PH 213 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</td>
<td>The phenomenon to be investigated is described, but there are minor omissions or</td>
<td>The phenomenon to be investigated is clearly stated.</td>
</tr>
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<td></td>
<td></td>
<td>described in a confusing manner.</td>
<td>vague details.</td>
<td></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</td>
<td>The experiment investigates the phenomenon and the data will probably show interesting</td>
<td>The experiment investigates the phenomenon; it is highly likely the data will</td>
</tr>
<tr>
<td></td>
<td></td>
<td>data containing any interesting patterns.</td>
<td>patterns, but its design will miss some features or patterns.</td>
<td>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</td>
<td>The chosen measurements will produce only data that is useful (at best) to</td>
<td>The chosen measurements will produce data useful in achieving the experiment’s</td>
<td>The chosen measurements will produce data useful for achieving the experiment’s</td>
</tr>
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<td>goals of the experiment.</td>
<td>partially achieve the goals of the experiment.</td>
<td>goals, but independent and dependent variables aren’t clearly distinguished.</td>
<td>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</td>
<td>All chosen measurements can be made, but no details are given about how they</td>
<td>All chosen measurements can be made, but the details of how they are done are</td>
<td>All chosen measurements can be made and all details of how they are done are</td>
</tr>
<tr>
<td></td>
<td>equipment.</td>
<td>are done.</td>
<td>vague or incomplete.</td>
<td>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.</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</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</td>
<td>Most assumptions are correctly identified.</td>
<td>All assumptions are correctly identified.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vaguely, or incorrect.</td>
<td></td>
<td></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>
<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>
</tr>
<tr>
<td>--------------------------------------------------------</td>
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</tr>
<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 – ΔX and X + ΔX (usually expressed in the standard form, X ± ΔX).

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 ± ΔX and Y ± ΔY 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: \(X = 50 \text{ m} \pm 1 \text{ m}\). Or, in other words: \(|\Delta X| = 1 \text{ m}\).

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 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 \( (0.5 \text{ s}/5 \text{ s}) \cdot 100\% = \pm 10\% \).

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 \( (0.5 \text{ s}/25 \text{ s}) \cdot 100\% = \pm 2\% \).

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: Introduction and Math Review

I. Introduction to Lab/Course Policies

II. Vector Math Review.

Because you will not be going to lab in Week 1, this is a good time to learn lab and course policies and refresh some vector math basics. 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 10 points)—to be turned in to your Lab TA’s box by 6:00 p.m. on Tuesday, April 9.

Click here to download these activities (it’s just one combined file for both parts I and II).
LAB 2: Electric Force

I. General Physics Knowledge “Pre-” Survey

This item is required (and worth 5 points to you)—please answer all items to the best of your current knowledge. The 5 points will be awarded not according to whether your answers are right or wrong, but only whether you participated fully and did your best. Your lab TA will explain the details of the survey and give you all materials necessary (write only on the answer form—not on the questions sheets).

IMPORTANT: If you have absolutely no idea what the question is talking about—or no idea about how to answer it—just leave the answer blank, rather than guessing randomly. But if you have at least some idea about the item, go ahead and give it your best try.
II. What’s the Charge? An Observation Experiment

Purposes:

• Design experiments to take appropriate data to find a relationship.
• Construct a mathematical model to describe that relationship.

Description:

You are given a variety of objects on the table, plus the following definitions:  An acrylic rod rubbed with cloth will have a net positive charge; and a foam board rubbed with the cloth will have a net negative charge. Your must design experiments to determine if the following objects are uncharged, positively charged or negatively charged.

• A foam board.
• A foam board rubbed with fur or cloth.
• A piece of scotch tape that was first stuck to the table top, then pulled off.
• A piece of scotch tape that was placed atop a second piece that was stuck to the table, then the top piece pulled off.
• One other object at your table.

Notes and Suggestions:

When you conduct your experiments, be careful that each object is isolated from other objects. For example, don’t hold a metal can with your hand while rubbing it with the cloth; instead, use some insulation between your hand and the can.

