PH 212 Labs

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Lab Policies and General Information

The purpose(s) of these labs: The lab portion of this course is not to test what you (may) already know about physics. Rather, it’s to help you sharpen that knowledge more fully and clearly, in a very practical setting—where you encounter first-hand the fundamental “testing” nature of science. Lab is not directly tested on the exams (nor does it prepare you directly for exams—though you’ll be practicing verbal/writing skills useful on the exams).

Unlike in other courses, moreover, these labs are not “cookbook” recipes of procedures that you just plod through. To a large extent, you will design your own experiments—so you must come to lab prepared. Your TA is there to act as your guide only in a minimal sense—as a resource or a sounding board, not to demonstrate or explain exactly what to do. And—like the rest of this course—you must continually hone the all-important skill of putting into words what you think and discover; you must be able to explain, reconcile and summarize your reasoning.

So resolve right now to embrace the real purposes of lab and take full advantage of it: (i) to apply physics principles appropriately; and (ii) to make sense of them, so that you can, likewise, convey that sense to others.

Attendance: Lab is a team effort; you will work each week as part of a group of 3. Usually, you will be allowed to form your own groups, but note that your TA has full discretion in this matter. And he/she may allow the same groups to form each week or ask you to form new ones.

Your participation is required throughout every lab session. In order to be counted as present for the lab (i.e. contributing to your group and receiving a non-zero score for that lab), you must arrive no more than “a few minutes” late (and you must stay until your group has turned in its lab write-up). What does “a few minutes” mean? That is up to your TA—he/she will tell you this in Lab 1 (either in person or via the Lab Syllabus, or both). Whatever rule he/she sets for that late “cutoff” is what you go by. And then note: Lab credit is not given just for “warming the chair.” To earn a share of the points each week, you must participate actively and contribute genuinely to your group. Your TA has full discretion to deduct points from your lab credit for marginal (or non-) participation.

Your lab grade: Your lab is worth 10% of your overall course grade (so: 100 points out of 1000 total possible for the course). There are 9 labs in all, each worth 1 to 1.5% (10 to 15 points out of 1000) of your total grade. This may seem trivial, but NOTE: For any lab you miss (i.e. score a 0 for that lab), 5% will be deducted from your total course score (not just your lab score). This is a serious penalty—DO NOT SKIP ANY LABS. (Notice that there is a chance during Week 10 to make up labs—but no more than two—that you missed during the term.)

There is one lab write-up per group, but each group member must clearly put his/her name and student ID at the top of the write-up in order to obtain credit. You will usually need to supply your own paper for the write-up—do not plan to write on the pages of this lab packet unless it specifically gives you space and directions to do so. When using your own paper, you should use whatever format your TA may prefer/specify, if any. (See the next page for more specifics about the content of the lab write-ups.)

The lab write-up is done entirely during the 3-hour lab; there is nothing more to do afterward. But you’d better read the lab ahead of time and familiarize yourself with what’s involved. Your TA will not be taking much time to explain it to you—you know how to read. As a professional, you are ALWAYS expected to arrive having read and prepared. And each write-up requires you to explain carefully (but consisely): Besides the physics, you’ll need to justify your experiment, its results and conclusions—accounting, too, for experimental uncertainty.
Lab Types, Reports and Scoring

**Lab Types:** You will conduct 3 different types of lab experiments during this term.

A. **Observation experiments.** These are intended for students to learn skills such as changing one variable at a time, clearly recording and representing observations, and making accurate observations without mixing them with explanations. This is the first step of the experimental cycle, and allows you to observe phenomena, look for patterns in data, and start to devise explanations (once observations are carefully completed).

B. **Testing experiments.** Once explanations have been devised, the next step is to conduct an independent test students design that will test a hypothesis based on a specific explanation or rule. This helps you practice the skill of making predictions about the outcome of an experiment based on an explanation/rule/relationship. For a testing experiment, you can’t just do the experiment and record what happens – they must have a predicted outcome based on some explanation – and if the outcome of the experiment agrees with the prediction it gives confidence that the explanation may be correct, but if it disagrees, then you know the explanation is incorrect. In order to make this judgment, you also need to apply basic uncertainty calculations. (A guide for understanding uncertainty is included in this packet.)

C. **Application experiments.** The third type of experiment is the application experiment, where you apply some explanation/rule/relationship that you have tested enough that you think it is ‘good’, and you apply it to understand a new situation. Some application experiments require that you determine some unknown quantity multiple ways – in order to determine if the methods are consistent, it is necessary to apply basic uncertainty analysis. By performing this sequence of experiments, it is possible to explore and devise a physics relationship, test it, and when you are convinced it is good, apply it to understand a new situation – providing you with a complete understanding of the basic physics relationships (equations). By designing your own experiments, it gives you creative control, and assures that you understand the steps that you perform, as they are done by your conscious choice, and not by following instructions or ‘playing around.’

**Your group lab write-up** is not a formal report, but it does need to be clear. The lab will often include a reminder of the general items that must always be included within your write-up (related to the type of experiment: observation, testing, or application). It may also have specific questions for you to answer and/or tasks to complete (answer and document) in your write-up. Your information does not need to be presented in paragraph form; use short, clear and **complete** sentences to address the required points **succinctly.** You may use equations and/or diagrams instead of trying to write the math out in words.

For a sample lab write-up, click here.

**Your TA will score each write-up** by evaluating a selected subset (usually 5-10) of the items required in the lab. Each item will be scored out of a possible of 3 points, according to a **rubric—**a scoring guide. For each of these three types of experiments, there is rubric for you and the TA to use to evaluate your work—**see the next three pages.** Plan to bring these rubrics (and also the section covering experimental uncertainty) to lab with you, so that you can check your write-up as you work on it. Then your TA will take your total lab score that week and convert it to a scale out of 10 or 15 points—1% or 1.5% of your overall course grade. (Again, see the online Course Syllabus for more about grading policies.)

