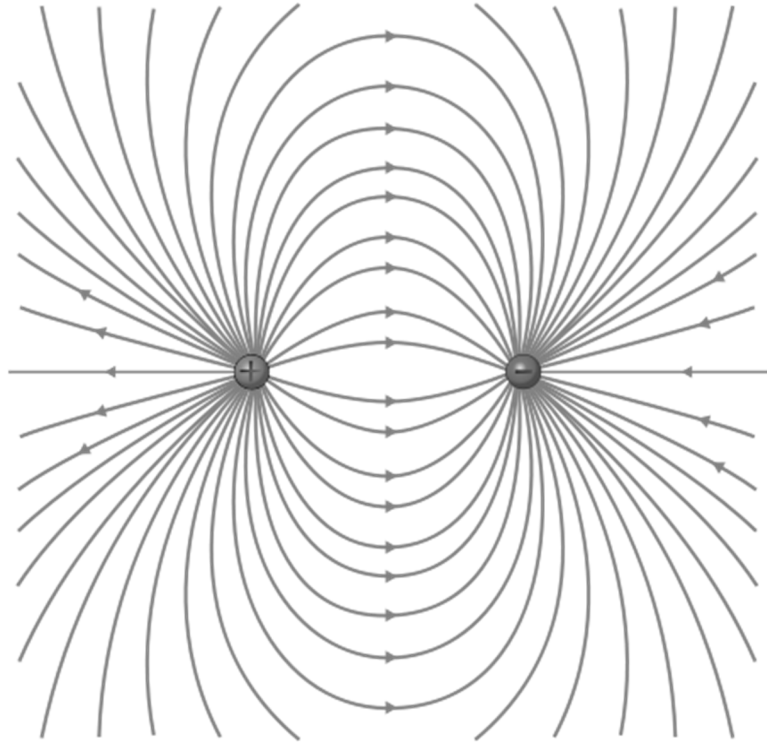


ANALYTICAL PHYSICS II LAB

LABORATORY MANUAL



SUNY GENESEO

Department of Physics and Astronomy

Spring 2024

Name: _____ **Section:** _____

LABORATORY CALENDAR

Read the manual section and prepare accordingly *before* coming to lab each week.

Week	Dates	Lab
1	Jan. 22-23	Lab 1: Standing Waves on a String
2	Jan. 29-30	Lab 2: Interference and Diffraction of Light
3	Feb. 5-6	Lab 3: Focal Length of a Lens
4	Feb. 12-13	Lab 4: DC Circuits
5	Feb. 19-20	Lab 5: Ohm's Law
6	Feb. 26-27	<i>No Labs — Tuesday Diversity Summit</i>
7	Mar. 4-5	Lab 6: The Inverse Square Law
8	Mar. 11-12	<i>No Labs — Spring Break</i>
9	Mar. 18-19	Lab 7: Plotting Electric Field Lines
10	Mar. 25-26	Lab 8: Resistance and Resistivity
11	Apr. 1-2	Lab 9: Capacitance — RC Time Constant
12	Apr. 8-9	<i>No Labs — Solar Eclipse</i>
13	Apr. 15-16	Lab 10: Oscilloscope Training
14	Apr. 22-23	Lab 11: Oscilloscope Use — Very Short Time Constant
15	Apr. 29-30	Lab 12: Charge-to-Mass Ratio of the Electron
16	May 6-7	Lab 13: Forces on a Current-Carrying Wire

Analytical Physics II Laboratory

PHYS 126

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GENERAL LAB INFORMATION

Participation in all labs is required throughout the semester. If you have a legitimate, unavoidable conflict that requires you to miss your regularly scheduled lab, your lab instructor may give you permission to make other arrangements (such as attending one of the other lab sections). To attend another section you must contact both your instructor and the instructor for the other lab to find if there is room available. *It is your responsibility to find out what your regular instructor requires for that lab, and to turn in whatever is required to your original lab instructor, not the substitute.*

THINGS TO BRING TO LAB EACH WEEK (REQUIRED)

- 1) **Lab Manual** (This will be provided to you in lab, week by week)
- 2) **Log Book** (check with your instructor, if not electronic then purchase *quad-ruled 7⁷/₈"×10¹/₄"*)
- 3) **Laptop, Calculator, Paper, Pencils and/or Pens**
- 4) A **working knowledge** of the general lab procedure. You will be asked to complete a pre-lab assignment before the lab period to assess your preparation. These assignments are not meant to be especially difficult, but to ensure that you read the lab manual carefully.

GENERAL INFORMATION

- 1) Students typically work in lab groups, usually of two (smaller sections may not have groups)
- 2) Labs begin on time; repeated lateness will adversely affect your performance.
- 3) You may not leave lab early without approval of the lab instructor. Normally early leave is not permitted.
- 4) After the completion of an experiment, lab assignments are often due at the beginning of the next scheduled lab period (check with the policies of your instructor). Work submitted late may be penalized, at the discretion of the lab instructor.
- 5) All written work handed in must be on **8¹/₂" by 11"** paper or submitted electronically. Check with your instructor for expectations. Paper with frayed edges, including spiral ring notebook paper, is not acceptable. Your name, the name of your lab partner(s), the dates of the experiment, and title of experiment should be displayed clearly on the front.
- 6) Grading of assignments always includes consideration of clarity, correctness, neatness, and proper use of the English language.
- 7) Any of the above requirements may be modified by your specific instructor. Please review the syllabus distributed by your specific instructor for additional information.

LABORATORY LOG BOOK

Your “log book” is an especially important tool in lab. Your instructor may ask you to purchase a physical *quad-ruled composition notebook* to record written entries. Alternatively, your instructor may ask that each log book entry be recorded electronically (using software such as Microsoft Excel). Log books are to be used exclusively for lab work. Record your name, the course number, and lab section clearly for each entry (and on the cover if a physical notebook is used). Your instructor may require you to include a Table of Contents. Information on each experiment should be recorded in the following order:

- Title of experiment
- Date(s) when work is performed
- Lab partner(s)
- Notes prior to the lab — recorded *before* you come to lab
- Notes taken *during* the pre-lab class discussion
- Equipment list - record identifying numbers
- Sketch of apparatus and experimental setup - make the sketch large with clear and detailed labels. Your instructor may require digital drawings (like with Excel drawing tools).
- Discussion of key concepts and observations. One sign that a topic is important enough to note in your log book is if the lab manual asks you to discuss something with your partner.
- Raw data and sample calculations.
- Final numerical results for a particular lab (make sure these are legible, easy to find, and easily recognizable as final results!)
- General comments and conclusions for the lab. Include items such as whether or not your results agree with any theoretical predictions, what were the leading sources of error or uncertainty in the experiment, what measurement should be repeated if time permitted, etc.
- At the end of certain experiments, your instructor may require that you answer, in your log book, the questions listed in the lab manual.

All data and calculations should be expressed with appropriate units. Your log book should be a complete and detailed record of your laboratory activities. It should be possible for you to repeat the experiment at some future time based on your log book. It should also enable you to answer questions concerning your calculations and other aspects of the experiment.

