 2f/3$ in the telescope and microscope. Note improvement in image over that of a single eyepiece lens. Adjust eyepiece for a sharp image of the cross hairs. Then move the objective lens until the image shows no parallax with respect to the cross hairs.

2. *Huygens eyepiece*: A common eyepiece in which the image (and hence cross hair) is within the eyepiece. It also employs two plano-convex lenses but both convex surfaces are toward the incident light. Minimum lateral chromatic aberration exists for a separation of $(f_1 + f_2)/2$. Usually $f_1 \sim 3f_2$.

   ![Figure 7: Construction of a Huygens eyepiece.](image)
3. **Eye ring.**

   A. Point the astronomical telescope at a lamp and explore with a screen the illumination back of the eyepiece. [Or remove diaphragm from telescope or microscope of optional (1)].

   ![Figure 8: Position of eye ring.](image)

   The light coming through the telescope has a minimum cross section at ER. This area ER is the image of the objective formed by the eyepiece. Obviously all light which gets through the telescope must go through this image, and thus ER is the best spot to place the pupil of the eye. Hence the name “eye ring”. Note that if one places a diaphragm with aperture appropriately larger than the eye ring a little ahead of the eye ring, then an observer looking through the aperture would position the pupil of her/his eye on the eye ring.

   B. Using the Ramsden eyepiece, place the diaphragm at the appropriate distance in front of the eye ring. Note the improvement in the ease of observing through it, especially for the compound microscope.

4. **OPTIONAL telescope**: Use an achromatic objective lens, of long focal length and a commercial Ramsden eyepiece (from instructor). Note the quality of the image.

5. **OPTIONAL microscope**: Use a short focal length achromatic objective and a commercial Ramsden eyepiece (from instructor). Note the quality of the image.

   It is interesting that one does not need an achromatic eyepiece because the virtual images for red and blue, though at different distances (e.g., red at 2 m, blue at $\sim\infty$), subtend almost the same angle at eye. As a result the eye doesn’t notice the aberration.
L-4: The optics of the eye and resolving power

OBJECTIVES:
To study eye optics and how resolving power depends on aperture.

APPARATUS:
PART I: Eye model, (fill with distilled water to simulate the aqueous & vitreous humors); light source, lens set, 6" plastic ruler.
PART II: (2) Optical benches, Na lamps, transparent mm slides, vernier calipers, L-2 telescopes; (1) 15 meter tape.

You may fix the moveable retina (cylindrical) in one of three positions:
R for the normal eye, R_h for the hypermetropic (farsighted) eye, R_m for the myopic (nearsighted) eye.

(An eye retina is actually spherical, but for small images the results are similar.)

The eye model has a fixed cornea C and racks for other lenses.

A lamp box serves as source for most of the experiment.

Set of lenses: (Strength in diopters = 1/f where f is in meters.)

<table>
<thead>
<tr>
<th>Diopters</th>
<th>Focal lengths in air</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Converging spherical + 7.</td>
<td>0.14 m</td>
</tr>
<tr>
<td>2. Converging spherical +20.</td>
<td>0.05 m</td>
</tr>
<tr>
<td>3. Converging spherical + 2.00</td>
<td>0.50 m</td>
</tr>
<tr>
<td>4. Diverging spherical - 1.75</td>
<td>-0.57 m</td>
</tr>
<tr>
<td>5. Diverging cylindrical - 5.50</td>
<td>-0.182 m</td>
</tr>
<tr>
<td>6. Converging cylindrical + 1.75</td>
<td>0.57 m</td>
</tr>
<tr>
<td>7. Diaphragm with small hole .</td>
<td>.</td>
</tr>
</tbody>
</table>
PART I - EXPERIMENTS WITH THE EYE MODEL

1. ACCOMMODATION: With the retina in the normal position, point the eye model at a window or other bright object 4 to 5 meters away. Insert the +7 diopter lens in the water at the inside mount farthest from the cornea. An image of the bright object should be in focus on the retina.

Next use as object the lamp box and place it about 30 cm from the cornea. The image is blurred until one replaces the +7 diopter lens by the +20 diopter lens. This change illustrates accommodation. Eye muscles make the lens thicker for close vision. (Under relaxed conditions the ligaments supporting the lens are in radial tension and hence thin the lens. The ciliary muscle contracts against these ligaments allowing the lens to thicken for viewing near objects. See Fig. 1.)

2. NEAR and FARSIGHTEDNESS (MYOPIA and HYPERMETROPIA): With lamp box at 30 cm and the 20 diopter lens at L, place the retina in the position R_m. Decide which lens placed in slot S_1 or S_2 will bring the image into focus. Try it.

Make the eye farsighted by moving the retina to R_h, and pick the proper lens to place in front of the eye to bring the image into focus.

Focus again on a window 4 to 5 meters away when the +7 diopter lens is in the normal position L and the retina in position R.

Make the eye nearsighted by moving the retina to R_m. Decide which lens will bring the image into focus. Try it.

Remove the correcting lens; the image again blurs. At S_2 place the diaphragm with hole and note image improvement. With sufficient light try a smaller hole (e.g. a hole thru masking tape on the diaphragm). Explain the effect of the reduced aperture.

3. ASTIGMATISM: With the +20 diopter lens at L in the eye and the retina in the normal position, adjust the distance to the lamp box to get a sharp image on the retina. Then produce astigmatism by placing the strong diverging cylindrical lens in mount G_1. (In the human eye astigmatism generally results from a cornea with different curvatures in the horizontal and vertical directions.) Turn this lens and note the effect on the image.