Then 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. Briefly describe how you will make use of the available equipment to make your observations. (O4)

Perform the experiments.

b. Describe what is observed (without trying to explain) by means of a data table. (O5)

c. Using your data, state any consistencies you found in your observations. (O7)

d. Devise an explanation for those observed consistencies. (O8)

e. Identify any assumptions made in devising the explanation. (O9)

f. How could you test the observations you found? Give a brief description in your lab report.

g. Use this test to check some of your observations and report the findings of your test: Did they confirm your previous observations, or did you need to make corrections?

h. 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)
III. Insulators vs. Conductors: 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:
A textbook says that metallic objects such as aluminum cans have electrically charged particles that can freely move, but that insulating objects such as plastic bottles do not have freely moving charged particles. Design an experiment to test this using any equipment at your table (cans, plastic bottles, tape, foil, and/or any objects from experiment I above).

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. (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. Make a prediction about the outcome of the experiment based on the hypothesis. (T4)
e. 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)
f. Determine specifically which assumptions might affect the prediction. (T6)

Perform the experiment

g. Clearly record the outcome of your experiment.
h. Decide whether the prediction and the outcome agree/disagree. (T7)
i. Make a reasonable judgment about the hypothesis based on your experimental outcomes and the assumptions you made. (T8)
j. Fill out a table with the arguments and evidence for testing your hypothesis (see example provided below).

<table>
<thead>
<tr>
<th>Explanation/Hypothesis</th>
<th>“If …”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment design</td>
<td>“and I do this …”</td>
</tr>
<tr>
<td>Predicted outcome</td>
<td>“then …”</td>
</tr>
<tr>
<td>Observed outcome</td>
<td>“And/But I saw …”</td>
</tr>
<tr>
<td>Conclusion (hypothesis supported or not)</td>
<td>“Therefore …”</td>
</tr>
</tbody>
</table>
IV. An Electric Restoring Force: An Observation Experiment

Purposes:

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

Description:

Your task is to create an oscillator, using electrostatic force as part of the restoring force.

Notes and Suggestions:

Hang a very small wad of tin foil (using string and a ring stand) within 1 cm of a smooth, charged, metal object (the Electrophorus or the side of your soda can). Make sure the metal object is isolated. Put your finger roughly 1 cm on the other side of the wad. Let the wad touch the metal, then try to get it oscillating between the metal and your finger—without you physically swinging it.

Then 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. Briefly describe how you will make use of the available equipment to make your observations. (O4)

b. Describe what is observed (without trying to explain). (O5)

c. Devise an explanation for your observations. (O8)

d. What evidence do you have to support whether or not your finger is a conductor?

e. Identify any assumptions made in devising the explanation. (O9)

V. Coulomb Calculations

This follow-up lab activity is a take-home assignment that each student must do (worth 5 points)—to be turned in to your Lab TA’s box by 6:00 p.m. on Tuesday, April 16.

Click here to download this take-home exercise set.
LAB 3: Electric Field

Do the following 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.

I. $E$ and $F_E$ Basics (click here)

II. Continuous Charge Distributions

   a. If a segment of wire has a net charge (uniformly distributed), and then its length is increased by 50%, by what factor has its charge density changed?

      If the original charge was 10.0 nC, how much charge must then be added to restore the wire’s original charge density?

   b. Consider a wire in the shape of a semi-circle of radius $R$, with a total positive net charge $Q$ distributed over the wire uniformly. Divide the wire into at least 8 equal point-like “chunks” of charge. Then, for each “chunk,” sketch (on the same diagram) the E-field vector that bit of charge would cause at the center of the (semi-) circle. Explain, using this picture, how each “chunk’s” field contributes to the net field at that center point.

      Would a full circle of charge double the net field at the center? Explain.
III. Modeling and Understanding Electric Flux: An Observation Experiment

Purposes:

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

Description:

You are given two nail-boards with differing numbers of nails in each, and a wire loop. Your task is to use these as visual aids and determine the parameters that affect electric flux.

Notes and Suggestions:

You can visualize flux as the number of nails (electric field lines) which pass through the loop.

Then 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. Draw a clearly labeled diagram of your experimental set-up. Make sure you represent the important aspects of your experiment.

b. Decide what is to be measured and identify independent and dependent variables. \((O3)\)

Perform the experiment.

c. Describe what is observed without trying to explain, both in words and by means of a data table. \((O5)\)

d. Explain specifically how you are finding proportionality relationships from your data.

e. What parameters does flux depend on, and how did you arrive at this conclusion?