Any past or present log book entries may be collected at any time during the semester. Log book submissions may involve regular (with warning) assignments and/or abrupt (without warning) collections depending on the policies of your instructor,

Note: You must ensure that your log book is kept current. All data, observations, final results, conclusions, etc. should be recorded in your log book *immediately*. Remember, your lab instructor may collect lab books at any time, so you must make sure your lab book is up-to-date. You should not plan on “going back” to previous labs to “fix up” your book.

ANALYTICAL LABORATORY REPORTS - GUIDELINES

For many of the labs, your instructor will require you to write an “Abstract,” which is a short summary of the experiment that you completed. Not all abstracts will follow exactly the same format, but here’s a common *suggested* format for an abstract:

- a) In the upper right corner put your **name** and the **date** you *performed* the experiment.
- b) Centered at the top, write a **title** for the experiment.
- c) Below the title should be the **abstract** itself (see below).
- d) In the lower right corner put the **name(s) of the colleague(s)** with whom you worked on the experiment. Indicate that they were your partners.

An abstract is a *concise* and *informative* statement of the experiment performed, with a brief mention of results and conclusions. You should address it to an audience who has a scientific background, but who is not familiar with the particular experiment you are reporting on. The abstract should include the following (the numbers of sentences are included only as a rough guide):

Statement of purpose. Often, the purpose of an experiment is to test a theory and/or measure a certain quantity (1 sentence).

Brief experiment description. Describe how the equipment was used, which requires explaining what it was. Don’t just list equipment! (2 or 3 sentences).

Analysis. Explain (but don’t show) calculations required on measurements to obtain results. If you refer to a plot, you must explain its usefulness (2 or 3 sentences).

Results. Provide the final quantity(ies) that you intended to discover. You must include a numerical uncertainty and units. (1 or 2 sentences).

Conclusion. Discuss whether your results are consistent within uncertainties. If your uncertainty is large, explain what caused it. (1 sentence)

The general emphasis on the sections listed above will vary from experiment to experiment. Note that abstracts may not contain figures, tables, or complicated equations. The abstract is to be one paragraph, *double spaced*, and should be **200-300 words**. It should be written in a formal style, with proper English. Write concretely, avoid ambiguity, and make it self-contained. It is a good practice to outline your experiment before writing the abstract, then work through a few drafts, and have a friend read it for comments. *Proof-read* your work before handing in.

The work you submit must be your own. You must write up your abstract independently from your lab partner or anyone else. Copying abstracts, or any parts thereof, from others or from this manual is plagiarism. Instances of plagiarism will be dealt with in accordance with the College policy (please see the Academic Dishonesty page of the Office of the Dean’s web site).

REMINDER: USING MICROSOFT EXCEL



EXCEL is a general purpose spreadsheet program. These files can include data, equations, plots, and text. As a student at Geneseo, you have access to the both the Desktop and Online editions of Excel as part of Microsoft 365. You **MUST** download and use the DESKTOP version of Excel as the online version is missing some important features that we commonly use. The instructions here will be for Excel 2019 (on Windows OS); other versions may differ somewhat.

1) Software Version

- You must have the desktop version installed on your laptop. Although there is an online version of Excel, it does not support some of the methods required in this class.

2) Organizing Data in Excel

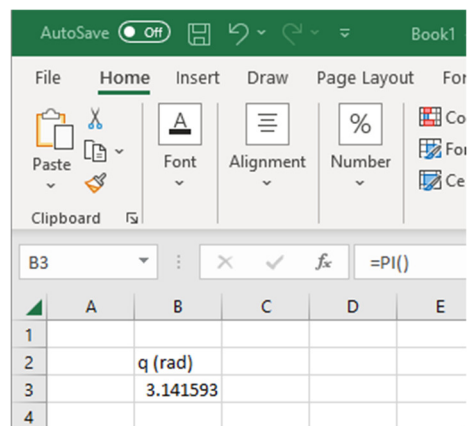
- Generally, you should organize your data into columns of measurements or calculations.
- Use the top row or two to label your data (e.g., “velocity”), including units (e.g., “m/s”). Numbers without labels and units are meaningless.

3) Saving your Work

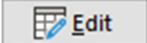
- Save your work periodically. Otherwise, an unexpected computer problem could force you to redo all of your work. Enabling AutoRecover can help if an accident occurs. AutoSave is a different function, which only works in certain circumstances.
- At the end of the lab period, copy or save your file to some place you can access.
- Both partners should have access to a copy of the file. “I couldn’t get the data from my partner,” is not an acceptable excuse for late assignments.

4) Using Functions in Excel

- Formulas must begin with an “=” sign. The figure shows a formula in the selected cell (B3). It is visible in the f_x box, and the result can be seen in the cell itself. A formula can refer to the contents of other cell(s) by using syntax such as “=SIN(A4)” or “=AVERAGE(C10:C25)” or “=STDEV(C10:C25)”. A formula in a cell may not refer to itself.
- Raising a number to an exponent (non-integer exponents are allowed) uses the syntax “D4^2”.
- Excel assumes that *all* angles are in radians.
- If a formula is copied from one cell into another, all simple cell references in the new formula will be adjusted to be in the same location *relative to* the new formula cell. This can be done with copy/paste, or by “filling” a formula using the small square in the lower right corner (see figure). References can be prevented from adjusting by placing a “\$” just in front of the thing to keep constant: in “D\$4” the “4” will not be changed, and in “\$B\$6” neither the “B” nor the “6” will be changed.



5) Graphing Columns of Data

- The simplest way to make a plot of the data is to first ***select the columns of data*** that you want to graph. The horizontal axis data must be in the leftmost column. All of the data that you want to plot for *both* axes must be selected. If you include the column labels in your selection, they will be used for the graph title and to name the data series.
- On the Insert tab, Chart section, click on the scatter chart menu and select the first icon (points only).
- On the Chart Design tab, Chart Layouts section, the Add Chart Element item allows for adding axis labels and otherwise formatting your graph.
- The data which is plotted on a graph can be adjusted by choosing “Select Data...,” either from the Chart Design tab, or by right-clicking on the graph to get the context menu. In the resulting “Select Data Source” window, select the correct Series in the left box, click on the Edit button , and adjust the cell ranges shown.



6) Finding a Best Fit Equation for Your Data

- There are two ways that Excel can help you determine an equation that closely matches your data. The first is called “Trendline.” This feature is quick, but does not compute uncertainties. To use Trendline, right-click on any data point on your plot, and choose “Add Trendline” from the menu that appears. Select an appropriate equation type (Linear, Polynomial, etc.), and at the bottom of the task pane select “Display Equation on chart.” In the resulting equation, Excel will incorrectly call your variables “x” and “y”, even though it is unlikely that these are the actual names for your axes.
- The second method to determine a “best fit” equation uses an Excel function called “LINEST,” which will provide both equation parameters and uncertainties. We will only use it for linear and quadratic equations. To use this function, you must first select an unused region of your spreadsheet where you want Excel to place the answers. Select 2 columns for a linear fit, 3 columns for a quadratic fit (listed in the order *ABC* where the equation is $Ax^2 + Bx + C$). In both cases, you must select 2 rows (one for the value, and one for the uncertainty).