Correct this defect by placing the converging cylindrical lens in front of the cornea and turning it to the position for which the image becomes sharp. Note the directions of the axes of the two cylindrical lenses. (They are not necessarily aligned with the tab.)

4. COMPOUND DEFECTS: Combine tests 2 and 3, i.e. make a nearsighted astigmatic eye. Correct by using both a cylindrical and spherical lens in front of the cornea. How is this double correction managed in actual spectacles?

5. CATARACTS and LENS REMOVAL: A cataract results from a cloudy lens. A cataract operation involves removal of the lens. An implanted plastic lens or a strong convergent lens in front of the eye restores vision. Remove the eye lens (L) of the model and place the +7 diopter lens in front of the cornea. A clear image reappears for nearby objects.
6. Action of a SIMPLE MAGNIFIER: With the lamp box at 35 cm, the +20 diopter lens and the retina in the normal position, measure the size of the image. Now place the +7 diopter lens in front of the cornea and move the lamp box toward the eye until the image becomes clear. Record the increased size of the image. With the lamp box at 35 cm, the 20 diopter lens and the retina in the normal position, note the size of the image. Now make the eye nearsighted and bring the lamp box toward the eye until the image becomes clear. Note the increased size of the image in the nearsighted eye.

NOTE: For a real eye and lens the index of refraction, $\mu$, of the lens varies from 1.42 at its nucleus to 1.36 at its edges, and these values are not so different from those of the adjoining aqueous and vitreous humor ($\mu = 1.330$ and $\mu = 1.337$). Hence the real eye lens is very weak and is primarily for fine focus adjustment. Most of the refraction in the eye actually occurs at the cornea where $\mu$ changes from 1.0 (in air) to 1.37 in the cornea.

PART II - RESOLVING POWER

Before doing this part, read in your text about resolving power.

SUGGESTED EXPERIMENTS:
1. Use as a source a slide with mm divisions and illuminated by a sodium discharge lamp. The wavelength of the sodium yellow light is 589.3 nm.
2. Back away from the slide until the mm lines become indistinct. Then advance far enough so that they are just clearly visible; this procedure insures that eye defects or the density of rods and cones do not (for this measurement) limit the resolving power.

Observing now with only one eye, place a vernier caliper$^2$ in front of the eye pupil with the caliper jaws parallel to the mm marks and open about 3 mm. Slowly close the jaws until the mm marks disappear. Note the separation of the jaws, $w$, and measure the distance, $D$, to the slide from the jaws.

Compare your measurements of the angular separation $\alpha$ of the mm marks at your observing distance,

$$\alpha = \frac{1 \text{ mm}}{D \text{ (in mm)}},$$

with the expression $\theta = \lambda/w$ where $\theta$ is the angular limit of resolution, (Rayleigh’s criterion).
3. Mount a telescope so its objective is at the same distance from the slide. Repeat the experiment with the caliper in front of the objective.$^3$ How do the results compare to your measurement without the telescope?
4. Move the telescope $\geq 4$ m from the slide and repeat the experiment.
5. Turn the vernier jaws perpendicular to the mm lines and repeat experiment #1. Comment on the result.

QUESTIONS:
1. Would an eye without any defects of vision have better resolving power at dusk or in bright sunlight? Explain.
2. Discuss how a contact lens functions. Would a “soft” contact lens correct well for astigmatism?

$^2$In all the following be sure you are not looking through the hole at one end of the jaws. It is advisable to cover the hole with masking tape.

$^3$Be sure no light enters the telescope except through the slit jaws. (You may need masking tape on the caliper jaws to prevent this from happening.)
L-5: Spectrometer and the H Balmer Series

NOTE: Consult your instructor for assignment of parts suitable for a single lab, e.g., do Part I, II (A or B), Part IV or Part V).

OBJECTIVES:

To become familiar with a precision spectrometer and some of its uses.

APPARATUS:

Precision spectrometer; mercury and hydrogen discharge tubes; prism; diffraction grating; light source for Gaussian eyepiece & its 12V power supply (L-2); ring stand & achromatic lens.

![Figure 1: The spectrometer (side view).](image)

INTRODUCTION and ADJUSTMENTS

PART I - A

1. Become familiar with the clamping and fine adjustment controls for telescope and prism table angles. **Never force a motion - you may damage the instrument. If at the end of a fine adjustment, loosen and reclamp!** The prism table clamp sets table elevation: no fine adjustment is necessary.

2. Note that 180° apart are two angle scale reading ports and verniers, I and J. The verniers have 30 divisions per half degree. Hence each division is \((1/30) \times (1/2) = (1/60)°\) or one minute (′) of arc.

3. The knurled ring about the collimator, B, controls the slit opening.

4. Staff have already focussed the collimator for parallel light and have set collimator and telescope \(\perp\) to spectrometer’s rotation axis.
REMINDER ON READING A VERNIER

1) Position and tighten the telescope.

2) Move the magnifying glass to see the scale marking.

3) Look where the zero mark on the upper scale is located. The degree reading is the first full degree mark to the left of the zero (210° in the top figure; 229° in the bottom figure).

4) Now make the minute reading: if the zero mark on the upper scale comes after a \( \frac{1}{2} \) degree mark (the short lines on the lower scale) then start at 30’, otherwise at 0’.

5) Next look for the two lines which match up best between the two scales. Read the number of the appropriate line on the upper scale and add it to the zero mark is just past a \( \frac{1}{2} \) degree mark so we begin with 30’. The 15’ mark is the one that lines up best so we get 210°15′ for the top reading and 229°146’ for the bottom one.

6) Now convert to decimal degrees, in this case \( 15/60 = 0.25 \), so \( \theta = 210.25° \).