To see how the above sample lab write-up would be scored, click here.
<table>
<thead>
<tr>
<th>Scientific Ability</th>
<th>Missing (0 points)</th>
<th>Inadequate (1 point)</th>
<th>Still needs improvement (2 points)</th>
<th>Adequate (3 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Clearly identify the phenomenon to be investigated.</td>
<td>No mention is made of the phenomenon to be investigated.</td>
<td>An attempt is made to identify the phenomenon to be investigated, but it is described in a confusing manner.</td>
<td>The phenomenon to be investigated is described, but there are minor omissions or vague details.</td>
<td>The phenomenon to be investigated is clearly stated.</td>
</tr>
<tr>
<td>2. Design a reliable experiment that investigates the phenomenon.</td>
<td>The experiment does not investigate the phenomenon.</td>
<td>The experiment involves the phenomenon but its design is unlikely to produce data containing any interesting patterns.</td>
<td>The experiment investigates the phenomenon and the data will probably show interesting patterns, but its design will miss some features or patterns.</td>
<td>The experiment investigates the phenomenon; it is highly likely the data will contain interesting patterns with all their features observable.</td>
</tr>
<tr>
<td>3. Decide what to measure; identify the independent and dependent variables.</td>
<td>The chosen measurements will not produce data that can be used to achieve the goals of the experiment.</td>
<td>The chosen measurements will produce only data that is useful (at best) to partially achieve the goals of the experiment.</td>
<td>The chosen measurements will produce data useful in achieving the experiment’s goals, but independent and dependent variables aren’t clearly distinguished.</td>
<td>The chosen measurements will produce data useful for achieving the experiment’s goals. Independent and dependent variables are clearly distinguished.</td>
</tr>
<tr>
<td>4. Use the available equipment to make measurements.</td>
<td>At least one of the chosen measurements cannot be made with the available equipment.</td>
<td>All chosen measurements can be made, but no details are given about how they are done.</td>
<td>All chosen measurements can be made, but the details of how they are done are vague or incomplete.</td>
<td>All chosen measurements can be made and all details of how they are done are clearly provided.</td>
</tr>
<tr>
<td>5. Describe observations without explaining them, using words and a picture of the experimental set-up.</td>
<td>No description is mentioned.</td>
<td>A description is offered but it is incomplete. No picture is present. Or, most of the observations are mentioned in the context of prior knowledge.</td>
<td>The description (with a labeled picture) is given but mixed with explanations/other material. Or, some observations are given in terms of prior knowledge.</td>
<td>Clear descriptions are given of what happens in the experiments—both verbally and via a labeled picture.</td>
</tr>
<tr>
<td>6. Identify the shortcomings in the experimental design—and suggest improvements.</td>
<td>No attempt is made to identify any shortcomings of the experimental design.</td>
<td>Some shortcomings are described—but vaguely—with no suggestions for improvements.</td>
<td>Some shortcomings are identified and some improvements are offered, but not all aspects of the design are considered.</td>
<td>All major shortcomings of the experiment are identified and specific suggestions for improvement are made.</td>
</tr>
<tr>
<td>7. Construct a mathematical relationship (if applicable) that represents a trend in the data.</td>
<td>No attempt is made (if applicable) to construct a relationship that represents a trend in the data.</td>
<td>An attempt is made (if applicable), but the relationship suggested does not represent the trend in the data.</td>
<td>The relationship (if applicable) represents the trend, but there is no analysis of how well it fits the data. Or, some features of the relationship are missing.</td>
<td>The relationship (if applicable) represents the trend accurately and completely; and an analysis of how well it agrees with the data is included.</td>
</tr>
<tr>
<td>8. Devise an explanation for an observed relationship.</td>
<td>No attempt is made to explain the observed relationship.</td>
<td>An explanation is offered, but it is vague, or not testable, or it contradicts the observations.</td>
<td>An explanation is made and is based on simplifying the phenomenon, but it uses flawed reasoning.</td>
<td>A reasonable explanation is made and is based on simplifying the phenomenon.</td>
</tr>
<tr>
<td>9. Identify the assumptions made in devising the explanation.</td>
<td>No attempt is made to identify any assumptions.</td>
<td>An attempt is made to identify assumptions, but most are missing, described vaguely, or incorrect.</td>
<td>Most assumptions are correctly identified.</td>
<td>All assumptions are correctly identified.</td>
</tr>
<tr>
<td>Scientific Ability</td>
<td>Missing (0 points)</td>
<td>Inadequate (1 point)</td>
<td>Still needs improvement (2 points)</td>
<td>Adequate (3 points)</td>
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</tr>
<tr>
<td>1. Clearly identify the hypothesis to be tested.</td>
<td>No mention is made of a hypothesis to be tested.</td>
<td>An attempt is made to identify the hypothesis to be tested, but it is described in a confusing manner.</td>
<td>The hypothesis to be tested is described, but there are minor omissions or vague details.</td>
<td>The hypothesis is clearly stated.</td>
</tr>
<tr>
<td>2. Design a reliable experiment that tests the hypothesis.</td>
<td>The experiment does not test the hypothesis.</td>
<td>The experiment tests the hypothesis, but due to the nature of the design it is likely the data will lead to an incorrect judgment.</td>
<td>The experiment tests the hypothesis, but due to the nature of the design, there is a moderate chance that the data will lead to an inconclusive judgment.</td>
<td>The experiment tests the hypothesis and has a high likelihood of producing data that will lead to a conclusive judgment.</td>
</tr>
<tr>
<td>3. Distinguish between a hypothesis and a prediction.</td>
<td>No prediction is made. The experiment is not treated as a testing experiment.</td>
<td>A “prediction” is made, but it is identical to the hypothesis.</td>
<td>A prediction is made and is distinct from the hypothesis but does not describe the outcome of the designed experiment.</td>
<td>A prediction is made that is distinct from the hypothesis, and it describes the outcome of the designed experiment.</td>
</tr>
<tr>
<td>4. Make a reasonable prediction based upon a hypothesis.</td>
<td>No prediction is attempted.</td>
<td>A prediction (distinct from the hypothesis) is made, but it is not based on the hypothesis.</td>
<td>A prediction is made that follows from the hypothesis, but it does not incorporate assumptions.</td>
<td>A prediction is made that follows from the hypothesis and incorporates assumptions.</td>
</tr>
<tr>
<td>5. Identify the assumptions made in making the prediction.</td>
<td>No attempt is made to identify any assumptions.</td>
<td>An attempt is made to identify assumptions, but the assumptions are either irrelevant or confused with the hypothesis.</td>
<td>Relevant assumptions are identified but are not significant for making the prediction.</td>
<td>All assumptions are correctly identified.</td>
</tr>
<tr>
<td>6. Identify specifically how the assumptions might affect the prediction.</td>
<td>No attempt is made to determine the effects of assumptions.</td>
<td>The effects of assumptions are mentioned but are described vaguely.</td>
<td>The effects of assumptions are determined, but no attempts are made to validate them.</td>
<td>The effects of the assumptions are determined and the assumptions are validated.</td>
</tr>
<tr>
<td>7. Decide whether the prediction and the outcome agree or disagree.</td>
<td>There is no mention made as to whether the prediction and outcome agree or disagree.</td>
<td>A decision is made about the agreement or disagreement, but it’s not consistent with the outcome of the experiment.</td>
<td>A reasonable decision about the agreement or disagreement is made, but experimental uncertainty is not taken into account.</td>
<td>A reasonable decision about the agreement or disagreement is made, and experimental uncertainty is taken into account.</td>
</tr>
<tr>
<td>8. Make a reasonable judgment about the hypothesis.</td>
<td>No judgment is made about the hypothesis.</td>
<td>A judgment is made but is not consistent with the outcome of the experiment.</td>
<td>A judgment is made and is consistent with the outcome of the experiment, but assumptions are not taken into account.</td>
<td>A reasonable judgment is made and assumptions are taken into account.</td>
</tr>
<tr>
<td>9. Revise the hypothesis if/when necessary.</td>
<td>A revision is necessary but none is made.</td>
<td>A revision is necessary and attempted, but the new hypothesis is not consistent with the results of the experiment.</td>
<td>A revision is necessary, and one is suggested that is consistent with the results of the experiment, but other relevant evidence is not taken into account.</td>
<td>A necessary revision is made and is consistent with all relevant evidence.</td>
</tr>
</tbody>
</table>
### Rubric A: Application experiment

<table>
<thead>
<tr>
<th>Scientific Ability</th>
<th>Missing (0 points)</th>
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<th>Still needs improvement (2 points)</th>
<th>Adequate (3 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Clearly identify the problem to be solved.</td>
<td>No mention is made of the problem to be solved.</td>
<td>An attempt is made to identify the problem to be solved, but it is described in a confusing manner.</td>
<td>The problem to be solved is described, but there are minor omissions or vague details.</td>
<td>The problem to be solved is clearly stated.</td>
</tr>
<tr>
<td>2. Design a reliable experiment that solves the problem.</td>
<td>The experiment does not solve the problem.</td>
<td>The experiment attempts to solve the problem but due to the nature of the design the data will not lead to a reliable solution.</td>
<td>The experiment attempts to solve the problem but its design allows a moderate chance that the data will not lead to a reliable solution.</td>
<td>The experiment solves the problem and has a high likelihood of producing data that will lead to a reliable solution.</td>
</tr>
<tr>
<td>3. Use available equipment to make measurements.</td>
<td>At least one of the chosen measurements cannot be made with the available equipment.</td>
<td>All of the chosen measurements can be made, but no details are given about how it is done.</td>
<td>All of the chosen measurements can be made, but the details about how they are done are either vague or incomplete.</td>
<td>All of the chosen measurements can be made, and all details about how they are done are clearly provided.</td>
</tr>
<tr>
<td>4. Make a judgment about the results of the experiment.</td>
<td>No discussion is presented about the results of the experiment.</td>
<td>A judgment is made about the results, but it is not reasonable or coherent.</td>
<td>An acceptable judgment is made about the result, but the reasoning is flawed or incomplete.</td>
<td>An acceptable judgment is made about the result, with clear reasoning. The effects of assumptions and experimental uncertainties are considered.</td>
</tr>
<tr>
<td>5. Evaluate the results using an independent method.</td>
<td>No attempt is made to evaluate the consistency of the result using an independent method.</td>
<td>An independent method is used to evaluate the results. However there is little or no discussion about the differences in the results of the two methods.</td>
<td>An independent method is used to evaluate results, with some discussion of the differences in results, but little about possible reasons for the differences.</td>
<td>An independent method is used to evaluate the results. Discrepancies between the methods’ results—reasons, % difference (if applicable)—are discussed.</td>
</tr>
<tr>
<td>6. Identify the shortcomings in an experimental design and suggest specific improvements.</td>
<td>No attempt is made to identify any shortcomings of the experimental design.</td>
<td>An attempt is made to identify shortcomings, but they are described vaguely and without specific suggestions for improvements.</td>
<td>Some shortcomings are identified, and some improvements are suggested, but not all aspects of the design are considered.</td>
<td>All major shortcomings of the experiment are identified and specific suggestions for improvement are made.</td>
</tr>
<tr>
<td>7. Choose a useful mathematical procedure for solving the experimental problem.</td>
<td>Either there is simply no mathematical procedure included, or the procedure included is irrelevant to the design.</td>
<td>A mathematical procedure is described, but it is incomplete, and therefore the final answer cannot be calculated.</td>
<td>A correct and complete mathematical procedure is described, but an error is made in the calculations.</td>
<td>A complete mathematical procedure described, fully consistent with the design. All quantities are calculated correctly, and the final answer is meaningful.</td>
</tr>
<tr>
<td>8. Identify the assumptions made in using the mathematical procedure</td>
<td>No attempt is made to identify any assumptions.</td>
<td>An attempt is made to identify assumptions, but most are missing, described vaguely, or incorrect.</td>
<td>Most assumptions are correctly identified.</td>
<td>All assumptions are correctly identified.</td>
</tr>
<tr>
<td>9. Determine specifically the way(s) in which assumptions might affect the results.</td>
<td>No attempt is made to determine the effects of assumptions.</td>
<td>An attempt is made to determine the effects of some assumptions, but most are missing, described vaguely, or incorrect.</td>
<td>The effects of most (but not all) assumptions are determined correctly, and/or a few contain errors or inconsistencies.</td>
<td>The effects of all assumptions are correctly determined.</td>
</tr>
</tbody>
</table>
Experimental Uncertainty