Do the following exercise 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.

IV. Practicing with Gauss’s Law (click here)
LAB 4: Electric Potential

Do the following exercises as a group (except #5—skip exercise #5). 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.

I. The Relationship Between Potential and Field (*click here*)
II. Mapping Electric Fields Near a Button & Ring Electrode Set: An Observation Experiment

Purposes:

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

Description:

Using a water-filled tray, a button electrode inside a ring-shaped electrode, and a voltmeter/probe, your task is to locate sets of points with equal potential values—i.e. potential **differences** between those points and one of the electrodes (and you can determine which electrode to denote as 0 V). You should trace out locations (over an arc of at least 90 degrees around the electrodes) where the potential difference is 1V, 2V, 3V, 4V, etc.

Notes and Suggestions:

A tray is filled to a depth of about 1/4” with tap water and two electrodes are placed in the tray. When a potential difference V is placed across the electrodes, an electric field is established in the water. Since the water is conducting and air is not, and the electric current is parallel to the electric field, virtually all the electric field lines in the water are parallel to the surface of the water. So you can treat the water and electrodes as a purely two-dimensional system. Make sure the water is very level before proceeding; any tilt in the tray/table will be a source of error.

The two electrodes are maintained at a constant voltage difference (usually somewhere between 10 and 12 V). One lead of the voltmeter should be connected to one of the electrodes; the other to a probe that you can place wherever you want in the water tank and then read the voltmeter.

Move the probe in the water and observe that the voltage varies from point to point (and remember to keep the probe vertical in the water for best results). Find several points in the tray which measure the same voltage. Try to find a curved path that has the same voltage everywhere. Use a sheet of graph paper to mark the positions and shapes of the electrodes and the voltages you probe.

Then 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. Decide what is to be measured and identify independent and dependent variables. (O3)

Perform the experiment.

b. Explain specifically your plan to find the relationship from your data.

c. Using your data and graph, what can you conclude about the relationship between distance from the central electrode and the potential around the electrode? (O7)

d. If necessary, review the relationship between equipotentials and electric field lines. Then draw a few representative field lines on your graph paper with a different color pencil (or pen) than you used for the equipotential lines.

e. Describe the shape of the electric field around the central electrode, and explain why it should have this shape.

f. Where is the electric field the strongest, and where is it the weakest? How do you know?

g. Choose a single electric field line. Using Cartesian graph paper, plot the electric potential along this line as a function of distance from the center of the tray. 5-8 well chosen data points are sufficient for this plot.

h. Comment on the shape of the graph and write a general statement describing the potential around the central electrode.

i. From your data, write a mathematical relationship for the potential around the electrode and compare it to your earlier observation. Is the mathematical relationship what you expected? If so, why? If not, reconcile any differences.
III. Electric Potential and Field Around Various Geometries: Observation Experiments

Purposes:

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

Description:

Using a water-filled tray, electrodes of various geometrical configurations, and a voltmeter/probe—same as in part II above—your task is to locate sets of points with equal potential values. Again, trace out locations (over an arc of at least 90 degrees around the electrodes) where the potential difference between there and the reference (0V) electrode is 1V, 2V, 3V, etc.

Notes and Suggestions:

Use the same apparatus and techniques as in part II, above, to find equipotential lines for electrode sets with the following geometries:

- Point electrodes in water, separated by about 6 inches.
- Long straight electrodes in water, separated by about 4 inches.
- Long straight electrodes in water, separated by about 4 inches, with a hollow conducting cylinder midway between the two electrodes.

Then all lettered steps must be addressed in your lab write-up for each of the above geometries; a random subset of those steps will be graded.

a. Use the probe to map out the equipotentials.
b. Represent them on your graph paper.
c. Use the equipotential lines to map out the electric field.
d. Identify regions of higher and lower electric field, and explain why the electric field has the distribution that it does.
e. For the ‘parallel plate’ geometry, devise a mathematical relationship for both the potential and the electric field between the plates (and not near the edges).
IV. Accelerating Electrons: 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:

In this experiment, you will use a cathode-ray tube (CRT) to accelerate and deflect a beam of electrons in order to investigate the mathematical relationship between the deflection of the electron, and each of two voltages, $V_A$ and $V_B$. You must take enough data to plot the relationship, and also work out the theoretical prediction based on your knowledge of electric force and field, then compare your plotted data to your derived equations.