PART I - B: FOCUS THE TELESCOPE FOR PARALLEL RAYS

1. i) Slide telescope eyepiece in or out until crosshairs are in sharp
   
   ii) Sight telescope at a distant object (thru an open window); then focus telescope by rotating its focus ring (Fig. 1) until the object’s clear image falls on the cross hairs. The test for proper focus is absence of parallax between the image and cross hairs (appendix 4). The telescope, now focused for parallel rays, will stay so as long as the focus ring is unmoved; but one may still adjust the eyepiece to suit the observer.

2. An alternative method to focus for parallel light is to use the Gaussian eyepiece + light source as described below in PART II B.

3. With collimator and telescope both properly focused one should get a sharp image of the slit and no parallax between slit image and cross hairs. If you still get parallax, recheck your telescope focus and/or consult instructor.

4. Optimizing light thru the collimator: A properly located short focal length lens can gather a large fraction of the light from a source and redirect it thru the collimator thereby facilitating detection of weak spectral lines. For strong lines it permits narrowing the slit width and thus improving resolution. Use such a lens (mounted on a ring stand) to find an arrangement which fills the collimator with light.
Figure 3: Proper, a), and improper, b) prism locations.

PART II-A: MEASUREMENT OF PRISM ANGLE

1. Mount the prism (in holder) on the dowel pins (in the prism table) so that the prism is far enough from the collimator that beams B₁ and B₂ are centered with respect to the spectrometer axis; otherwise much of the reflected light may miss the telescope. Turn the table so that the apex angle A (Fig. 3) splits the beam into nearly equal parts.

2. Using the prism table levelling screws adjust the plane of the prism table so it is close to horizontal.

3. With the prism table clamped at the proper elevation, set the telescope to receive beam B₁ and form an image of the slit on the intersection of the telescope cross hairs. Record both VERNIER readings (in minutes). Average the two vernier readings (to eliminate any systematic error from misalignment of the circle scale with respect to bearing axis), and add the result to one of the angle scale readings. Note that the angle scale reads in half-degree units and the vernier in minutes (not in decimal degrees!). The zero position on the vernier determines the angle to the nearest half-degree (30 minutes) and the vernier reads the number of minutes past the half-degree mark.

4. Then with telescope in the 2nd position, set on the slit image. The change in reading of the same angle scale should be the angle D. (See Fig. 3.) Be sure you don’t get the angle scales mixed up and subtract the first reading of angle scale 1 from a reading of angle scale 2. Also some students incorrectly handle the subtraction when the scale passes through 360° or 0°.

5. OPTIONAL: Try to prove that angle D is twice the prism angle A.

PART II-B: ALTERNATE method for prism angle measurement using Gaussian eyepiece

Figure 4: Spectrometer telescope
Introduction: The Gaussian eyepiece (Fig. 4) has a partially reflecting glass plate G set at 45° to telescope axis so that light from the lamp reflects down the telescope tube, past the cross hairs and out the objective. If in front of the objective you place a reflecting surface perpendicular (⊥) to the telescope axis, the light will reflect back into the objective and form a real image of the cross hairs. If the cross hairs are in the focal plane of the objective, their reflected image will form in the same plane. Thus both the cross hairs and the image will be in focus through the eyepiece. When one orients the reflecting surface so that the image coincides with the cross hairs, the reflector is accurately ⊥ to telescope axis.

Thus the Gaussian eyepiece permits both focusing the telescope for parallel rays and setting a reflecting surface ⊥ to the telescope axis.

1. To focus the telescope for parallel light:
   a) Rotate the Gaussian eyepiece to open the hole between reflecting plate G and lamp. Adjust eyepiece to give a sharp image of the cross hairs, but don't turn the eyepiece to block the light hole. Next, with prism on the table, adjust the prism table screws to make the table nearly horizontal.
   b) Now rotate the prism table until the prism face is approximately ⊥ to telescope axis. Clamp the telescope and mount a light on the Gaussian eyepiece. (Check that the light hole is still open). With no illumination on the prism except that from the telescope, next rotate the prism table back and forth a few degrees until maximum reflected light appears in the eyepiece. Clamp the table in this position, and then focus the telescope (by turning the focus ring) until the reflected image of the cross hairs appears and shows no parallax with respect to the cross hairs. The telescope is now focused for parallel rays. Fine adjustments of the prism table leveling screws may help the images coincide and thus set telescope axis accurately ⊥ to the reflecting surface. See Part VI, Sec. 3.

2. To find the prism angle set the telescope ⊥ to first one prism face and then the other. The angle between these two positions is the supplement of the prism angle. See Part IIA for detail about angle readings.

PART III: INDEX OF REFRACTION

Introduction: When the path thru a prism is symmetric, the deviation is a minimum. At this angle of minimum deviation the index of refraction, \( n \), is

\[
n = \frac{\sin \left( \frac{(A + d)}{\delta} \right)}{\sin \left( \frac{A}{2} \right)}
\]

where \( A \) = angle of prism
\( \delta \) = angle of minimum deviation
\( n \) = refractive index of the prism.

Devise your own methodology and determine the prism’s refractive index for one or more lines of the Hg spectrum.
PART IV: CALIBRATION OF PRISM SPECTROSCOPE

1. Set the prism for minimum deviation for a green line in the Hg spectrum.

2. Determine the angle readings for the yellow, green, blue-violet, and deep-violet Hg lines. Repeat this for the red line from a hydrogen discharge.

3. Plot telescope angle vs accepted $\lambda$’s for these lines.

4. For the same setting of the prism table, find the angles for the blue-green and two violet lines of the hydrogen spectrum.