You can’t measure any physical quantity exactly. You can say only that its value lies within a certain range of uncertainty. Therefore, as an experimenter measuring any value, X, you must make a judgment that the “true” value of X lies somewhere between $X - \Delta X$ and $X + \Delta X$ (usually expressed in the standard form, $X \pm \Delta X$).

Why is this important? Why do you need to know about uncertainty—and how to estimate it? Because otherwise you can’t answer even the simplest questions in scientific experimentation. For example:

“Is the measured value in agreement with the prediction?”

“Do the data fit the physical model?”

To answer either of these questions, you need to use numbers—the data you’ve measured. But what value(s) should you use, when all of them contain uncertainties?

Consider even the most basic physical question:

“Are two measured values, X and Y, different or the same?”

Your measurements may show them to be slightly different, but what if that difference is smaller than the uncertainty with which you can measure them? If the ranges $X \pm \Delta X$ and $Y \pm \Delta Y$ overlap, then you cannot make a valid argument that X and Y are actually different. You must declare that they are the same within your experimental uncertainty.

Which bunch of grass is higher here? You cannot tell this, because their heights are measured with an uncertainty that is comparable to the height difference.

The issue of uncertainty directly impacts your physics lab measurements and conclusions. You’ll need to be aware of it not only as you make your experimental measurements, but much earlier, too—as you design those experiments in the first place.

All in all, to correctly and completely analyze your experimental results, you’ll need to know...

• How to identify the sources of measurement uncertainty.

• How to estimate the quantitative effects (magnitude and sign) of each source of uncertainty.

• How to compare seemingly unlike types and magnitudes of uncertainties—by converting them to relative uncertainties.

• How to make measurements in ways that reduce their relative uncertainties.

• How to account for various combinations of (relative) uncertainties as you calculate results using more than one measured value: Are the uncertainties about equal, or is one significantly larger than the rest?

Here’s a short look at each of the above....
Sources of Uncertainty in Measurements

**Instrumental uncertainties.** Every measuring instrument has an inherent uncertainty that is determined by the precision of that instrument.

How can you estimate (quantify) instrumental uncertainty? Usually its absolute value is half of the smallest increment of the instrument scale. For example, if the most finely spaced marks on a ruler are 1 millimeter apart, then 0.5 mm is that ruler’s precision. Likewise, a clock marked with 1-second intervals has a precision of 0.5 s.

Instrumental sources of uncertainty are the easiest to estimate, but unfortunately they’re not the only sources—and often not even the most significant. You’d have to be a very skillful (and lucky) experimentalist indeed to eliminate all other sources of uncertainty; the overall uncertainty of the measurement is almost never equal to the instrumental uncertainty.

**Random uncertainties.** Often when you measure the same quantity more than once, you’ll get a slightly different value each time—due to various uncontrollable factors that can randomly affect your results.

How can you estimate (quantify) random uncertainty? You must repeat the measurement several times, take an average, then look at how far the data typically vary from that average.

For example, if you are measuring the distance at which a cannonball hits the ground, you could get a slightly different distance every time you repeat the shot—say 50 m, 51 m and 49 m. The average is then \((50+51+49)/3 = 50\) m. And the data values are spread around this average by about a meter: \(X = 50 \pm 1\) m. Or, in other words: \(|\Delta X| = 1\) m.

You’d therefore estimate that (speaking for the moment only of random uncertainty) most cannonballs will fall in the range from 49 m to 51 m (i.e. from \(X - \Delta X\) to \(X + \Delta X\)).

**Uncertainties due to experimental design and assumptions.** The simplifying assumptions that are inherent in your model may also contribute to the uncertainty of the desired quantity. For example, suppose you’re measuring the diameter of a baseball and are assuming it is perfect sphere. But its actual diameter may differ by about a millimeter, depending what axis you measure across (and the seams are yet another question).

This type of uncertainty is not easy to recognize, let alone evaluate. First of all, you have to determine the nature of the effect (whether the assumption increases or decreases the measured value—or affects it randomly). Then you must somehow estimate the magnitude of the effect. As another example, suppose you wish to find the speed of a ball moving on the floor. You are assuming that a ball moves along a straight line while in fact the surface of the floor is bumpy —and the bumps contribute significantly to the distance that the ball covers, thus decreasing the speed that that you calculate. Note that, while there is a certain randomness in the amount of “bumpiness” encountered by the ball in each particular trial, the effect is always to decrease your result—it’s not truly random; and repeating the measurement will not eliminate this effect.

As you can see, it is difficult to give strict rules and instructions on how to estimate uncertainties in general. Each case (each measurement within each experimental design) is unique and requires a thoughtful approach.

The best advice: Be observant—and then reasonable.
Comparing Uncertainties

If you’re comparing the uncertainties in the values of two different quantities, then analyzing the absolute uncertainty ranges won’t tell you which of the measurements is more accurate. Even if you’re making the same type of measurement (say, cm), the absolute amount of the uncertainty can have a larger or smaller effect, depending on the value of the measurement itself. (And then what if the units or dimensions of the two quantities are different?) How can we decide which quantity has a larger uncertainty?

In general, we need to compare relative uncertainties—taking, for each measurement, the ratio of the absolute uncertainty to the quantity itself: \( \Delta X/X \). You can express this as a fraction (decimal) or as a percentage (by multiplying by 100%).

Even our very senses operate on relative uncertainty. The thickness of the “fuzzy” edge is the same (9 units) for both blue circles, but the larger blue circle (90 units) looks sharper than the small one (30 units). That happens because we unconsciously compare relative uncertainties (which are 10% for the large circle; 30% for the small one).

Note here: Some measurements, such as temperature, are not absolute in the first place; it is actually the change in the measured value(s) that you’re interested in. Consider a thermometer known to be reliable to ± 0.5°C. Does this mean you have a 0.5% uncertainty in measuring the temperature of 100°C water—but a 10% uncertainty when using the same thermometer in cold water at 5°C? (No.) But even if you express the temperatures on an absolute scale (Kelvins), that’s still not an accurate accounting for the relative uncertainty of your measurements. After all, a single temperature reading is unlikely to be experimentally significant; usually you’re measuring a change—a difference. And so you’d compare the uncertainty of the difference to the calculated difference itself. (see the next page for more about calculating with uncertainties).

Reducing Uncertainties

The above example with the circles suggests one way to reduce the relative uncertainty in your measurement: The same absolute uncertainty will yield a smaller relative uncertainty if the measured value is larger.

Example: Suppose you want to measure the time interval needed for a bob on a spring to oscillate up and down once. If you’re using a watch to measure that interval, the absolute uncertainty of the measurement will be 0.5 s. And if you measure, say, 5 s as the interval, then your relative uncertainty will be \((0.5 \text{ s}/5 \text{ s}) \times 100\% = \pm 10\%\).

But suppose you instead measure the time interval for 5 oscillations (25 s). It’s still a single measurement, so the instrumental uncertainty is still 0.5 s, but now the relative uncertainty is \((0.5 \text{ s}/25 \text{ s}) \times 100\% = \pm 2\%\).