Notes and Suggestions:

The CRT is a glass vessel which contains:

- an electron gun that emits electrons into a beam that is accelerated along the tube by an applied voltage;
- a deflection system to change the direction of the beam, via another applied voltage; and
- a viewing screen. (CRTs are used in oscilloscopes, and older TV sets and computer monitors.)

A disassembled tube is available for inspection. The voltages are established by parallel plate capacitors, and therefore have nearly uniform electric fields between their plates. (Reminder: For a uniform field, $E = \Delta V / x$, where $x$ is the distance between the two plates).

There are 3 ‘stages’ for the electrons moving from the filament to the CRT.

a. The electrons leave a heated filament (approximately from rest) and are accelerated horizontally down the tube for a distance $L_1$, due to a voltage difference $\Delta V_A$ applied across this section of the tube. The assumption is that the electrons have reached a maximum constant speed just at the end of this distance $L_1$, and that the entire acceleration is due to the applied voltage $\Delta V_A$.

b. The electrons then enter the deflection region of length $L_2$, where they are bent from their horizontal path by a deflection voltage difference $\Delta V_D$. This deflection is perpendicular to their horizontal motion (either up, down, left or right—or some displacement $r$—when facing the tube).

c. Finally, the electrons travel some distance $L_3$ at constant velocity, through a region with no voltage difference applied, until they hit the screen.

All devices should be correctly wired up ahead of time, but nevertheless: Before turning on the power supply to the CRT, verify (or have your instructor verify) all proper connections. The power supply has a standby position that warms the filament before applying the high voltage. Leave it in standby for about 30 seconds before turning on full power. Make sure that the meter switch is set correctly to read the B+ voltage and set the voltage to around 250 V. Adjust the focus knob for the best spot size.

Note: It sometimes happens at start up that electrons collect on the phosphor screen and don’t migrate back to ground. These electrons can repel the beam from the area and make the screen look like it has a burned spot on it. Time will usually create a conducting path and correct the problem, but sweeping the electron beam back and forth across the spot might speed up the process.

The deflection voltage difference $\Delta V_D$ is obtained from the table outlets. Make sure that the middle terminal (GND) from the table outlet connects to the red terminal on the CRT table power input terminal (GND). Positive and negative table power voltages connect to the black CRT table power input through a reversing switch. This allows positive and negative voltages to be put across the CRT’s deflection plates, thereby reversing the direction of the deflecting electric field $E_x$. The actual deflection voltage is measured with a voltmeter connected across the output of the table outlets and in parallel with the CRT’s deflection plates.
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. Draw physical representations for appropriate portions of the electron’s motion.

c. Choose a productive mathematical procedure to derive the relationship between the deflection of the electrons and the voltages in the tube using your physical representation. (A7)

d. Complete your derivation and from it, predict the mathematical relationship between the deflection of the electrons and each of the two voltages.

e. Explain qualitatively why the relationships you found make sense. (For example, if you throw a baseball with more force, it will have a higher initial velocity and travel further.)

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. For one particular assumption, describe in detail how this assumption would affect the equation and the prediction for the deflection of the electron. (For example, will it be deflected more than you predict because you have chosen a particular assumption in deriving the equation?)

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

Perform the experiment to test your relationship.

j. Record the outcome of your experiment in an appropriate format, including graphing the electron deflection vs. each of the two voltages (separately).

k. How does the outcome of your experiment compare with your mathematical prediction? Resolve, or suggest and explain physical reasons, for any discrepancies.

l. What are the possible sources of experimental uncertainty when taking your data? How could you minimize them?

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

V. Practice with Potential

This follow-up lab activity is a take-home assignment that each student must do (worth 5 points)—to be turned in to your Lab TA’s box by 6:00 p.m. on Tuesday, April 30.

Click here to download this take-home exercise set.