The screenshot shows an Excel spreadsheet with the following data:

#	t(s)	x(cm)
0	0.0000	4
1	0.0167	4.3
2	0.0333	5.9
3	0.0500	8.3
4	0.0667	11.6

The formula bar shows the formula: `=LINEST(C3:C7,B3:B7,1,1)`

The spreadsheet also shows the results of the LINEST function in the following table:

	slope	intercept
value	115.2	2.98
uncertainty	19.97198	0.815353

You enter the function as a formula while all these 4 (or 6) cells are still highlighted. The form of the function is (your spreadsheet will usually have the data in the opposite order):

For linear fit equation	For quadratic fit equation
<code>=LINEST(y_axis_data, x_axis_data,1,1)</code>	<code>=LINEST(y_axis_data, x_axis_data^{1,2},1,1)</code>

Notice the curly brackets. ***After this is typed, do not press ENTER!*** Instead, press Ctrl-Shift-Enter. If you have a Mac, note that Ctrl (^) is different from command (⌘).

REMINDER: UNCERTAINTY IN MEASUREMENT

Science is successful partly because in addition to reporting what they know (results), scientists also report how well they know it (uncertainties). Throughout the semester you will be estimating and reporting uncertainties on the measurements you make.

I. Experimental Uncertainty - General Description

Any measurement of a physical quantity consists of two parts: the observed *value* of the quantity (including units), and an estimate of the *uncertainty* (sometimes called *standard error*) associated with the measurement. Both the value and the uncertainties should be expressed in the same units; if scientific notation is used, they should use the same exponent. Note that “error” here does not mean “mistake,” but rather “lack of precision.” No physical measurement anyone makes ever yields the “real” result. There are no references in which anyone can look up the “exact” value of *any* physical quantity.

The uncertainty suggests a “range” surrounding the measured value, inside of which the “real” value most probably lies. We estimate the uncertainty based on reasonable judgment gained from experience. Since the experimental uncertainty ultimately must be estimated, we can only speak of a “probability” that the uncertainty range assigned to a measured value does indeed surround the “real” value.

A WORD OF CAUTION: In previous science courses, you may have been taught that “experimental error” consists in the percentage difference between your experimentally determined number and some “accepted value”. *This is not what we are talking about.* Uncertainty has *only* to do with the measurement itself, and is an intrinsic part of the measurement process; it has *nothing* to do with how far away it is from some “accepted value.” This applies whenever the words “error” or “uncertainty” appear in this manual. Uncertainties are *internal* to an experiment.

II. Experimental Uncertainty - Systematic and Random

There are two categories of errors: *systematic errors* and *random errors*. A *systematic* error is one that consistently shifts a measurement in one direction. Systematic errors can be very difficult to detect since one is often unaware of their presence. Sometimes systematic errors can be determined by comparing the measured value of a “standard” quantity with its accepted value. In principle, systematic errors are avoidable, and correctable if discovered.

Random, or *statistical*, errors are those errors that arise when repeated measurements of the same quantity fail to give exactly the same value (which is virtually always). They arise from physical limitations on the accuracy of a measurement and from uncontrollable fluctuations in the measuring instruments and in the objects measured. Such errors are equally likely to result in measurements that are larger or smaller than the “true” value. Random errors are neither avoidable

nor correctable, but taking sufficient care with your experiments can minimize them. We will use common statistical methods to estimate the random errors in our experiments.

Precision vs. Accuracy

Technically, the terms “precision” and “accuracy” are not synonymous. The *precision* of an experiment is a measure of how exactly the result is determined, without reference to its correctness. It is a measure of how reproducible the result is. The more precise an instrument is, the smaller its random uncertainty. The *accuracy* of an experiment is a measure of how close the result of the experiment comes to the “correct” value. Hence, we can talk about the precision of a measurement even though the accepted value may not be known. A measurement has high precision if it has small *random* errors and has high accuracy if it has small *systematic* errors.

III. Determining Uncertainties

Experiments are usually performed with the assumption that there are no systematic uncertainties present. So, determining the uncertainty on a measurement involves a statistical analysis of the *random* errors. When you report a measurement \bar{x} with its uncertainty Δx you are indicating that you are rather confident that the real value lies between $(\bar{x} - \Delta x)$ and $(\bar{x} + \Delta x)$. We will refer to \bar{x} as the best value, and Δx as the uncertainty. Formally, the mathematics of probability suggests that, *if you have a large number of measurements of the same quantity*, then 68% of the measurements should lie within this range. About 95% of the measurements should lie between $(\bar{x} - 2\Delta x)$ and $(\bar{x} + 2\Delta x)$.

Method One: From Very Few Measurements - “The Art of Estimated Uncertainty”

If only one or two measurements of a quantity are made, all one can do is *estimate* the uncertainty based on consideration of the experiment. One should ask questions such as: “How much can I increase the voltage before I see any change in electric current?”, “What is the smallest scale division on my ruler?”, “If I ‘jiggle’ the apparatus, does it return to the same starting point?”, “Is my friend likely to get a similar number when he or she measures it?” and so on. This estimation takes practice, and there are no hard rules one can follow.

Method Two: From Several Measurements - Standard Deviation

If you have many measurements of the quantity x in question, the uncertainty Δx can be calculated using the formula

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

where n is the number of measurements of x , x_i is each individual measurement of x , and the best value \bar{x} is the average value of the x 's. The quantity Δx in equation (1) is referred to as the *sample*

standard deviation in x . We will take the standard deviation of a group of measurements to be the best choice for the random uncertainty associated with the measurement.

A related method of estimating uncertainties comes from graphing the measurements, determining the best-fit line that represents the data, and determining how well the best-fit line is known. This is essentially a more complicated version of the standard deviation.

IV. Reporting Results and Uncertainties

Uncertainties are estimates of our ignorance, so it is silly to claim that an uncertainty is very precisely known (even when it is calculated using the standard deviation method.) Therefore, although during calculations you should keep several significant figures, when you report the final result you should follow these rules.

- Report uncertainties rounded to **two significant figures**.
- Since the measurement can't be known to better than this uncertainty, round the best value to **the same decimal place** as the uncertainty.
- Format these two numbers as $\bar{x} \pm \Delta x$ [units].
- If scientific notation is used, format the numbers $(\bar{x} \pm \Delta x) \times 10^{\text{exp}}$ [units].

Note that the two numbers are reported to the same decimal place, but usually have a different number of sig-figs. You may never use different units, or different scientific notation exponents, for the best value and its uncertainty.

Examples:

Best value	Uncertainty	Report as
0.00566 mm	0.00129 mm	$(5.7 \pm 1.3) \times 10^{-3}$ mm , or 5.7 ± 1.3 μm
35.6 m/s	3.423 cm/s	35.600 ± 0.034 m/s
1759 g	783 g	1760 ± 780 g , or 1.76 ± 0.78 kg
0.000873 m	3.22×10^{-5} m	$(8.73 \pm 0.32) \times 10^{-4}$ m , or 873 ± 32 μm

Note that for powers of ten that are close to 1, scientific notation may not be the most convenient. For instance, 35.600 m/s is more convenient than 3.5600×10^1 m/s.

V. Comparing Experimental Results

Often you may need to compare different results for the same quantity to see whether they agree. Measurements are said to “agree” if their uncertainty ranges overlap.

Example: Terry reports the length of a stick to be 12.00 ± 0.10 cm, Larry gets 12.20 ± 0.40 cm, and Mary gets 11.800 ± 0.050 cm. Terry's measurement (11.90 to 12.10 cm) overlaps with Larry's (11.80 to 12.60 cm), but not with Mary's (11.750 to 11.850 cm). So Terry's measurement “agrees” with Larry's measurement but not with Mary's.