5. Use your calibration curve to determine $\lambda$ of the blue-green and violet lines in the atomic hydrogen spectrum. Compare results to accepted values.

OPTIONAL: The calibration curve is very non-linear. Since a more linear plot facilitates interpolation of an unknown $\lambda$, try plotting deviation vs $1/\lambda^2$.

**TABLE OF WAVELENGTHS:**

<table>
<thead>
<tr>
<th>Mercury lines</th>
<th>Hydrogen lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ (in nm)</td>
<td>$(1/\lambda^2) \times 10^6$ (nm)$^{-2}$</td>
</tr>
<tr>
<td>Yellow$_1$ 579.0</td>
<td>(unresolved)</td>
</tr>
<tr>
<td>Yellow$_2$ 577.0 Avg. = 578</td>
<td></td>
</tr>
<tr>
<td>Green 546.1</td>
<td></td>
</tr>
<tr>
<td>Blue 496.0*</td>
<td>4.065</td>
</tr>
<tr>
<td>491.6*</td>
<td>4.138</td>
</tr>
<tr>
<td>Blue 435.8</td>
<td>5.265</td>
</tr>
<tr>
<td>-violet 434.7*</td>
<td></td>
</tr>
<tr>
<td>Deep-violet 433.9*</td>
<td></td>
</tr>
<tr>
<td>407.8*</td>
<td>6.013</td>
</tr>
<tr>
<td>404.7*</td>
<td>6.106</td>
</tr>
</tbody>
</table>
PART V: DIFFRACTION GRATING

CAUTION: Do not touch grating surface under any circumstance!

1. **Grating constant (number of lines per cm):** The lines/cm marked on these replica gratings is only approximate because the plastic often changes dimensions when it is stripped from the master grating. To achieve quantitative results calibration of the grating constant is desirable and can be performed using the known \( \lambda \), 546.1 nm, of the Hg green line.

**CALIBRATION PROCEDURE:**

a) Align telescope with collimator so the slit image falls exactly on the vertical cross hair.

b) Mount grating on the dowel pins in the prism table. Adjust and clamp the table so the grating is approximately \( \perp \) to telescope-collimator axis.

c) Then adjust the table so that the front grating face is accurately \( \perp \) to telescope. Use the Gaussian eyepiece (see Part II - B) for the final adjustment: the reflected image of the cross hairs should fall on the cross hairs. (Two reflected images can result if the sides of the grating glass are not parallel. If so, test which image comes from the grating side by wetting the other side.) Clamp prism table in this position and record telescope direction.

d) Next set telescope on the first and second orders of the Hg green line. Use both \( \pm \) angles. The \( \pm \) angles should of course agree. Use them and \( \lambda_{\text{green}} = 546.1 \text{ nm} \) to calculate the grating spacing \( d \) from

\[
n\lambda = d \sin \theta.
\]

2. **Measurement of the wavelengths in the Balmer series in hydrogen:**

a) Use the calibrated grating spectroscope to measure \( \lambda \) for three or four atomic hydrogen spectral lines.

b) Compare these \( \lambda \)'s to those from the Balmer formula

\[
\frac{1}{\lambda} = R \left[ \frac{1}{2^2} - \frac{1}{n^2} \right] \quad \text{where} \quad R = 10,967,758 \text{ m}^{-1}
\]

or calculate the frequencies of these lines and compare to

\[
f = cR \left[ \frac{1}{2^2} - \frac{1}{n^2} \right] \quad \text{where} \quad R = 10,967,758 \text{ m}^{-1}.
\]

c) Use Planck’s relation, \( \Delta E = hf \), to calculate the energies in eV of the photons for each frequency and, therefore, the energy change in the hydrogen atom associated with each frequency.

d) Assuming that each observed \( \Delta E \) leaves hydrogen in the \( n = 2 \) state, show the observed transitions on a hydrogen energy level diagram (drawn to scale; consult textbook).
PART VI: ADJUSTMENT OF A SPECTROMETER

NOTE: Not to be performed without permission of the instructor

1. Use Gaussian eyepiece and prism face method to focus telescope for parallel rays. If necessary adjust prism table to make reflected image of the cross hairs coincide with the cross hairs.

2. Remove prism from the table and align telescope and collimator approximately. Focus the collimator until there is no parallax between the image of the slit and the cross hairs. Adjust the ring on the collimator focusing sleeve so that the collimator is in focus with the “V” in the slot. Clamp the telescope in line with the collimator so that the image of the slit (vertical) falls on the vertical cross hairs. Now rotate the slit through 90° as permitted by the “V” projection and slot. Adjust the level of the telescope so that the image of the slit falls on the horizontal cross hair. The axes of telescope and collimator are now in line but not necessarily perpendicular to the axis of rotation of the instrument.

3. Replace the prism on the prism table and clamp it relative to the adjusting screws as shown. (Line AB ⊥ face 1. Line AC ⊥ face 2. Thus screw B will adjust face 1 without disturbing face 2, and screw C will adjust face 2 without disturbing face 1.

Bring the telescope to within < 90° of the collimator and use a face of the prism to reflect light from the collimator down the telescope tube. Adjust the prism face so that the center of the slit image falls on the intersection of the cross hairs. The prism face is now parallel to the instrument axis.

4. Set the telescope ⊥ to the adjusted prism face (use Gaussian eyepiece method). Return to part 3 setup and adjust the collimator so that the center of the slit image falls on the cross hair’s intersection. Telescope and collimator are now properly focused and are perp to the instrument axis.