It’s a simple technique, but effective. Just don’t rely on it alone. Don’t overlook ways to reduce your relative uncertainties by minimizing the absolute uncertainties, whenever possible (e.g. by using better design, or fewer assumptions, or measuring instruments of greater precision).
Calculating with Measured Values: Combining Uncertainties

Uncertainties in your data measurements will propagate through any calculations you make with those data, producing uncertainties in the calculated results. For example, suppose you know the average mass, \( m \), of one apple, with an uncertainty \( \Delta m \). If you want then to calculate the mass, \( M \), of a basket of, say, 100 apples, you will get \( M \pm \Delta M = 100m \pm 100\Delta m \). Thus, in this case, the relative uncertainty of the calculated value \( M \) remains the same as the relative uncertainty of the single measurement: \( \Delta M / M = \Delta m / m \). However, if you are using more than one measured value in your calculation, estimating the uncertainty of the calculated result is more complicated.

**Comparable uncertainties:** If your measured values have comparable relative uncertainties, then the uncertainty in a calculation using those values depends on the specific math you use in the calculation. There are many cases, therefore—and entire books on the topic—but take some common examples here:

- When you add or subtract two measured values, their absolute uncertainties add. By extension, therefore, taking a multiple of a single measured value (which is, essentially, “adding it to itself”) simply multiplies the absolute uncertainty—see the basket of apples above. A coefficient multiplies the absolute uncertainty.

- When you multiply or divide two measured values, their relative uncertainties add. By extension, therefore, squaring a measured value (raising it to the 2nd power) will double the relative uncertainty; and cubing a measured value (raising it to the 3rd power) will triple the relative uncertainty; etc. (Thus, in the baseball example earlier, if you use your diameter measurement to calculate the volume of the ball—assuming it to be spherical—the relative uncertainty in the calculated volume will be three times larger than the relative uncertainty in the measured diameter.) An exponent multiplies the relative uncertainty.

**Unequal uncertainties (the “weakest link” rule):** The relative uncertainty in any calculated value is always at least as great as the greatest relative uncertainty among the values used to make the calculation. Therefore, if one of your measurements has a relative uncertainty much larger than any of the others, then that measurement is your “weakest link”—you can generally ignore the other, insignificant uncertainties and take the uncertainty of the calculation to be that of the most uncertain measurement.

**Your Lab Strategy for Uncertainty: A Summary**

When you are designing a lab experiment and measuring some quantities to determine an experimental result:

- Decide which factors affect your result most; wherever possible, try to minimize these factors.
- Wherever possible, try to reduce unavoidable uncertainties by measuring longer distances or times etc.
- Decide what the absolute uncertainties of each measurement are.
- Then find the relative uncertainties of each measurement.
- If you need to do any calculations with your measurements, then:
  - If the measurements have relative uncertainties of comparable magnitude, use the math rules above (and if you need more rules, find an online resource); but if one relative uncertainty is much larger than all the others, ignore the others and use the largest as the uncertainty of the calculated result.
- **Find the range where your experimental result lies; and take into account its uncertainty when you make a judgment regarding that result and the experiment’s outcome.**
LAB 1: Introductions

I. Introduction to your Lab and Lab TA

No labs meet during Week 1. (That is, Lab 1 is entirely a take-home exercise—see part II below.) Your first in-lab session will be Lab 2. When your lab section does first meet, that will be for your Lab 2, and at that time, your lab TA will give you a paper copy of his/her syllabus and review it briefly, before you start on Lab 2. (Remember: You’re always expected to arrive at lab having read the lab in advance! Your TA will not be going over the lab in detail—only mentioning key points.)

Important scheduling note: Each “lab week” starts on the Tuesday of the week and continues through the following Monday (and this is indicated on the Course Calendar, as well—see the notes at the left of each week). For example, the week when everyone is doing Lab 2 starts on Tuesday, January 16 and continues through Monday, January 22. Then Lab 3 sessions start on Tuesday, January 23 and continue through Monday, January 29; and so on.

II. Course Policies and Math Exercises

Because you will not be going to lab in Week 1, this is a good time to learn course policies and also to brush up on some necessary math concepts. So, unlike the other labs this term, this first lab activity is not the usual 3-hour, in-lab group-work format. Rather, it’s a take-home assignment that each student must do (worth 15 points, rather than the usual 10 points)—to be turned in to your Lab TA’s box no later than 6:00 p.m. on Tuesday, January 16.

Click here to download this activity.
LAB 2: Rotational Motion

I. Review: Free-Body Diagrams and Circular Motion

Do the three exercises below as a group. Do these carefully, neatly and completely. That means you will need to discuss and make preliminary sketches and explanations before you do the final versions that will be turned in as part of this lab.

1. A ball on a string moves in a vertical circle, as shown. When the ball is at its lowest point, is the tension in the string greater than, less than, or equal to the ball’s resting weight? Explain fully, using a free-body diagram and accompanying equations.

2. A marble rolls around the inside of a cone, as shown. Draw two free-body diagrams of the marble: once when it’s on the left side of the cone, again when it’s on the right side.
3. A jet airplane is flying on a level course at constant velocity.
   
a. What is the net force acting on the plane?
   
b. Draw a free-body diagram of the plane and identify as many forces as you can that might be acting on the plane.
   
c. Airplanes bank when they turn. *Explain why*, using a free-body diagram viewing the plane from behind..
II. Determining the Tension in a String (an Application Experiment)

Purpose:
To design, implement and report on an application experiment—or a series of related experiments—with a minimum of guidance (i.e., to conduct a reasonably authentic scientific experiment).

Description:
A string is strung through a hollow glass rod. Attached to one end of the string will be a mass \( m \); on the other end will be a larger mass, \( M \). You have various masses to choose from. You also have a ruler, and a stopwatch (and a mass hanger to use for \( M \)). Your task is to determine how fast you need to spin \( m \) in a horizontal circle (keeping the glass rod vertical) so that mass \( M \) hangs at rest.

Notes and Suggestions:
Use the following guide, with these reminders: All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in a rubric. Thus, (A3) would refer to ability 3 in the Application experiment rubric.

a. Identify the problem to be solved. (A1)

b. Design a reliable experiment that solves the problem. (A2)

c. Draw a sketch of your experimental design.

d. Draw a free-body diagram. Include an appropriate set of co-ordinate axes.

e. Choose a productive mathematical procedure for solving the problem. Use the free-body diagram to devise the mathematical procedure to solve the problem. (A7)

f. Discuss how you will use the available experiment to make the measurements. (A3)

g. Identify the assumptions made in using the mathematical procedure. (A8)

h. Determine specifically the way in which assumptions might affect the results. (A9)

i. What are the possible sources of experimental uncertainty? How could you minimize them?

Perform the experiments.

j. Record the outcome of your experiment.

k. Make a judgment about the results of your experiments. (A4)

l. Identify the shortcomings in the experiment and suggest specific improvements. (A6)
III. Friction and Drag Slowing a Flywheel: An Observation Experiment

**Purposes:**

- Design an experiment to take appropriate data to find a relationship.
- Construct a mathematical model to describe that relationship.

**Description:**

You are given a flywheel, a silver strip to mark the location of one point on the wheel, a ruler, and a stop watch. Design an experiment to determine the average angular acceleration due to friction and air resistance in a flywheel. Determine if this value is dependent or independent of the initial angular velocity of the flywheel.

**Notes and Suggestions:**

All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Note: Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (O3) would refer to ability 3 in the Observation experiment rubric.

- **a.** Design a reliable experiment that will investigate the phenomenon. (O2)
- **b.** Draw a clearly labeled diagram of your experimental set-up. Be sure to represent the important aspects of your experiment.
- **c.** Decide what is to be measured, and identify the independent and dependent variables. (O3)
- **d.** Briefly describe how you will make use of the available equipment to make your measurements, explaining explicitly how you plan to find angular acceleration from your data. (O4)
- **Perform the experiments.**
- **e.** Describe what is observed *(without trying to explain)*, both in words and by means of a data table. (O5)
- **f.** Explain specifically how you are finding the acceleration from your data and why you are being asked to do a fit from the velocity graph (why is this better than just using an equation?).
- **g.** Using your data, construct a mathematical relationship that represents a trend in the data. (O7)
- **h.** Determine the average angular acceleration of the flywheel.
- **i.** Determine a relationship (from your observed data) between the initial angular velocity and the angular acceleration of the flywheel (using as many trials as needed to obtain a ‘good’ relationship).
- **j.** Devise an explanation for the relationship you observed in your data. (O8)
- **k.** Identify any assumptions made in devising the explanation (the relationship between the initial angular velocity and the angular acceleration). (O9)
- **l.** How could you test the relationship you found? In your lab report, give a brief description of an experiment that will test the relationship. (You do not need to conduct the test.)
- **m.** Identify shortcomings of your experimental design by listing the sources of experimental uncertainty. Describe improvements you could and/or did make to minimize them. (O6)
IV. Shared Acceleration in Parts of a Connected System: A Testing Experiment

Purpose:

To design, implement and report on a testing experiment with a minimum of guidance (i.e., to conduct a reasonably authentic scientific investigation).