Occasionally you may want to compare your result with some “accepted” value. The uncertainty associated with that accepted value may be very small, perhaps so small (compared to your own measurement) that we choose to ignore it. If your measured value, plus or minus the uncertainty, does not contain the accepted value, then your result is **inconsistent** with it, even though you might feel it is quite close in an absolute sense. For example, a measurement of $9.8087 \pm 0.0012 \text{ m/s}^2$ **does not agree** with an accepted value of 9.81 m/s^2 .

VI. Propagation of Uncertainty

Often an experimentally measured quantity x (with the best value *and* an uncertainty) is not the end result of our experiment, but contributes to a calculated result $F = F(x)$. If we have uncertainty in x , then there will also be uncertainty ΔF in our computed value of F . In this case, where F depends on only one variable x , the uncertainty ΔF is obtained from

$$\Delta F = \left| \frac{dF}{dx} \Delta x \right| \quad . \quad (2)$$

In general, the result F may depend on many variables, $F = F(x, y, z, \dots)$, each of which has a value and an uncertainty. The extension of equation (2) to this case is straightforward. We can isolate each variable's individual effect on this total uncertainty (i.e. $\Delta F_x, \Delta F_y, \Delta F_z, \dots$) by using the above expression, except we replace the normal derivative with a *partial* derivative:

$$\Delta F_x = \left| \frac{\partial F}{\partial x} \Delta x \right|, \quad \Delta F_y = \left| \frac{\partial F}{\partial y} \Delta y \right|, \quad \Delta F_z = \left| \frac{\partial F}{\partial z} \Delta z \right|, \dots \quad . \quad (3)$$

A partial derivative such as $\partial F / \partial x$ is nothing more than a derivative of F with respect to x alone, treating all other variables (y, z, \dots) as constants.

Once we have all individual uncertainties as they pertain to the individual variables, we combine all of these to obtain the overall uncertainty ΔF as follows:

$$\Delta F^2 = \Delta F_x^2 + \Delta F_y^2 + \Delta F_z^2 + \dots \quad (4)$$

or

$$\Delta F = \sqrt{\left(\frac{\partial F}{\partial x} \Delta x \right)^2 + \left(\frac{\partial F}{\partial y} \Delta y \right)^2 + \left(\frac{\partial F}{\partial z} \Delta z \right)^2 + \dots} \quad (5)$$

As an example, imagine that the final quantity in which we are interested, i.e. “ F ”, is the volume of a cylinder (which we will label “ V ” instead of “ F ”), with radius r and height h . Because the volume is given by $V = \pi r^2 h$, the individual contributions to the uncertainty in V , from the two variables r and h , using Equation (3), are

$$\Delta V_r = \left| \frac{\partial V}{\partial r} \Delta r \right| = \left| \frac{\partial [\pi r^2 h]}{\partial r} \Delta r \right| = \left| \pi h \frac{\partial [r^2]}{\partial r} \Delta r \right| = \pi h \cdot 2r \cdot \Delta r \quad , \quad (6)$$

and
$$\Delta V_h = \left| \frac{\partial V}{\partial h} \Delta h \right| = \left| \frac{\partial[\pi r^2 h]}{\partial h} \Delta h \right| = \left| \pi r^2 \frac{\partial[h]}{\partial h} \Delta h \right| = \pi r^2 \cdot \Delta h \quad . \quad (7)$$

You should verify that these expressions have the correct units (i.e., units of volume).

Suppose that r is measured at six different points along the cylinder (see table) and the height is measured to be $h = 4.00 \pm 0.20$ cm (estimated uncertainty). From the table, the average radius is

$$\bar{r} = \frac{1}{6} \sum r_i = 1.1333 \text{ cm}$$

<u>r (cm)</u>
1.2
1.1
1.2
1.0
1.3
1.0

which is our best value for the radius. Using equation (1), the uncertainty in the radius is calculated to be

$$\Delta r = \sqrt{\frac{1}{6} \sum_{i=1}^6 (r_i - \bar{r})^2} = 0.1211 \text{ cm}$$

Next, we substitute the best radius \bar{r} and best height \bar{h} into the formula $V = \pi r^2 h$, resulting in a best value for the volume of $\bar{V} = 16.1408 \text{ cm}^3$. Finally, we plug our earlier results from (6) and (7) into (4), resulting in:

$$\Delta V = \sqrt{\left(\frac{\partial V}{\partial r}\right)^2 \Delta r^2 + \left(\frac{\partial V}{\partial h}\right)^2 \Delta h^2} = \sqrt{(2\pi r h \Delta r)^2 + (\pi r^2 \Delta h)^2}$$

For each occurrence of r in this expression we use the best value \bar{r} , and for each h we use the best value \bar{h} . Plugging in values, we obtain $\Delta V = 3.5427 \text{ cm}^3$.

To report these correctly, we round uncertainties to two significant digits, and round the best values to the same decimal place. Thus we report $r = 1.13 \pm 0.12$ cm and $V = 16.1 \pm 3.5 \text{ cm}^3$. Notice that although the uncertainty in r is rounded for reporting purposes, the unrounded value $\Delta r = 0.1211$ cm was used in the calculation of ΔV .

LAB 1: STANDING WAVES ON A STRING

TOPIC OF INQUIRY

In this experiment we will explore how standing waves are formed by appropriate interference of incident and reflected waves.

THEORY

When two waves travel in opposite directions, their net behavior can be predicted through a mathematical sum of the two waves. It is called *superposition* when simultaneous physical effects are combined (as above) through addition, and superposition of waves causes *interference*. When incident and reflected waves of the same frequency on a string interfere with a pattern that spatially varies from totally destructive to totally constructive interference, it is called a *standing wave* (illustrated in Figure 1). The

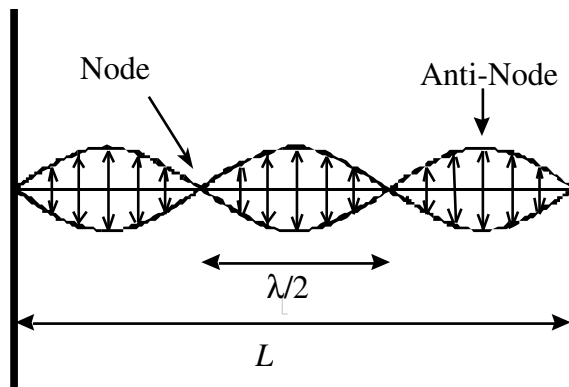


Figure 1: A standing wave on a stretched string, showing the position of the nodes and anti-nodes.

left- and right-traveling waves continually propagate by reflection from the two ends. Notice that some portions of the string remain stationary due to destructive interference; these locations are called *nodes*. The locations of the string where it oscillates vertically with the largest amplitude due to constructive interference are called *anti-nodes*. It is useful to picture the energy of the wave as “standing” in the wave envelope as it alternates between the kinetic and potential energies of the string portions.