5. To adjust the second prism face ⊥ to the axis of the telescope (again use the Gaussian eyepiece method). Turn only the proper screw on the prism table: otherwise one disturbs the adjustment of the first face. Recheck the first face and, if necessary, readjust it. Continue this process until both faces are parallel to the axis of the instrument. Turn collimator slit to vertical position. The spectrometer should now be in adjustment.
L-6: Polarization

OBJECTIVE: To study polarization and double refraction of light.

APPARATUS:

- Polarization kit plus a polariscope; Brewster angle assembly (laser + mount on M-2 force table, slotted pin & black piece of plastic).

SUGGESTED EXPERIMENTS:

1. **Polarization by ABSORPTION**: Observe a light source (desk lamp) thru each of two polaroids, and then thru both together. Rotate one of the two about the line of sight. Explain what occurs.
   
   Orient the two polaroids of the polariscope so no light is transmitted. Then introduce a third polaroid between the first two and rotate it about the line of sight. Explain what happens.
   
   HINT: there will be an amplitude component $E \cos \theta$ in the direction of the transmission axis.

2. **Polarization by REFLECTION from a dielectric**: Observe thru the small polaroid (the one with the rim index marks) the light reflected from the black plastic (see figure at right). Rotate the polaroid about the line of sight. Note position of the index marks (i.e. the $E$ vector direction) on polaroid when the transmitted reflected light is a minimum.

   ![Figure 1: Reflection and transmission of light at Brewster’s angle.](image)

   Now find an incident angle $\theta_i$ (and reflection angle $\theta_r$) for which this minimum is zero. Then $\theta_i$ is Brewster’s angle, $\theta_B$, and $\tan \theta_B = n_2/n_1$. Estimate $\theta_B$ roughly. What is the refractive index $n_2$ of the plastic?

   *Alternatively* for greater accuracy use a laser plus polaroid to prepare a beam polarized in the plane containing the incident ray and the normal to the reflecting surface. The reflected beam then vanishes at Brewster’s angle. Mount laser plus polaroid on the M-2 force table and point it toward a dielectric (plastic or microscope slide) in the slot of the central pin. Rotate the sample until the reflected beam (on the wall) disappears. A thread from the center pin to this point on the wall will help locate the angles on the M-2 table.

Observe any polarization of light reflected from painted or varnished surfaces, floor tile, *clean metal* (e.g. aluminum foil) etc.
3. **Polarization by SCATTERING**: Try to detect the polarization of skylight: **one needs a blue sky**! Explain (use a diagram) in what direction relative to sunlight should one look to see this polarization best.

4. **Polarization by a DOUBLY REFRACTING CRYSTAL**: Uniaxial doubly refracting crystals (e.g. calcite) are highly anisotropic and, as such, contain an axis of symmetry (the optic axis) for which the velocity of light depends on whether the $E$-field vector (polarization plane) is $\perp$ to this axis (the ordinary “$o$” ray) or parallel to the optic axis (the extraordinary “$e$” ray). In the principal plane (i.e. a plane containing the optic axis but $\perp$ to the surface) the new wave front of the ordinary ray involves the usual spherically expanding wavelets, but to construct the front for the extraordinary ray requires ellipsoidally expanding wavelets where the two axes of the ellipse are proportional to the velocities of the parallel and $\perp$ vibrations to the optic axis.

Calcite ($\text{CaCO}_3$) has a large velocity differences between the $o$ and $e$ rays, and its optic axis is the direction at equal angles with the crystal edges at the obtuse corners.

Observe through the calcite crystal a dot on a piece of paper. Rotate the crystal about the line of sight. Describe the behavior of the two images of the dot. Introduce a polaroid between your eye and the crystal. Note how the appearance of the two images changes as you rotate the polaroid about the line of sight. Explain.

**NOTE**: For the remaining experiments use the POLARISCOPE. The polaroid next to the light is the “POLARIZER,” the other is the “ANALYZER.” Place the samples to be studied on top of the polarizer.

5. **CIRCULAR POLARIZATION**: A thin doubly refracting crystal cut so that the optic axis is parallel to a surface constitutes a retardation plate. The difference in velocity of the $o$ and $e$ rays then gives a phase difference between the emerging orthogonally polarized rays. If the phase difference is $90^\circ$, the retardation is $\lambda/4$: hence a “quarter wave plate”.

![Diagram of polarization](image)

**Figure 2**: Obtaining circularly polarized light from unpolarized light

Set the analyzer of the polariscope to transmit no light. Then place the $\lambda/4$ plate between the polarizer and analyzer and rotate the $\lambda/4$ plate so that extinction again results. You will find two such extinction positions $90^\circ$ apart. Why?

**HINT**: When the optic axis is aligned with the polarization direction of the incoming plane polarized wave, will there be any ordinary ray amplitude? Then when you turn the plate (and thus the optic axis) thru $90^\circ$, will there be any extraordinary ray amplitude.
Rotate the \(\lambda/4\) plate to a position halfway between the two extinction positions; thus the optic axis will make a 45° angle to the incident plane of polarization. Explain why the plate now looks bright. Leaving the \(\lambda/4\) plate in this position, rotate the analyzer through \(2\pi\) radians. Why does the brightness stay approximately constant?  

HINT: Recall the conditions for a circular Lissajous figure (see E-8 Part B, Fig. 3).

* If it doesn’t, repeat the preceding operations. You may not have set the \(\lambda/4\) plate close enough to the halfway or 45° position. Also remember that a \(\lambda/4\) plate is exactly \(\lambda/4\) only for a single \(\lambda\).