Description:

Newtonian mechanics declares that two objects moving as a connected system should have the same acceleration. Test this for a hanging mass falling from a flywheel, by comparing the tangential acceleration of a point on the rim of the flywheel with the acceleration of the hanging mass as it falls. You are given a flywheel, a string (you can wind around the hub), a weight hanger, some masses, silver tape to mark a location on the flywheel, a ruler, and a stopwatch.

Notes and Suggestions:

All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (T3) would refer to ability 3 in the Testing experiment rubric.

a. Identify the hypothesis (rule) to be tested.

b. Explain why you are comparing the acceleration of a point on the rim rather than some other point on the flywheel.

c. Design a reliable experiment that tests the hypothesis. Include a brief description of your procedure. (T2)

d. Draw a labeled sketch of the experimental set-up.

e. Devise the mathematical procedure that you will use to make your prediction.

f. Explain what you will measure and (explicitly) how you will find the acceleration(s) from your data.

g. Make a prediction about the outcome of the experiment based on the hypothesis. (T4)

h. Identify the assumptions made in making the prediction. What assumptions about the objects, interactions, and processes did you need to make to solve the problem? (T5)

i. Determine specifically in what way the assumptions might affect your prediction. (T6)

Perform the experiment

j. Record the outcome of your experiment clearly in a table.

k. Decide whether the prediction and the outcome agree/disagree. (T7)

l. Decide whether your assumptions and experimental uncertainties can account for any discrepancy between the predicted and measured values.

m. Make a reasonable judgment about the hypothesis based on your experimental outcomes, the assumptions you made, and the estimated uncertainty. (T8)

V. Calculating Mass Distributions

This last portion of Lab 2 is a take-home assignment that each student must do (worth 5 points)—to be turned in to your Lab TA’s box no later than 6:00 p.m. on Tuesday, January 23.

Click here to download this activity.
LAB 3: Rotational Dynamics

I. When Angular Momentum Does Not Change: Isolated Systems

While a truly isolated system (collection) of objects is difficult to achieve, there are many that approximate an isolated state well enough to offer examples of the basic consequences of the Conservation of Angular Momentum: a figure skater; a well-balanced, well-oiled rotating chair or rotating bicycle wheel; even the rotating earth itself.

Do the following experiments as a group, taking observations and offering explanations carefully, neatly and completely. That means you will need to discuss and agree before completing this part of the lab, ready to be turned in.

a. Most of us have seen a figure skater whose big spinning finale at the end of her routine makes her into a veritable blur. At first, she’s spinning at some reasonable rate, but then—with nobody giving her any kind of push to go faster, she’s able to increase her rate of rotation a LOT. How does she do that? Find out.

The lab is short on ice rinks, but we do have a rotating chair. Have someone from your group—(someone who is not prone to motion sickness) climb aboard the chair. To accentuate the effect, have him/her take one of the weights in each hand and hold out his/her hands and also extend his/her legs straight out. Have everyone else back up, then one other team member give the volunteer a (gentle) turn—not very fast! After that person has finished accelerating the volunteer and has stepped back—assuming the chair’s axle is has low friction (and ignoring the slow rotation of the earth), the volunteer and chair are essentially an isolated rotating body—like a figure skater spinning on slick ice.

Let the volunteer go around a couple of times, then ask him/her to draw in his/her arms and legs... then extend them out again.... What happens—and why? Answer by using the Conservation of Angular Momentum: Write an appropriate equation and rearrange it to make your point. (When the volunteer has had enough, be sure to stop the chair.)

b. Now, let another volunteer from the group—someone with good arm strength—put on the gloves and sit in the chair. This time he/she should remain basically still. Then someone else should hold the bicycle wheel so that its axis is vertical and someone should give it a strong spin—get it going pretty good—clockwise, as viewed from above. Now, without changing the orientation of that axis, carefully give the spinning wheel to the person in the chair and stand back. That person should hold the bottom axis in one hand and use the other (gloved) hand to brush against the outside of the spinning wheel (don’t catch any fingers in the spokes!), until the wheel is at rest against the glove. What happens? Why? Answer by using the Conservation of Angular Momentum: Write an appropriate equation and rearrange it to make your point.

c. Predict: What would have happened if the bike wheel had been going counterclockwise instead of clockwise? Explain your prediction with an equation.

Now test your prediction—repeat step b with the bike wheel going counterclockwise (as viewed from above). What happens?
d. *Predict:* What will happen if the volunteer in the chair, holding the stopped bike wheel (always with its axis vertical), now gives it a strong push to *start it turning* again? Will direction matter? Explain your predictions with equations.

*Now test your prediction*—once for each spinning direction. What happens?

e. When land ice on Antarctica melts and flows into the sea, eventually it circulates and therefore distributes uniformly over the earth’s oceans. As a result, does the earth’s rotational speed increase, decrease or remain unaffected? (Does this change the length of one day? If so, how?) *As always, explain your thinking fully.*
II. When Angular Momentum Does Change: Torque, Angular Acceleration and Moment of Inertia

Do the following two exercises as a group. Do these carefully, neatly and completely. That means you will need to *discuss and make preliminary sketches and explanations* before you do the final versions that will be turned in as part of this lab.

1. This pulley has two rims of differing radii, connected at their common center. The pulley is free to rotate around the fixed axis shown and is rotating in the clockwise direction.

   a. Describe in words what will happen in the time after the moment depicted here. *Explain/show your reasoning with words and/or equations.*

   

   ![Diagram of pulley with two strings and tension](image)

   b. If the tension in the right string remains as shown in the drawing, what tension should the left string exert so that the angular velocity of the pulley would no longer change? *Explain/show your reasoning with words and/or equations.*

   

   c. If the tension in the left string remains as shown in the drawing, what minimum tension should the right string exert so that the pulley would go faster in the clock-wise direction? *Explain/show your reasoning with words and/or equations.*
2. Two pails hang from opposite ends of a rope suspended over a flywheel, as shown here. Assume that the rope does not slip on the pulley, that the bearing of the pulley axle exerts negligible friction, but that the pulley wheel has considerable mass. Starting in the positions shown, the pails are released from rest.

a. Construct a free-body diagram for each pail. *Use the lengths of your force arrows meaningfully—to indicate their relative magnitudes.*

b. Construct a free-body diagram for the flywheel. (You may assume that its axle is supported by a single pin.) *Use the lengths of your force arrows meaningfully—to indicate their relative magnitudes.*

c. Describe the rotational motion of the flywheel after the pails are released from rest. *Explain/show your reasoning with words and/or equations.*
III. The Moment of Inertia of a Flywheel: An Application Experiment

Purpose:

To design, implement and report on an application experiment—or a series of experiments—with a minimum of guidance (i.e., to conduct a reasonably authentic scientific experiment).

Description:

You are given the density of steel \((7.8 \times 10^3 \text{ kg/m}^3)\), a ruler, a piece of string, a mass hanger, some masses, and a stopwatch. You must design at least two independent experiments to determine the moment of inertia of the flywheel. The experiments must be truly independent (not just different trials of the same experiment—using, for example, different amounts of mass). One of your experiments should be static, and the other should be dynamic. The static experiment can be measurements based on theoretical equations for moments of inertia.

Notes and Suggestions:

All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (A3) would refer to ability 3 in the Application experiment rubric.

- a. Identify the problem to be solved. (A1)
- b. Design two reliable experiments that solve the problem. (A2)
- c. Draw a sketch of your experimental designs.
- d. Draw an appropriate free-body diagram. Include a set of co-ordinate axes.
- e. Choose a productive mathematical procedure for solving the problem. Use the free-body diagram to devise the mathematical procedure to solve the problem where applicable. (A7)
- f. Discuss how you will use the available experiment to make the measurements. (A3)
- g. Identify the assumptions made in using the mathematical procedure. (A8)
- h. Determine specifically the way in which assumptions might affect the results. (A9)
- i. What are the possible sources of experimental uncertainty? How could you minimize them?