For a string fixed at both ends with a given length, L , standing waves occur only for certain distinct wavelengths (and, therefore, frequencies). Since the string is fixed at each end, a standing wave must have a node at each end, meaning that the string length must equal some integer number of “half-wavelengths”. Therefore, the allowed wavelengths, λ , for standing waves are given by

$$\lambda = \frac{2L}{n} \quad n = 1, 2, 3, 4 \dots \quad (1)$$

In equation (1), does n represent the number of nodes or anti-nodes (make a note to discuss with your partner)? The wave speed, v , in a stretched string is given by (we take this for granted here)

$$v = \sqrt{\frac{\tau}{\mu}} \quad (2)$$

where τ is the tension in the string and $\mu = m/L$ is the linear mass density (mass per unit length of the string). Since velocity, v , wavelength, λ and frequency, f , are also related by the equation $v = f\lambda$, only certain frequencies will produce standing waves for a given string tension, density, and length. These frequencies are called the *natural frequencies* or *normal modes of oscillation* of the string. The lowest natural frequency, f_1 , is called the *fundamental frequency* ($n = 1$). The other larger frequencies are higher ($n > 1$) harmonics.

APPARATUS

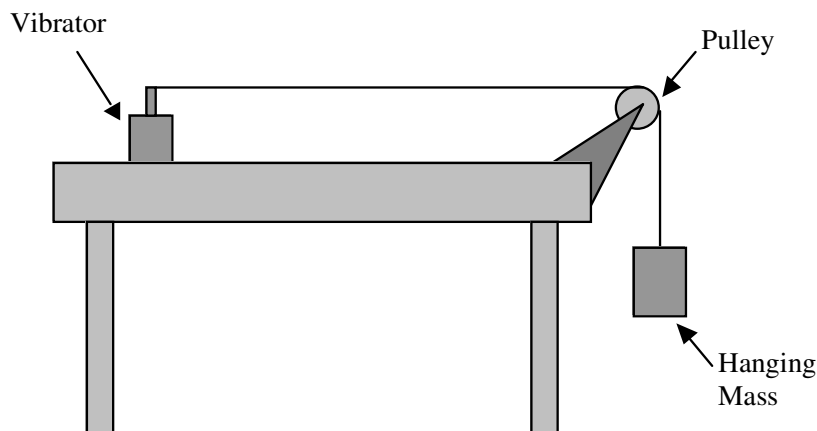


Figure 2: Experimental schematic

A schematic of the apparatus for this experiment is shown in Figure 2. The vibrator is driven by an amplified signal from the function generator, which controls the frequency. A long piece of string is connected to the vibrator. The string runs over a pulley fixed to the end of the lab table. Weights are suspended on the end of the string such that the hanging mass produces tension in the string.

EXPERIMENT

NOTE: Be sure to unlock the string vibrator before use. Lock it again when you are finished.

- 1) Suspend a 100 g mass from the end of the string and adjust the frequency (which device governs the frequency? See above description of Figure 2) to cause a standing wave with 3 anti-nodes (*i.e.*, one for which the total number of nodes is 4, including the ends).
- 2) Record the wave's frequency, f (given by the digital display). You should also measure and record the wavelength, but what procedures are available for accurate measurement of λ ? Could you measure the entire string length, L , and then calculate λ ? Could you measure λ directly for a given number of nodes? There are subtleties in either approach. If you look carefully, you might notice that the end of the string attached to the vibrator is not exactly a node, and also that the node near the pulley can be hard to locate precisely. Perhaps you could

measure between nodes that do not include the ends (only near the center of the string), but that might not be possible for certain configurations (*i.e.*, a certain total number of nodes). Discuss the merits of possible wavelength measurement procedures with your partner before finding and recording λ . Document your discussion and conclusion in your log book.

- 3) Change the frequency to produce as many harmonics as you can, from a single anti-node to at least 8 or 9. Record the frequencies, wavelengths, and number of anti-nodes for each harmonic. For this part, maintain constant values for L and τ (and record those values).
- 4) Plot the frequency, f , as a function of n . Based on this graph, extract an experimental value for the wave speed, v . Derive a theoretical relationship between f and n based on equation (1) and other wave-related principles. Discuss that mathematical relationship with your partner to find a strategy for extracting v from appropriate trendline properties. Compare with a direct calculation of v from equation (2). To apply equation (2), what other properties of the string might you need to measure? The level of agreement between v measured from these two independent methods can supply evidence supporting the theory behind equations (1) and (2).
- 5) We will also investigate the dependence of the wave speed on the tension. Set the frequency of the function generator so that, with a mass of 50 g on the string, there are 3 anti-nodes. Measure the wavelength and frequency of the wave. Vary the tension by increasing the mass up to near 300 g, changing the frequency each time to maintain 3 anti-nodes. If you must exceed ~275-300 g, hold the driver in place so it does not slide or tip. Make sure to have at least 10-12 datapoints.
- 6) Analyze these data by constructing a plot of the hanging mass versus the square of the frequency. From this graph determine the linear mass density, μ , of the string (discuss with your partner how the theoretical equations imply relationships between trendline properties and μ). Compare this value to the directly measured value. Do your measurements agree?

LOG BOOK QUESTIONS

Stringed musical instruments, such as violins and guitars, use stretched strings. In your log book, explain:

- 1) how tightening and loosening the strings tune them to their designated pitch or frequency,
- 2) why the strings for the lower notes are thicker or heavier than those for the higher notes, and
- 3) why notes of higher pitch or frequency are produced when the fingers are placed on the strings.

LAB 2: INTERFERENCE AND DIFFRACTION OF LIGHT

TOPIC OF INQUIRY

In this experiment we will explore the wave nature of light by studying the intensity pattern formed when a laser shines through one or two narrow slits.

THEORY

I. Double Slit

After coherent light, from a laser for example, passes through a pair of narrow, closely-spaced slits (a double slit), the intensity pattern viewed on a distant screen varies due to interference. Each slit behaves like a point source emitting circular waves. This is consistent with the *Huygens-Fresnel principle*, a model of wave propagation where every point on a wavefront is itself a spherical emitter. One prediction of this principle is *diffraction*, where waves seem to bend around sharp edges like the edges of a slit.

In Figure 1, the intensity of the diffraction pattern is plotted sideways, so that the peaks represent regions of maximum intensity (maxima) and the valleys represent minima. Interference depends on the difference in the path length from each emitter to the viewing screen, which would be $\overline{AB} - \overline{GC}$. In a realistic experiment examining interference with light, the distance between the slits, d , will be on the order of 1 mm or less, while the perpendicular distance to the screen, D , will be on the order of 1 m. In such a realistic situation where $D \gg d$, the path lengths \overline{AB} and \overline{CB} are approximately equal. Then, \overline{GC} is the path length difference (PLD). If the PLD is an integer multiple of the wavelength ($PLD = m_c \lambda$ where m_c is an integer which is the “order” of the constructive interference), constructive interference of the waves from the two slits will cause a bright spot on the screen at point B . If the PLD equals an integer plus one-half times the wavelength there will be a dark spot on the screen because the waves will be completely out of phase and will exactly cancel each other. This is called destructive interference.