6. TWO \(\lambda/4\) PLATES: Place a \(\lambda/4\) plate on the polarizer so as to produce circularly polarized light. Place a second \(\lambda/4\) plate on top of the first and similarly oriented. Observe and explain what happens when you now rotate the analyzer. Turn the top \(\lambda/4\) through 90° about the line of sight. Observe and explain what happens now when you rotate the analyzer.

7. COLOR EFFECTS: If the plate is thick enough for retardations of several (but not too many) wavelengths, color effects may result. For a constant refractive index:

\[
\lambda_{\text{red}} \sim 660 \text{ nm} \sim \frac{3}{2} (\lambda_{\text{blue}} \sim 440 \text{ nm}).
\]

Thus a \(\lambda/2\) plate for red is a 3\(\lambda/4\) plate for blue. [In general, a \(n(\lambda/2)\) plate for red \(\sim 3n(\lambda/4)\) plate for blue where \(n\) is an odd integer.] Hence for white light such a plate at 45° between parallel polaroids would completely extinguish the red but pass the circularly polarized blue light. The resultant color is complementary to that removed. The intensity (hue and saturation) will of course vary with the relative orientation of polarizer, the retardation plate, and the analyzer. As \(n\) becomes large the range of \(\lambda\) extinguished narrows. Hence that passed is more nearly white.

a) Place thin mica on the polarizer (with analyzer crossed). Try various mica orientations. Explain.

b) Repeat a) for the mounted specimen of cellophane tape.


With the polariscope set for extinction:

a) Insert and flex the U-shaped lexan (a polycarbonate resin) sample.

b) Insert a microscope slide vertically. View the long edge and stress the slide by gently flexing it. Note result. (Glass blowers use polarized light to test for residual glass strains).

9. LCD APPLICATIONS: Watches and calculators often use LIQUID CRYSTAL DISPLAYS (LCD) in which nematic liquids (thread like molecules arranged nearly parallel to each other) can become optically active, rotate the plane of polarization and thus permit light to pass thru crossed polaroids. A reflector after the analyzer returns the light through the cell.

To produce the optical rotation: two glass plates, which have been rubbed in one direction to produce invisible scratches, attach aligned nematic molecules. If a few
micron thick *nematic* liquid separates the plates, and if one plate is rotated relative to the other, then the helical arrangement of the *nematic* liquid produces a rotation of the plane of polarization.

To extinguish the light one applies a voltage between the transparent (but conducting) tin-oxide coated glass surfaces. A sufficient voltage gradient will align the dipole moments of the molecules and thus destroy the optical rotatory power. Voltages applied to segments of the seven segment pattern (see figure) permit display of any numeral 0 to 9.

The power consumption of such an LCD is almost negligible.

**OPTIONAL QUESTIONS:**

1. How experimentally can one tell whether a light beam is unpolarized? Plane polarized? Circularly polarized?

2. How could you tell whether an object is a gray plastic, a polarizing sheet, a $\lambda/4$ plate or a $\lambda/2$ plate?

3. How could you change right circularly polarized light to left circularly polarized light?

4. Why does the flexed lexan show colors but not the microscope slide?
Appendices

A. Precision Measurement Devices

Vernier Calipers:

A Vernier consists of a fixed scale and a moving vernier scale. In a metric vernier the fixed scale is marked in centimeters and millimeters, the vernier scale is nine millimeters long, and is divided into ten parts each 0.9 millimeters long. The distances of each line from the first are therefore 0.9, 1.8, 2.7, \ldots mm or generally: \( d_i = 0.9 \times i \), where \( d_i \) is the distance between the zero line and the \( i^{th} \) line of the vernier scale. If the vernier caliper is closed, so that the two jaws touch each other, the zero of the fixed scale should coincide with the zero of the vernier scale. Opening the jaws 0.03 cm = 0.3 mm will cause the fourth line (the three line which is a distance of 2.7 mm from the zero line of the of the vernier scale) to coincide with the 3 mm line of the fixed scale as shown below.

Below is another example of vernier reading; the arrow shows which mark on the vernier scale is being used.

Figure 1: The vernier caliper

Figure 2: The vernier reads 0.03 cm

Figure 3: The vernier reads 9.13 cm
EXERCISES:

A. Close the vernier and observe that the first vernier mark coincides with the zero of the centimeter scale.

B. Open the jaws of the vernier very slowly and observe how the different vernier marks coincide successively with the millimeter marks on the fixed scale: the first mark coincides with the 1 \(\text{mm}\) mark on the fixed scale; then the second mark coincides with the 2 \(\text{mm}\) mark on the fixed scale; then the third mark coincides with the 3 \(\text{mm}\) mark on the fixed scale and so on.

C. Estimate the dimension of an object using a meter stick and then Use the vernier caliper to measure the dimension precisely.

D. In the four examples of Fig. 4 determine the actual reading.

![Figure 4: Test cases](image)

Micrometer:

A micrometer can measure distances with more precision than a vernier caliper. The micrometer has a 0.5 \(\text{mm}\) pitch screw, this means that you read millimeters and half millimeters along the barrel. The sleeve is divided into 50 divisions corresponding to one hundredth of a millimeter (0.01 \(\text{mm}\)) or 10 \(\mu\) each. The vernier scale on the micrometer barrel has ten divisions, marked from 2 to 10 in steps of two. The “zero” line is not marked ‘0’, but is longer than the others. The vernier allows you to read to the nearest thousandth of a millimeter, \textit{i.e.}, to the nearest micron (0.001 \(\text{mm} = 1 \mu\)).