Perform the experiments.

- j. Record the outcome of your experiments.
- k. Make a judgment about the results of your experiments. (A4)
- l. Evaluate your results by comparing the two independent methods. Use your uncertainty to make an explicit comparison of the two values you obtained for the moment of inertia. (A5)
- m. What are possible reasons for the difference? If you have a large difference between your values, re-check your work. Did you account for all of the energy? Did you account for the non-zero acceleration?
- n. Which experiment was more accurate and why?
- o. Identify the shortcomings in the experiments and suggest specific improvements. (A6)
LAB 4: Fluids

I. Archimedes’ Principle of Buoyancy: A Testing Experiment

Purpose:
To design, implement and report on a testing experiment with a minimum of guidance (i.e., to conduct a reasonably authentic scientific investigation).

Description:
Using a cylinder, two pan balances, and a beaker of water, collect data to test the mathematical relationship between the buoyant force and the forces you measure directly from the balances and Archimedes’ principle.

Notes and Suggestions:
Take data for at least four different cylinder locations: Fully out of the water, partially submerged, fully submerged but near the surface (and not touching the bottom), and fully submerged near the bottom (though still not touching the bottom). Your TA will demonstrate how to take one set of measurements and find the buoyant force using the given setup: Rest the container of water on one of the pan balances. That balance will measure the force necessary to hold the container of water. Use the string to suspend the cylinder from the other pan balance; that balance therefore measures the force necessary to hold the cylinder. Before taking any data, don’t forget to zero both balances with nothing resting on them.

Then use the following guide, with these reminders: All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (T3) would refer to ability 3 in the Testing experiment rubric.

a. Identify the hypothesis (rule) to be tested. (T1)
b. Design a reliable experiment that tests the hypothesis including a brief description of your procedure. (T2)
c. Draw a labeled sketch of the experimental set-up.
d. Draw a free-body diagram of the object while it is in the “region of interest” and determine the direction of the net force on the object. Indicate the force on your diagram that equals a force measured by one of the pan balances.
e. Devise the mathematical procedure that you will use to make your prediction.
f. Make a prediction about the outcome of the experiment based on the hypothesis. (T4)
g. Identify the assumptions made in making the prediction. What assumptions about the objects, interactions, and processes you need to make to solve the problem? (T5)
h. Determine specifically which assumptions might affect the prediction. (T6)
i. What are experimental uncertainties in this experiment?

Perform the experiment
j. Record the outcome of your experiment, including a data table and these calculations:
   1. Determine the value of the buoyant force for the partially and fully submerged cylinder three different ways: from the reading on the upper balance, the lower balance, and from Archimedes’ principle.
   2. For the fully submerged, but not touching, cylinder, also determine the buoyant force by calculating the water pressure on the top and bottom surfaces of the cylinder. Clearly show your work.
k. Decide whether the prediction and the outcome agree/disagree. (T7)
l. Decide whether your assumptions and experimental uncertainties can account for any discrepancy between the predicted and measured value.
m. Make a reasonable judgment about the hypothesis based on your experimental outcomes, the assumptions you made, and the estimated uncertainty. (T8)
II. Fluid Pressure

Observe and explain: Thumbtacks have been used to pierce several holes in the side of a plastic soda bottle—all at the same height. Then the holes have been taped over, and the bottle has been filled with water (and the lid left off). When you remove the tape, you should see something like the drawing here.

a. How do the various streams of water compare with each other?
   What does this behavior indicate about the water pressure in the bottle at the level of the holes?
   How must that water pressure compare to the pressure of the air outside (which is essentially equal to the pressure at the top surface of the water, too)?

b. Explain specifically why/how fluid pressure can exert forces in such directions. Think microscopically. Use the following prompts to help your thinking (you don’t have to answer these additional questions):
   Would all fluids (gases and liquids) do something like this? A bottle of molasses? How about a bottle of air?
   What is it about a fluid that allows this? Would a bottle of sand behave similarly if you made holes in the side?
   How about a bottle of marbles (assuming the holes were large enough for marbles to pass through)?
   How about a barrel full of bricks (assuming the holes were large enough for bricks to pass through)?
   What if the bricks were stacked in the barrel instead of tossed in randomly?
Observe and explain: Thumbtacks have been used to pierce at least three holes in the side of a plastic soda bottle—each at a different height (but all below the water level). Then the holes have been taped over, and the bottle has been filled with water (and the lid left off). When you remove the tape, you should see something like the drawing here.

c. Modeling the water in several “stacked sections” (with the hole levels located between adjacent sections, as shown) on the diagram here, draw force arrows, with lengths proportional to force strengths, to represent $F_{N,12}$, $F_{N,23}$, and $F_{N,34}$.

d. Again, modeling the water in the same “stacked sections,” now draw force arrows on this diagram (with arrow lengths proportional to force strength), to represent $F_{N,21}$, $F_{N,32}$, and $F_{N,43}$.

e. This diagram depicts small bodies of water located at the levels of the holes. Using what you concluded above (in parts a, b, c and d), draw force arrows (again, with arrow lengths proportional to force strength), acting on each body. (Don’t forget what you observed/explained in part b!)

f. Using your illustration in part e, explain in words why the water behaved as you observed it (i.e. explain the drawing at top right on this page).

Predict and test: Put the tape back over the three holes in the bottle. Add water, as needed, so that all holes are below the water surface. Cap the bottle securely. Now, using everything you’ve observed and concluded previously (a-f)...

g. Predict what will happen when you remove the tape from only the top and bottom holes (but don’t do this yet).

h. Explain the reasoning behind your prediction:
i. Now perform the experiment—remove the tape over the top and bottom holes. Observe what happens and record your observations here:

j. Judge the reasoning that led to your prediction. Do your observations support it?

Reason: While hiking in the mountains, you drink all the water from a plastic bottle. Then you re-cap the empty bottle and carry it back to your car, placing it on the seat beside you. It resembles drawing a here. You drive to your oceanside home, where you notice the empty bottle on the car seat. Now it resembles drawing b here.

k. Why/how did the bottle change from a to b? Explain this—thoroughly.

III. Frequently Asked Questions About Ideal Fluids

This last portion of Lab 4 is a take-home assignment that each student must do (worth 5 points)—to be turned in to your Lab TA’s box no later than 6:00 p.m. on Tuesday, February 6. Click here to download this activity.
Lab 5: Refraction

I. Background Information: Parallax

To complete the following experiments, you will need to understand parallax—what our brains use to help us with depth perception: If you move your head from side to side, objects close to you appear to move back and forth more rapidly than objects far away from you.

To observe this, one person should look along the tabletop while another person places a pin somewhere in the corkboard. The first person (the observer) should then hold a finger over the corkboard so that it appears to be directly above the pin and then move his/her head back and forth. Unless the finger is indeed directly above the pin, there will appear to be relative motion between the finger and the pin. The observer then adjusts his/her finger toward or away until the apparent relative motion ceases. Everyone should practice this method before conducting the following experiments.
II. Measuring the Index of Refraction (an Application experiment)

Purpose:
To design, implement and report on an application experiment—or a series of experiments—with a minimum of guidance (i.e., to conduct a reasonably authentic scientific experiment).

Description:
Given a glass prism, a dish of water, a corkboard, paper, a ruler, and pins, you are to use Snell’s law to determine the index of refraction for a piece of glass and a dish of water.

Notes and Suggestions:
You do not need a generated ray of light; you can simply map out the path of the light by marking pins along your lines of sight using the method of parallax. It helps to place one pin a bit away from the glass/water, and the other pin directly next to it, then line up those two pins, looking through the glass/water, and find the location of a third and fourth pin (adjacent and a bit away) on the other side of the glass/water that appears to line up with the first two pins. You should trace a ray that passes through at least two surfaces of the glass or water, and you should not use an incident angle near 0° or 90°.

Then all lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (A3) would refer to ability 3 in the Application experiment rubric.

a. Identify the problem to be solved. (A1)
b. Design a reliable experiment that solves the problem. (A2)
c. Draw an appropriate physical representation.
d. Choose a productive mathematical procedure for solving the problem. (A7)
e. What are the possible sources of experimental uncertainty? How could you minimize them?

Perform the experiments.

f. Record the outcome of your experiment.
g. What do you find for the index of refractions?
h. Make a judgment about the results of your experiments. Do these values seem reasonable? (Justify this assertion.) (A4)
i. Identify the shortcomings in the experiment and suggest specific improvements. (A6)
III. Predicting Apparent Depth (a Testing experiment)

Purpose:

To design, implement and report on a testing experiment with a minimum of guidance (i.e., to conduct a reasonably authentic scientific investigation).