For **constructive interference**, we can write

$$\sin \theta = \frac{PLD}{d} = \frac{m_c \lambda}{d} \quad m_c = \pm 0, 1, 2, 3 \dots \quad (1)$$

where d is the center-to-center distance between the slits. If the distance from the double slit to the screen, D , is large compared to the positions of the pattern y (measured from the middle of the pattern), then θ is a small angle and one can make the further approximation

$$\sin \theta \approx \tan \theta = \frac{y_c}{D} \quad (2)$$

Combining Equations (1) and (2) we obtain

$$\frac{y_c}{D} = \frac{m_c \lambda}{d} \quad m_c = \pm 0, 1, 2, 3 \dots \quad (3)$$

Here we have substituted the symbol y_c for y to emphasize that this equation is specifically for the locations of *constructive* interference (distance from the central maximum).

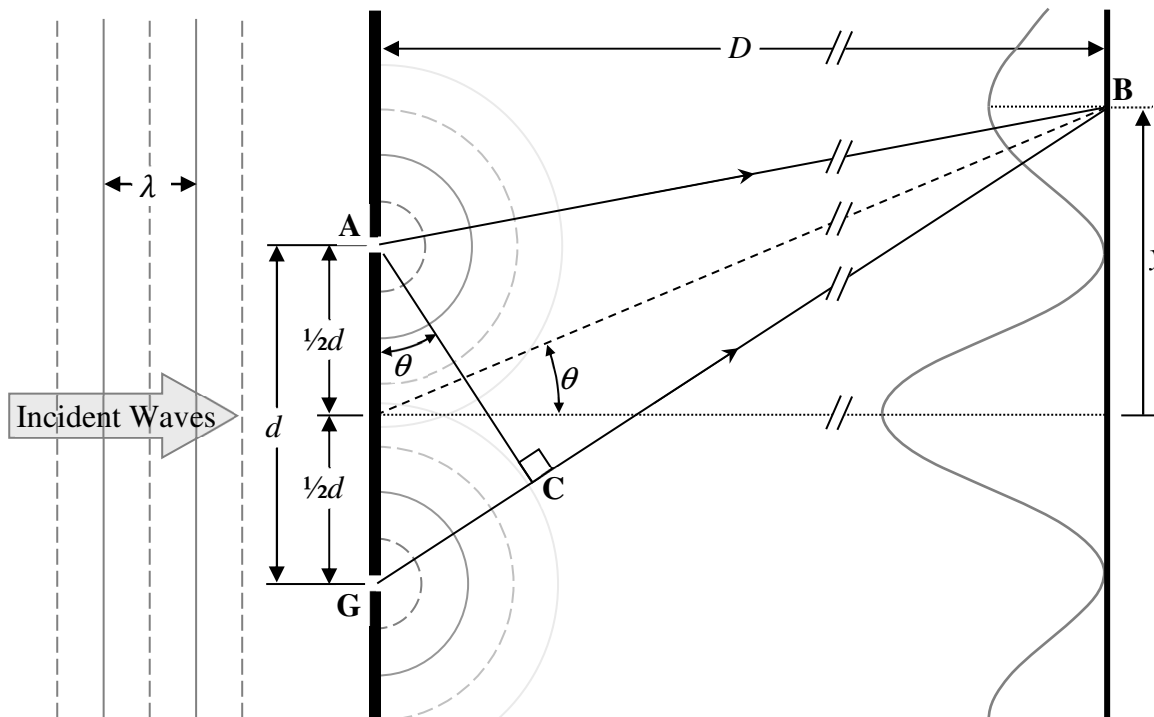


Figure 1: Illustration of interference of light passing through two narrow slits.

Intensity maxima are referred to by their “order,” where 0th order is the central peak, 1st order are the peaks on either side of that, and so on. Equation (3) has been written so that the value of m_c gives the order of the corresponding peak.

NOTE: In the above analysis, we assumed that the slits have no width, which of course is impossible physically. The derivation to account for finite slit widths is challenging, but the consequences of such a derivation are summarized by two additional considerations:

- 1) The slit-to-slit distance, d , is the **center-to-center** distance of the two slits.
- 2) The series of bright spots will not be equally bright, but will be “modulated” by a broader diffraction pattern consistent with a single slit (see next section).

II. Single Slit

Even when a wave passes through a single slit, there are still maxima and minima observed on the screen. We can describe the central maximum by considering many closely separated spherical emitters within the slit (applying the Huygens-Fresnel principle). If we consider two emitters symmetrically located above and below the center, they have equal travel distances to the center of the screen and will interfere constructively. Each such pair of sources will do so. This proves nothing (we don't know the phase relationship between one pair and another), but it is at least consistent with screen center having a maximum.

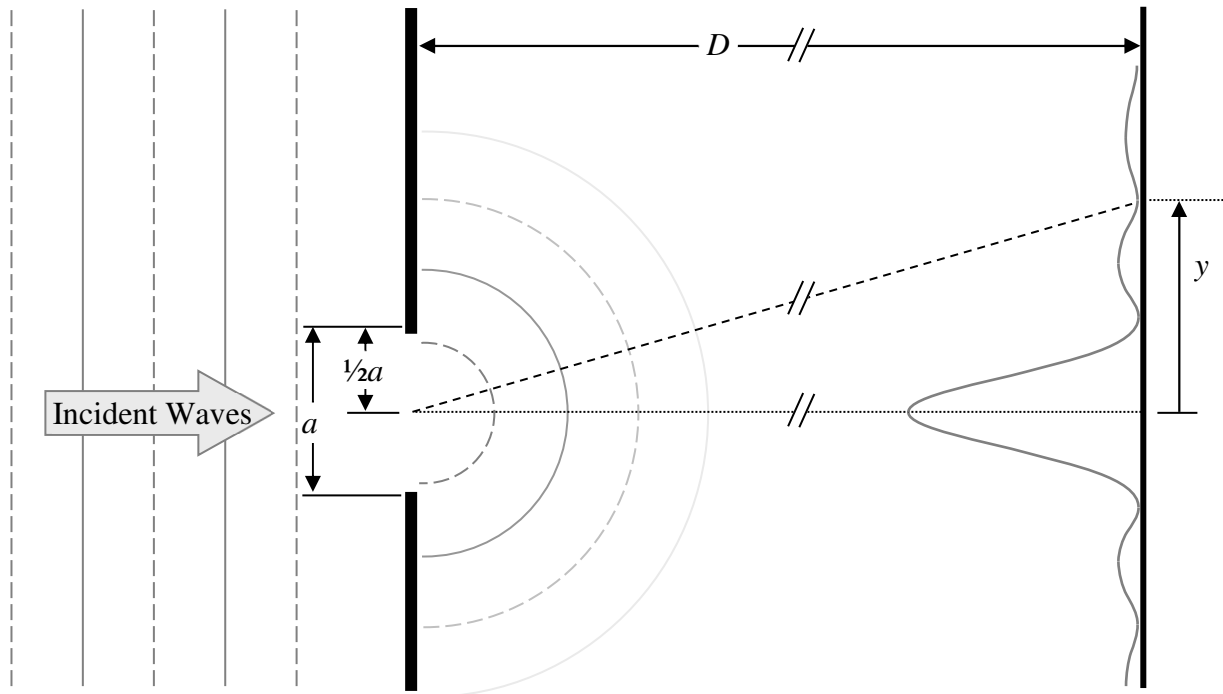


Figure 2: Destructive interference from a pair of emitters.