**Precaution:**
Great care must be taken in using the micrometer caliper; A ratchet knob is provided for closing the caliper on the object being measured without exerting too much force. Treat the micrometer with care, **ALWAYS** close the calipers using the ratchet knob, this prevents tightening the screw too strongly. Closing the calipers too hard damages the precision screw.
Below are two examples of micrometer reading; the arrow shows which mark on the vernier scale is being used.

In Fig. 7 the zero line on the barrel is barely visible, and the vernier reads 0.003 mm = 3 μ; the zero error is $\epsilon_0 = 3\mu$. 

A negative zero error, as shown below requires a moment of thought.

![Figure 8: The micrometer reads -4 µ](image)

In Fig. 8 the zero line on the barrel of the micrometer is obscured by the sleeve, (the “zero” line on the sleeve is above the “zero” line on the barrel) this corresponds to a reading of -0.5 mm; the vernier reads 0.496 mm the zero error is then $\epsilon_0 = -0.5 + 0.496 = -0.004 mm = -4 \mu$. 
B. The Travelling Microscope

The sliding carriage of the traveling microscope rides on carefully machined ways, pushed by a nut under the carriage which rides on the micrometer screw. The nut must not fit tightly on the screw or it will bind; hence there is always some slack built into the mechanism.

When the nut is being pulled to the right (dial being turned toward larger numbers), the screw threads will press against the threads in the nut as shown in Fig. 1, with the screw threads in contact with the back side of the threads on the nut. When the direction of turning reverses, the screw threads then push on the front side of the nut threads.

For the microscope set initially on the same line for both directions of motion, the readings will differ by distance $S$, the backlash (slop) in the mechanism.

One way to avoid trouble with this slack is always to make settings after turning the screw more than the slack in one direction, say the direction of increasing readings. If one overshoots on a reading, go back by more than the slack and then turn forward again. The screw will then always press on the same side of the nut and no error arises.

A much better experimental technique is to take readings both ways. Suppose one wants to measure the distance between two lines, 1 and 2. Call the reading turned toward larger readings on line 1, $D_1$ and when turning in the reverse direction, $R_1$; similarly for $D_2$ and $R_2$. Then the distance between the lines will be $D_2 - D_1$ and also $R_2 - R_1$ so that one has immediately two independent readings to compare. More important, $D_1 - R_1$ is the slack in the mechanism; it should equal $D_2 - R_2$ and should be the same for all pairs of readings. If $D - R$ changes by more than the experimental error in setting, you know immediately you have made a blunder in either setting or reading and can immediately repeat the measurement. The constancy of $D - R$ is actually an excellent measure of the uncertainty in the measurements you are taking.

Figure 1: Backlash in screw mechanism.
C. The Optical Lever

An optical lever is a convenient device to magnify a small displacement and thus to make possible an accurate measurement of the displacement. Experiment M-11, Young’s modulus, uses an optical lever to magnify the extension of a wire produced by a series of different loads.

The plate P carries a mirror M. The mirror mount has two points resting in a fixed groove, F, and at the other end has a single point resting on the object whose displacement one is measuring. Raising the object through a distance $\Delta L$ will tilt the mirror through an angle $\theta$ or $\Delta L/d$ radians (approximately) but will turn the light beam through an angle $2\theta$.

![Figure 1: Schematic of the optical lever.](image)

Hence

$$\theta = \frac{\Delta L}{d} \sim \frac{1}{2} \frac{(y_1 - y_0)}{D}$$

if $\theta$ is small so that $\theta \sim \tan \theta$. Therefore

$$2\theta = \frac{2\Delta L}{d} = \frac{y_1 - y_0}{D}, \text{ and } \Delta l = (y_1 - y_0) \left[ \frac{d}{2D} \right].$$

Note that with the telescope nearly perpendicular to the scale at the beginning then $y_0$ is close to the telescope, and the difference between two elongations ($\Delta L_2 - \Delta L_1$) is very accurately given by

$$\Delta L_2 - \Delta L_1 = \frac{y_2}{2D} - \frac{y_1}{2D} = \frac{(y_2 - y_1)}{2D},$$

where $y_i$ is the scale reading. This relation holds so long as $2\theta$ is small enough that $\tan 2\theta \sim 2\theta$. 
D. PARALLAX and Notes on using a Telescope

1. PARALLAX:
   To do quantitative work in optics one must understand parallax and how it may be eliminated. PARALLAX is defined as apparent motion of an object caused by actual motion of the observer.

   As the observer moves left and right, object 1 appears to move to the left and right of object 2. The amount by which object 1 appears to move is proportional to the distance between object 1 and object 2. If object 1 comes in front of object 2, the direction of its apparent motion reverses.

   Try this with two fingers.

   Note that if object 1 is an image and object 2 a cross hair, the absence of parallax shows that the cross hairs are in the plane of the image.

2. Focusing a Telescope for Parallel Rays:

   The eyepiece E slides back and forth in the tube T and one should first adjust the eyepiece to give a clear image of the cross hairs. Then move the tube T back and forth in the barrel B until the image of a distant object, formed by the objective O, falls on the plane of the cross hairs. The test for this is the absence of parallax between the cross hairs and image.

   The rays from a distant object are nearly parallel. For viewing a distant object, use an open window if the window glass is not accurately plane. Otherwise poor image formation may result. You can check by trying it both ways. At night use a distant object in the hallway.

   The telescope, now focused for parallel rays, will stay so as long as the distance between O and C is unchanged. One may still adjust the eyepiece position to suit the observer.