Description:

Using the same equipment as in the previous experiment—and also its result (i.e. the index of refraction you determined for water)—predict the apparent depth of a pin placed at a random position on the opposite side of the water dish, then test your prediction with your experimental setup.

Notes and Suggestions:

Use the following guide, with these reminders: All lettered steps must be addressed in your lab write-up; a random subset of those steps will be graded. Any step followed by a code refers to a specific skill in one of the rubrics. Thus, (T3) would refer to ability 3 in the Testing experiment rubric.

a. Identify the hypothesis (rule) to be tested. (T1)

b. Design a reliable experiment that tests the hypothesis including a brief description of your procedure. (T2)

c. Draw a labeled sketch of the experimental set-up.

d. Draw an appropriate physical representation.

e. Devise the mathematical procedure that you will use to make your prediction.

f. Make a prediction about the outcome of the experiment based on the hypothesis. (T4)

g. Identify the assumptions made in making the prediction. What assumptions about the objects, interactions, and processes did you need to make to solve the problem? (T5)

h. Determine specifically which assumptions might affect the prediction. (T6)

i. What are experimental uncertainties in this experiment?

Perform the experiment

j. Record the outcome of your experiment.

k. Decide whether the prediction and the outcome agree/disagree. (T7)

l. Decide whether your assumptions and experimental uncertainties can account for any discrepancy between the predicted and measured value.

m. Make a reasonable judgment about the hypothesis based on your experimental outcomes, the assumptions you made, and the estimated uncertainty. (T8)

IV. Refraction and Imaging

This last portion of Lab 5 is a take-home assignment that each student must do (worth 5 points)—to be turned in to your Lab TA’s box no later than 6:00 p.m. on Thursday, February 15. Click here to download this activity.
LAB 6: Optical Imaging

I. Image Basics

First, keep in mind that every physical object is always an active source of electromagnetic (EM) rays, due to its own thermal energy. But we don’t necessarily see those rays with our eyes; much of that kind of “light” is in the infrared portion of the spectrum. This lab addresses only how we can use lenses (and/or mirrors) to form images with visible light.

Next, keep in mind that, unless it’s in total darkness, any physical object is generally a source of visible light rays. It may be an active (“self-luminous”), of course—such as a glowing light bulb—radiating visible light from some internal energy source. Or (far more common), the object is simply reflecting light that is incident upon it from some outside source. Either way, every point on the object is a light source that sends out millions of rays of light—in all directions.

Lenses (and/or mirrors) can be used to re-direct those rays to create an image—a set of points in space where you can look to see a reproduction of the original object, instead of looking at the object itself. To accomplish this, of course, the lenses (or mirrors) are simply re-directing the rays from the object—in one of two ways:

Real image. A lens (or mirror) creates a real image when it causes the rays from the object to converge at a set of points that resemble the real object. That is, the light rays sent out from each point on the object actually pass through the corresponding point on the image. And after doing so, of course, those rays then continue on, re-radiating out from that point of the image—just as if they did from the corresponding point on the object itself. Thus, you can view the image just as readily as the original object; either one is an actual source of light rays radiating from a similar distribution of points:

A real image formed by a mirror:

Your eye can view rays such as these, coming from each point on the object itself...

... OR it can view rays such as these, coming from each point on the image.

A real image formed by a lens:

Without the lens, your eye would view rays such as these, coming from each point on the object itself...

... but with the lens, your eye would instead view rays such as these, coming from each point on the image.

Rays from each point on the object are actually passing through each corresponding point on the image (only a few rays from one such point are shown here). So this is a real image.
Virtual image. A lens creates a virtual image when it causes the rays from the object to merely appear to “converge-then re-radiate” at a set of points resembling the object. That is, the light rays sent out from every point on the object do not actually pass through the corresponding point on the image. Those rays have been re-directed so that (because your eyes & brain extrapolate back in a straight line), they appear to radiate out from that point of the image. Thus, you can view the image just as readily as the original object. Either one is a set of light rays that arrive at your eyes as if they had radiated from a similar distribution of points:

A virtual image formed by a mirror:

If you look directly at the object, your eye could, of course, view rays coming from each point on the object itself...

... or, if you look at the mirror, your eye can view rays such as these, which have been re-directed by the mirror to appear to be coming from each point on the image.

A virtual image formed by a lens:

These are not real light rays but merely how your brain extrapolates back in a straight line from the lens, where the true rays have been re-directed.

Thus, the perceived “rays” from each point on the object are NOT actually passing through each corresponding point on the image. So this is a virtual image.

The refracted rays are diverging and appear to come from P’.

... but with the lens, your eye would instead view rays such as these, which appear to come from each point P’ on the image.

Your eye “sees” the virtual image at P’.

This lab will demonstrate the types of lens (or system of lenses) that can create real and/or virtual images—along with the simple math and geometry needed to predict the location, size and orientation of the image. (The math and logic for mirrors are very similar, but we won’t address them in this lab.)
II. Thin-Lens Basics

- An object located a distance \(d_o\) from a thin lens of focal length \(f\) has its image formed at a distance \(d_i\) from the lens (with all measurements made from the lens center along a normal optical axis), according to the thin-lens equation:

\[ \frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \]

where, by convention (so that the above math works correctly), light from the object travels left-to-right in order to strike the lens; and:

- \(f\) is positive for a converging lens; negative for a diverging lens.
- \(d_o\) is positive (a real object) when the object is located to the left of the lens; negative (a “virtual object”) when the object is located to the right of the lens.*
- \(d_i\) is positive (a real image) when the image is located on the right side of the lens; negative when the image is located on the left side of the lens.

- The image height, \(h_i\), and orientation (same or inverted) relative to the object height, \(h_o\), are indicated by the value of the absolute (or “lateral”) magnification value, \(m\), given by the magnification equation:

\[ m = \frac{h_i}{h_o} = \frac{-d_i}{d_o} \]

where:
- \(h_o\) is positive for an upright object; negative for an inverted object.
- \(h_i\) is positive for an upright image; negative for an inverted image.
- \(d_o\) is as calculated via the thin-lens equation and its sign conventions.
- \(d_i\) is as calculated via the thin-lens equation and its sign conventions.
- \(m\) is positive if the image has the same orientation as the object; negative if the image is inverted relative to the object;

  greater in magnitude than 1 if the image is enlarged (i.e. larger than the object);

  lesser in magnitude than 1 if the image is reduced (i.e. smaller than the object).

- If more than one lens is used, then the image formed by the first lens (i.e. the lens encountered first by light from the actual object) becomes the object for the next lens, etc. For example:

  In the drawing, the lenses have focal lengths of \(f_A = 4\) cm, \(f_B = 12\) cm, and \(f_C = -8\) cm. The object is located at \(x = 0.00\).

  a. Find the total magnification \((m)\) of this lens system.

  That is, find the ratio \(h_{final}/h_o\).

  b. What is the \(x\)-position of the final image?

<table>
<thead>
<tr>
<th>Lens A: (1/4 = 1/8 + 1/d_i)</th>
<th>(d_i = 8)</th>
<th>(m_A = -(8/8) = -1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens B: (1/12 = 1/4 + 1/d_i)</td>
<td>(d_i = -6)</td>
<td>(m_B = -(6/4) = 1.5)</td>
</tr>
<tr>
<td>Lens C: (-1/8 = 1/16 + 1/d_i)</td>
<td>(d_i = -5.33)</td>
<td>(m_C = -(-5.33/16) = 0.333)</td>
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</table>

\(m_T = m_A m_B m_C = (-1)(1.5)(0.333) = -0.500\)

\(d_i = 5.33\) cm to the left of lens C. That’s \(x = (30 - 5.33) = 24.7\) cm

*Assuming that we always place the original object to the left of the first lens (A)—so that light always travels left to right as it refracts (as per the conventions given here), you might wonder how/when you’d ever have a “virtual object”—located to the right of the lens that must form its image. This happens sometimes in multiple lens systems. In the above example, suppose that \(f_A\) were 6 cm, rather than 4 cm. The resulting image would form 24 cm to the right of lens A (that’s 12 cm to the right of lens B). And yet the image of A must become the “object” for lens B. In such cases, we are not, of course, saying that the light rays forming image A then somehow reverse direction in order to travel from that point back to the left to pass through lens B. Rather, we are saying that the angles of all rays that would have formed image A (had lens B not intervened) are exactly right when they reach lens B so that the thin lens equation still correctly computes where lens B places its image—provided that we use a negative value for \(d_o\). You will encounter this situation in part V(c) of this lab.
For the next two or three sections of this lab, you will be working with four lenses—three converging lenses of different focal lengths ("short," "medium" and "long") and one diverging lens. You will also have an optical bench (to mount aligned lenses), some light sources, and a small card to act as a projection screen, among other misc. tools. Guided by a few hints here (and possibly from your lab instructor), it will be up to your group to devise ways to acquire the requested data to verify/test the applicability of the thin-lens and magnification equations. Be sure to answer each question fully—with sketches and full explanations, as required.