A stronger argument can be made to locate minima. Consider the top of the slit as one emitter and the position just below the center of the slit as another emitter (see Figure 2). If the distance traveled by the lower emitter is a half wavelength more than that traveled by the top emitter, they will interfere destructively. *So, also, will the waves from the two emitters just below these.* Thus, pair by pair, we find that there is destructive interference for the entirety of the slit, and hence a dark spot on the screen. This geometry is similar to that described for the double slit, except for a minimum instead of a maximum. Alternatively, we could divide the slit into quarters, and apply the same reasoning to light from the bottom two quarters, and also for the top two quarters, (or in 6ths or in 12ths). For a given slit width a , you should be able to show that a dark spot occurs when

$$\frac{y_d}{D} = \frac{\frac{\lambda}{2}}{\frac{a}{2n}} = \frac{n_d \lambda}{a} \quad n_d = 1, 2, 3, 4 \dots \quad (4)$$

Where n_d is the order of the destructive interference and y_d is the position of the d^{th} minimum.

APPARATUS

Use the laser with care. Be careful not to shine it in anyone's eyes.

EXPERIMENT

I. Single Slit Measurements

- 1) Position your slit in a holder. Place a screen (piece of white paper or cardboard) several meters away. Keep in mind that the greater the distance between the slit and screen the larger the spread in your diffraction pattern. Try it and see. Position the laser so you can easily aim the laser beam on the single slit.
- 2) Measure the distances of the destructive interference points, y , from the center.

Note: It will be easier, and more accurate, to measure the distance between *corresponding points on opposite sides of center* and to divide this distance by 2.

II. Double Slit measurements

- 3) With the laser shining through the double slit obtain a pattern in a similar manner to that above.
- 4) Record the distance from center, y_c , for as many bright spots as you can measure.

Note: Again, measuring the distance between corresponding spots and dividing by 2 will be more accurate. If a diffraction minimum of the single slit pattern happens to coincide with the location of a bright spot in the double slit pattern, you may miss seeing the bright spot. If you think this happens, be sure to record the fact.

ANALYSIS

- 5) Equation (4) for the single slit destructive interference points can be re-written

$$y_d = \frac{Dn_d\lambda}{a}, \quad n_d = 1, 2, 3 \dots$$

This is the equation of a straight line with no intercept if you plot y_d vs. n_d . The slope of the line is given by $D\lambda/a$. Plot and fit this graph to find one value for the wavelength λ .

- 6) Similarly rewrite equations (3), for the bright spots of the double slit pattern. Plot of y_c vs. m_c and find a value for λ .
- 7) Compare your two values of λ . Do they agree with each other within their uncertainties? Do they agree with the quoted value for a He-Ne laser (632.8 nm)?

LAB 3: FOCAL LENGTH OF A LENS

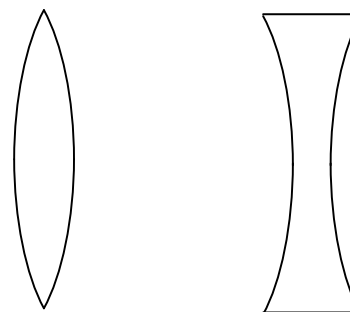
TOPIC OF INQUIRY

In this experiment we will investigate the optical properties of convex lenses.

THEORY

Lenses operate based on *refraction* of light. Refraction occurs when waves transition from one medium into another (like air-to-glass or glass-to-air). You will learn more about refraction in the future, but here we take the optical consequences of refraction for granted during a first exploration into the nature of light.

There are two primary types of lenses: “convex” lenses and “concave” lenses. A convex lens is thicker in the middle than it is on the edge, and a concave lens is thinner in the center than it is on the edges. Side views of a convex and concave lens are shown in Figure 1.



Convex Lens

Concave Lens

Figure 1: Convex and Concave Lens.

Our predictions here are based on the simplifying *thin lens approximation*, where the distance light travels inside the glass is very small compared to the distance travelled in the air. Parallel light rays that are incident on one side of a convex lens will be deflected toward the central axis of the lens and will be focused to a point on the other side of the lens, as shown in Figure 2. This point is called the “focal point” for the lens. The distance from the lens to the focal point is called the “focal length” of the lens. Parallel light rays that are incident on one side of a concave lens will be deflected away from the central axis of the lens, as shown in Figure 2.

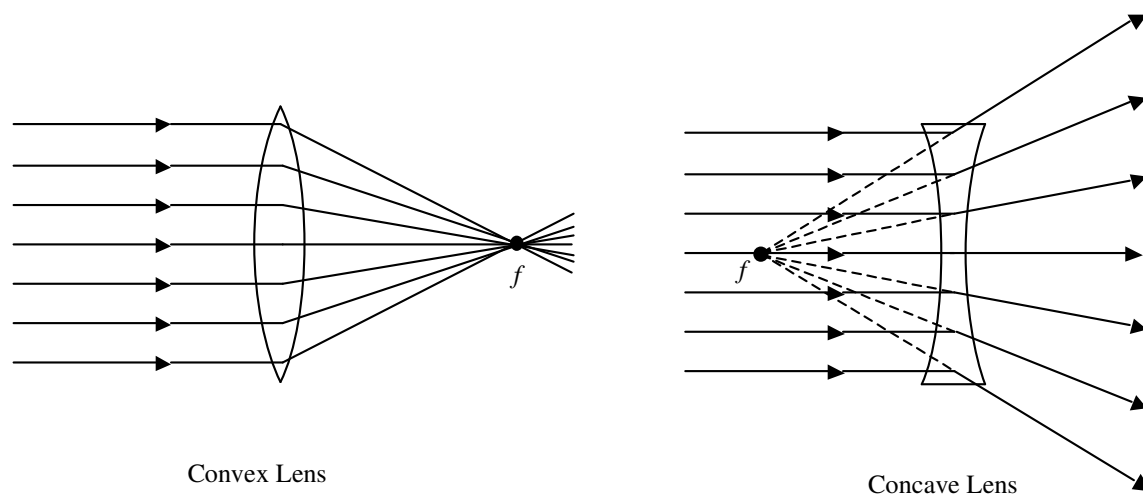


Figure 2: In a convex lens, parallel light rays are deflected toward the central axis so that they converge at a point f on the right side of the lens. In a concave lens, parallel light rays are deflected away from the central axis so that it appears as if they are emerging from a point f on the left side of the lens.

Image formation by thin lenses can be treated in several ways. One method is by drawing a ray diagram. The key to a good ray diagram is to make it large (one ray diagram per page), and to use a ruler. Also, it's usually a good idea to turn your paper into the “landscape” orientation. First, setup the diagram by drawing the lens near the middle of the page, and then drawing the central axis (the line which passes horizontally through the center of the lens). Next, label the focal points of the lens, one on each side of the lens. Finally, place an object to be viewed through the lens on the diagram and represented, by convention, by an arrow on the left side of the lens. Now you are ready to draw some rays on your diagram!

I. Convex Lens, Object Behind Focal Point

In this example, let's consider an "object" that is placed behind the focal point of a convex lens, as shown in Figure 3. For all ray diagrams, you will *draw three lines* originating at the arrow's head, each representing a ray of light that bounces off the object. The first line is parallel to the central axis. We know this ray must pass through the focal point on the right side. The second line, drawn through the center of the lens, is not deflected at all (and so is straight all the way). The third line is drawn through the focal point on the left side of the lens. This line will be deflected such that it emerges parallel to the central axis on the right side. Note that all three lines converge on one point, which then becomes the head of the "image". The position, orientation, and size of the image arrow is a representation of the object's appearance *as viewed through the lens*. Here the image arrow also shows the result when light is projected through the lens onto a screen.