3. Finding an Image in a Telescope:

   If you have trouble finding an image in a telescope, locate the image first with your unaided eye, and then pull the telescope in front of your eye, aligning it with your line of sight. With high magnification it is difficult to find the image in the telescope because the alignment must be nearly perfect before the image appears in the field of view. The eye has a rather large field of view so that the image will be visible over a range of positions.
E. PASCO® Interface and Computer Primer

INTRODUCTION:

The Physics 201/207/207/208 laboratories utilize a Web-browser based display format in combination, when necessary, computer controlled data acquisition interface (typically the PASCO CI-700 or 750). Various sensors are plugged into either digital I/O (phone jack style inputs 1 to 4) or analog I/O ports (DIN-9 style inputs A, B and C). To aid in the data acquisition and analysis PASCO module also requires use of a special purpose software package which can be easily reconfigured for the particular need of a experiment. In general all experiment starting configuration will be preset and launched through a Web-browser button at the appropriate place in the lab.

THE MOUSE

CLICKING: Most of the operations of your computer are controlled by locating the cursor on the appropriate symbol (icon) and by clicking (CLICK) or double clicking (DCLICK) the left button of the mouse.

If the operation you have to perform requires clicking the right button this will be shown by CLICK-R or DCLICK-R. Double clicking means pressing the mouse button twice in rapid sequence without moving the mouse. The image of an hour glass appears momentarily indicating that the computer is loading the program, that is, getting ready to do what you requested. It will not do this if you moved the mouse while double clicking.

WINDOWS

The monitor usually displays various “windows” with a title bar. If you CLICK anywhere inside the window, the title bar turns blue, and the window is “active” (i.e. the computer will respond to any clicks on the “icons” on the border of the window).

BASIC OPTIONS:

I. CLICK on the head bar to “drag” the window to a different position.

II. Enlarge the window by placing the cursor on the corner, a diagonal arrow will appear, then CLICK and drag to change the size of the window.

Depending on which experiment you are performing you will see various windows. These will be discussed separately.

![Figure 1: The main PASCO Data Studio window](image)

ICONS:
• SUMMARY: CLICKing on this alternately opens and closes the summary area on left (i.e., frame with Data and Displays).
• SETUP: CLICKing on this open the “Experiment Setup” window.
• START: CLICKing on this begins the data acquisition and the icons changes to “STOP”. CLICKing on the STOP ends the data acquisition.
• CALCULATE: CLICKing on this open a calculator window as shown.

THE GRAPH WINDOW:
Across the top of the graph window you will find a litany of icons: The icons that appear at the top right of all windows are (see Fig. 2):

(a) EXIT: The window is removed permanently.
(b) RESIZE: The size is changed from large to small, or vice-versa.
(c) MINIMIZE: The window is shrunk and should appear as an icon in the Data Studio workspace.

(d) SCALE TO FIT will rescale the x and y axes to fit the current data set.
(e) ZOOM IN will enhance the size of the graph features.
(f) ZOOM OUT will reduce the size of the graph features.
(g) ZOOM SELECT: After CLICKing on this icon move the cursor into the plot and CLICK then DRAG to select a region of interest. All calculations will refer to this region of interest.
(h) ALIGN X SCALE: If there are multiple graphs this will align all the X axes.
(i) SMART TOOL turns on cross hairs so that graph x,y positions are read out directly.
(j) SLOPE TOOL determines the slope at a point.
(k) CURVE FIT
(l) CALCULATE launches the calculator applications
(m) TEXT
(n) DRAW PREDICTIONS
(o) SHOW STATISTICS shows/hides statistics for a selected region of interest. You must first select the area of the graph you want to analyze by CLICKing on the ZOOM SELECT icon and the moving to the upper left corner of the ROI. The drag the cursor (CLICK and hold) diagonally across the graph to generate a rectangle that encloses the area chosen.

(p) REMOVE DATA:
(q) GRAPH SETTINGS: This icon allows for complete customization of the plot.

THE EXPERIMENT SETUP WINDOW:

Usually you will find this window in its “minimized” form but this window control the physical instrumentation connected to the PASCO computer interface

![Figure 3: The Experimental Setup Window.](image)

(a) **Sensors** Icon: CLICKing here alternately open and closes the sensor list on left. A sensor must be “grabbed” from the list and then “dropped” onto the appropriate PASCO channel.
(b) **Options** Icon: CLICKing here open a window for various custom data acquisition options (Manual sampling, Delayed acquisition, Automatic start)
(c) **Timers** Icon: CLICKing, if active (by using e.g. the “Time of Flight” sensor), will allow for a customized time sequence.
(d) **Change** Icon: CLICKing here will allow you to change the type of Pasco computer interface (e.g., CI-750, CI-700, etc.)
(e) FUNCTION GENERATOR: Output from a built-in signal generator (e.g. sine or square waves) and allows control of both frequency and amplitude.
(f) DIGITAL CHANNELS: These components produce or require signals (i.e., input/output) that switch between two levels, typically 0 and 5 volts. NOTE: Exceeding 10 volts may damage the port.
(g) ANALOG CHANNELS: These components produce or require signals that have a large range of values. If voltage is specified then the range is typically between -5 and 5 volts. NOTE: Exceeding 10 volts may damage the port.
(h) GROUND: Electrical access for *signal ground*. Note that this does not necessarily mean the ground of the outlet.
THE TABLE WINDOW:

(a) SHOW TIME: Alter the display to include time at which data was recorded.
(b) SHOW STATISTICS: Toggles off and on a display for various selected values including: minimum, maximum, mean, standard deviation and the count.
   NOTE: Subsets of the full data set can be analyzed by using the mouse and highlighting (through a CLICK and drag motion) the rows of interest.
(c) Almost all of the headings are self explanatory.