III. Forming Real Images

Here is a sketch of how a converging lens forms a real image:

![Image of a converging lens forming a real image]

a. Of the four lenses you are given, explain how you can identify the three that are converging lenses (besides their being labeled or your being told). Offer at least two methods, and describe them here, using sketches as needed.

b. For each of the three converging lenses, find the focal length. First, describe here how you will do this, then in the spaces below, enter the data (and show any needed calculations) for each lens:

"Short" focal length (cm):

"Medium" focal length (cm):

"Long" focal length (cm):
c. For the “short” and “medium” converging lenses, fill in the tables below by arranging the object, the lens and the projection screen appropriately, taking all measurements in cm, then calculating \( f \) and \( m \) (two different ways for \( m \)), and comparing your results to your predictions.

\[
\text{Short focal length, converging lens} \quad \text{(preliminary measurement of} \ f \text{from part IIIb:} \quad \underline{__________} \text{ cm)}
\]

<table>
<thead>
<tr>
<th>( d_o ) (cm)</th>
<th>measured ( d_l ) (cm)</th>
<th>calculated ( f ) (cm)</th>
<th>measured ( h_o ) (cm)</th>
<th>measured ( h_i ) (cm)</th>
<th>calculated ( m = h_i/h_o )</th>
<th>calculated ( m = -(d_l/d_o) )</th>
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Average of \( f \) for these 4 trials: \quad \underline{__________} \n
\[
\text{Medium focal length, converging lens} \quad \text{(preliminary measurement of} \ f \text{from part IIIb:} \quad \underline{__________} \text{ cm)}
\]

<table>
<thead>
<tr>
<th>( d_o ) (cm)</th>
<th>measured ( d_l ) (cm)</th>
<th>calculated ( f ) (cm)</th>
<th>measured ( h_o ) (cm)</th>
<th>measured ( h_i ) (cm)</th>
<th>calculated ( m = h_i/h_o )</th>
<th>calculated ( m = -(d_l/d_o) )</th>
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</table>

Average of \( f \) for these 4 trials: \quad \underline{__________} \n
\[
\text{d.} \quad \text{Describe—with words and a diagram—how you find each real image by locating the projector screen.}
\]

Now draw a ray diagram to show what’s happening when the screen is close to the image point but not quite correctly located. Explain why the image is fuzzy but still recognizable. (Hint: Look at any one point on the image and notice what happens as you slide the screen farther and farther “out of focus.”)
IV. Forming Virtual Images

• First, consider this issue: You cannot place a virtual image on a projection screen. Why not? Explain fully, with ray diagrams, as needed.

So, how do you locate a virtual image when that’s the result being produced by a lens? You use an additional lens: It takes the first lens’ virtual image as its object and creates a second image*—this one real, so that you can locate it with a projection screen, as usual.

Then, without moving the additional lens (or the projector screen), remove the original lens and simply adjust the object’s location until you get a sharp image on the screen once again. The new position of the object must have been where the virtual image was.

Practice this method of “Object Replacement” now, with three diagrams (using the space below) to illustrate how you’d locate a virtual image in this hypothetical example....

• Suppose your original lens is a diverging lens (which can create only virtual images). Draw a simple ray diagram of an object and the diverging lens and its virtual image:

• Now show the diagram again, but this time with an additional lens (a converging lens) that creates a real image.

• Now show the diagram a third time, this time without the original lens (but with the additional lens and final image as the previous diagram, and with the object moved to a location that results in that same final, real image.

*Recall how the basic process works with multiple lenses—see the summary on page 31.
Now, for the diverging lens and then for the “medium” converging lens, fill in the tables below by using the method of Object Replacement (use the “short” converging lens in each case as your additional lens), taking all measurements in cm, then calculating the $f$ values they indicate.

**Note:** When finding virtual images produced by the medium converging lens, keep in mind that those images may be located well behind (to the left of) the object. So, in order to keep that location on the optical track (so that you can re-locate the object there), you’ll probably need to locate the medium lens (and the additional, short lens) toward the far right end of the track. (Consider: Why isn’t this necessary for the diverging lens?)

### Diverging lens

<table>
<thead>
<tr>
<th>measured $d_o$ (cm)</th>
<th>measured $d_i$ (cm)</th>
<th>calculated $f$ (cm)</th>
<th>calculated $m = -(d_i/d_o)$</th>
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<tr>
<td>10</td>
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</table>

*Average of $f$ for these 3 trials:* _________

### Medium focal length, converging lens (best estimate of $f$ from parts IIIb and IIIc: ____________ cm)

<table>
<thead>
<tr>
<th>measured $d_o$ (cm)</th>
<th>measured $d_i$ (cm)</th>
<th>calculated $f$ (cm)</th>
<th>calculated $m = -(d_i/d_o)$</th>
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*Average of $f$ for these 3 trials:* _________
V. More Practice with Two-Lens Systems

For the following three arrangements, your task is to locate the final image (i.e. the image produced by the second lens).

a. Object at $x = 0$ cm; medium lens at $x = 45$ cm; short lens at $x = 130$ cm.

b. Object at $x = 0$ cm; diverging lens at $x = 40$ cm; short lens at $x = 70$ cm.

c. Object at $x = 0$ cm; medium lens at $x = 40$ cm; short lens at $x = 70$ cm.

• Using the space below (and showing all calculations), predict for each case the location of the final image, its size and orientation ($\pm$). Calculate the predicted overall magnification value, $m$, for the two-lens combination. Notice that in case c, the intermediate image (that formed by the first lens, which then becomes the object for the second lens) will be to the right of the second lens, which means you'll need to use a negative object distance for the second lens (and see also the note at the bottom of page 31).

• (OPTIONAL) Next, draw a simple ray diagram—roughly to scale—for each case (using the templates given on the next page), showing both the final image and the intermediate image (that formed by the first lens, which then becomes the object for the second lens).

• (OPTIONAL) Now assemble the lenses as shown and measure the actual location, size and orientation of the final image for each of the three cases. Compare with your predictions.
VI. Extension Questions

1. a. You’re designing a lighthouse beacon—and ships will need to navigate by it: a very sharply located ray of light that arrives with as much brightness as possible—as far away as possible. Explain how you can accomplish this with a single (very bright) light bulb filament and a single lens. Sketch a simple ray diagram.

b. Many common flashlights and car headlamps use a light bulb and a mirror instead of a lens. Explain the basics of how that works (no need for any math—just a sketch will do); use the logic from 1a, above..

(As you might guess, real lighthouses generally use a combination of both of the above.)

2. Could a lens that normally acts as a converging lens somehow become a diverging lens (without changing the lens itself in any way)? Explain your reasoning.

3. A converging lens is used to project a real image onto a screen. If an opaque card is then placed over the upper half of the lens, what will you see on the screen? Explain your reasoning, using a brief ray tracing to illustrate.

Now try this with one of the converging lenses you’ve been using.
4. **OPTIONAL** Select some small object to view and close one eye. What is the **nearest** distance (cm) at which you can hold that object to your open eye and focus on it **clearly**? Note that distance here:

Now place that open eye against the **short converging lens** to use it as a magnifying glass to view the small object. What is the **greatest** distance you can hold the object (on the other side of the lens) and still view its image **clearly**? Note that distance here:

And **how far away is that image?** (Estimate its distance, if you can. If you can’t choose an actual number, **is it nearby or far away?** Move your head back and forth—use parallax—to compare how its distance looks versus other objects in the room.)

*Use the thin-lens equation to explain this:*

Keep your open eye against the **short converging lens**. Now what is the **least** distance you can hold the object (on the other side of the lens) and still view its image **clearly**?

And **how far away is that image?** (Estimate its distance, if you can. Again, if you can’t choose an actual number, **is it nearby or far away?** Move your head back and forth—use parallax—to compare how its distance looks versus other objects in the room.)

*Use the thin-lens equation to explain this (and keep in mind what you first observed—top item) here:*