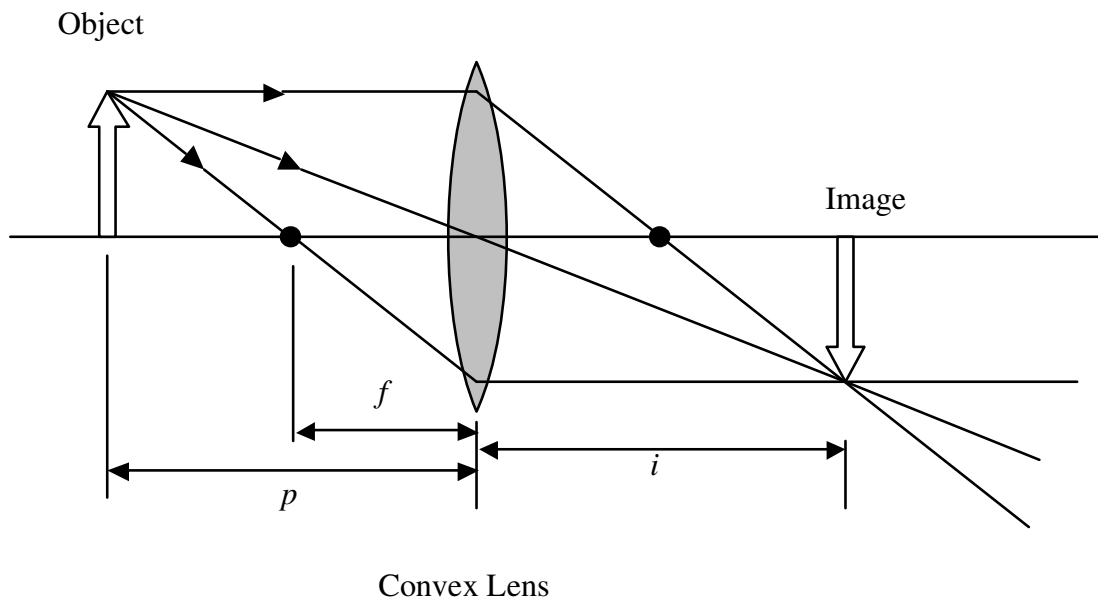


Figure 3: Ray diagram for an object placed behind the focal point of a convex lens. Note that the image produced is real and inverted (upside-down).

II. Convex Lens, Object in Front of Focal Point

What happens if we place the object inside the focal point for a convex lens, as shown in Figure 4? Again, we draw three rays coming from the head of the object: one parallel to the central axis, one that goes straight through the center of the lens, and another whose extension passes through the focal point on the left. Note that the rays are diverging on the right side of the lens, therefore there is no *real* image (real images can be projected onto a screen). However, the extensions of the rays on the left side of the lens converge at a point on the left side of the lens. Therefore, these ray extensions indicate a *virtual* image on the left side of the lens (both real and virtual images are representations of an object's appearance as viewed through the lens).

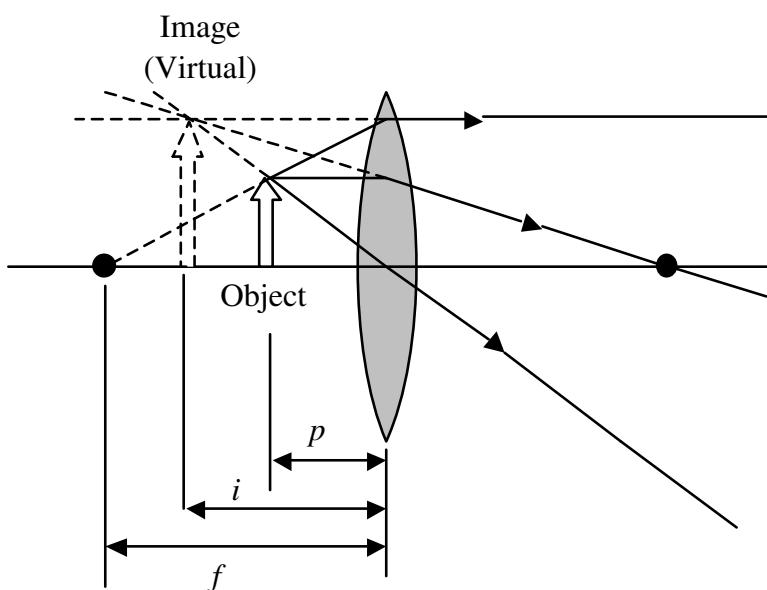


Figure 4: Ray diagram for convex lens with object placed inside the focal point. Note that the image produced here is upright and virtual.

For thin lenses, the relationship between the object distance p , the focal length f , and the image distance i is given by the *thin lens equation*

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad (1)$$

There are a few important sign conventions to remember when using this equation. First, if the lens is convex the focal length f is positive, if the lens is concave the focal length f is negative. If the image is real (actual light rays intersect there) then the image distance i will be positive, if the image is virtual (intersection occurs by extension of the light rays, as indicated by dashed lines) then the image distance i will be negative. Likewise, the object distance p is positive if we have a *real* object, and negative if we have a *virtual* object (which can only occur with multiple lenses).

Similar triangles on these diagrams involving the object and the image also yield an equation for the magnification of the object.

$$\frac{h_i}{h_o} = m = -\frac{i}{p} \quad (2)$$

where h_i and h_o are the heights of the image and object respectively, and m is the magnification. Here again there is a sign convention to follow: heights are positive if they have the same orientation as the object, regardless of whether they extend above or below the midline. Thus h_o is always positive. The image in Figure 4 is described as *upright* and has a positive h_i . The image in Figure 3 is inverted *relative to the object*, and thus h_i (and therefore m) are negative.

EXPERIMENT

I. *Drawing Ray Diagrams*

- 1) Using a piece of graph paper and a ruler, make a ray diagram showing the formation of an image for a given object distance and focal length. Your lab instructor will give you two convex lenses of different focal lengths and object distances. Pick one of those values for your diagram. Verify that the position of the real image formed according to your ray diagram agree with the values calculated using equation (1).

II. *Measuring the Focal Length of Convex Lenses*

- 2) Measure the focal length directly by taking your lens to the window and measuring the image distance of objects far away (somewhere across campus). Since these rays from a distant object are essentially parallel, they converge at the focal point. Thus, we can easily find the focal length of our lenses. If the apparatus is occupied by another team, do this part later on.
- 3) Using one converging lens with a variety of object distances, find the screen position that yields a sharp, focused image. For each focused image, record the object position, the lens position, the screen position, and the height of the image. Also record the height of the object. Make sure to take note of the lens you are using.

III. *Analysis*

- 4) Use Excel to convert your raw data into object distances p and image distances i . Note that equation (1) is linear if you plot $1/i$ vs. $1/p$. What relationships involving the slope and y-intercept of $1/i$ vs. $1/p$ are implied by equation (1)? Use *linest* to calculate the focal length of the lens. Remember to use Excel for all calculations, not your calculator.
- 5) For each measurement, also calculate the expected and observed magnifications, given by the left and right sides of equation (2) respectively. How do they compare?

