# Lab Writeups for Physics 101

In physics, as in all of science, experiment is the final authority. Physics is all about making models that describe, explain, and make predictions about what will happen *in the real world*. If a model does not correspond with anything in the real world, it might be an interesting philosophical exercise or a nice piece of pure mathematics, but it is *not* physics. The purpose of our labs is to give you real, hands-on evidence that the equations and concepts you've learned do make accurate statements about the way the universe works, and perhaps to give you an inkling of how you might go about testing more speculative ideas in an equally rigorous way.

The labs in the RealTime Physics series (and others used in this class) have a different format from those used in many other science classes. These notes are designed to clarify what is expected of you in lab and in your written work; I hope they will help you to learn more from the labs, as well as to earn better grades on the lab reports.

**Predictions:** "Predictions are difficult, especially about the future."
       *-variously attributed to quantum physicist Niels Bohr, or former baseball player Yogi Berra*

Most of our experiments in this class are designed to confront misconceptions that many students have; the idea is to get you to think about what will happen, and then to do an experiment to test your hypothesis. The whole point here is to make a prediction **BEFORE** you do the experiment, not after. **You will not lose points for making an incorrect prediction.** You *will*, however, lose points if it appears that you did the experiment first and then went back to fill in or change your prediction.

The labs ask you to make predictions because we want you to spend a little time thinking about your expectations and assumptions. What principles are operating in a given situation? In many situations, you will have encountered the relevant principles already in the textbook and in lecture (though you may or may not remember them, or fully understand them yet). In others, the lab will serve as your introduction to a new topic. In either case, most people start out with some intuition about what will happen in most of these experiments. It's all right, and generally useful, for you to discuss the predictions with the rest of your lab group. However, it is not necessary for the whole group to agree on the same prediction. And don't spend too much time on this step; it's usually not worthwhile to make a lot of calculations or search through your textbook for the "right" answer. Just use the ideas that first come to mind.

After doing the experiment: If your prediction was right, great; you can now be more confident of your understanding and of the usefulness of the theory involved. If you were wrong, no need to feel bad; being wrong (and then figuring out why, and correcting your mistake) is an important part of learning. When answering the questions, admit you were wrong, and thoughtfully consider the reasons why. Seeing an experimental result that contradicts your intuition should help fix the correct model firmly in your mind.

**Comparisons, Percent Differences and Errors:** Quite frequently, the labs will ask you to compare your measured value with a known physical constant, or to compare two different measurements that are supposed to give the same result. It's quite unlikely that the two numbers you're comparing will be identical; there is some uncertainty associated with every measurement. **Error analysis** is a rich and complex subject, with many mathematical techniques for figuring exactly how much uncertainty you expect, given the imprecision in your equipment and the calculations you made. In this class, we will barely skim the surface of error analysis; I will not expect you to make a careful calculation of the uncertainty in every result. However, when comparing two numbers, I do expect you to say something more rigorous than "They're close enough."

If you are attempting to measure some constant of nature, I will always expect you to give the **percent error** in your result. The idea here is that you are looking not only at the *difference* between your result and the accepted value, but also at how big that difference is, compared to the quantity you are trying to measure. For example, if you measured the distance between LA and New York, and were off by 1 meter, that would be very impressive; 1 meter is a very tiny percentage of this distance, which is a few thousand kilometers. On the other hand, if you measured a person's height, and were off by 1 meter, that would not be impressive at all; 1 meter is more than 50% of a typical person's height. To reflect this, the definition of percent error is the difference between the measurement and the true value, divided by the true value (and then multiplied by 100 to convert it to a percent):

$$\text{percent error} = \left| \frac{(\text{measured value}) - (\text{accepted value})}{(\text{accepted value})} \right| \times 100\%$$

Why the absolute value signs? The difference may be positive or negative. Generally, we don't really care whether your measurement was too high or too low, only how far off it was. So percent error is always defined to be a non-negative number. Notice that the percent error is always **dimensionless**: whatever units the numerator has, the denominator has the same units, so they cancel to give a pure number. This means percent error doesn't depend on what system of units you happen to be using.

Here's an example: let's say we're measuring $g$, the acceleration due to gravity of objects near the Earth's surface. Our textbook tells us that $g = 9.80665$ m/s$^2$ is the accepted value. Suppose that in lab, we obtained the value $9.3$ m/s$^2$. The percent error for our result is

$$\left|9.3\,\text{m/s}^2 - 9.80665\,\text{m/s}^2\right| = \frac{0.5\,\text{m/s}^2}{9.80665\,\text{m/s}^2} = 0.05,$$

or 5%.

A closely related situation is the case when we've made two measurements that should be equal. Whenever a lab asks "How well do these agree?" or something similar, I *always* want to see a calculation of **percent difference**, even if the lab does not specifically say so. Essentially, this is the same thing as calculating percent error: first, we take the absolute value of the difference between the two values. Then, we need to divide by something, in order to compare the difference to the size of the measurements themselves. But what should we divide by? We have no "accepted value" here; we could use either of the two measurements, but which? It shouldn't much matter which one we pick. We're hoping that the two are relatively close together; if so, either choice should give nearly the same result. But for those who would like an ironclad rule that treats both measurements equally: set the denominator to the **average** of the two measurements:

$$\text{percent difference} = \frac{|(\text{measured value 1}) - (\text{measured value 2})|}{(\text{average measurement})} \times 100\%$$

So what is a "good" percent error or difference? The answer obviously depends on what you hope to accomplish. A rough rule of thumb for most of our labs: less than 5% error is very good. 5-10% is not bad, but requires a little thinking about possible sources of error; more than 10% usually means something is wrong or needs further investigation.

**Sources of Error:** You will often be asked to think about sources of error in an experiment. There are four basic causes for error: (1) equipment failure, (2) mistakes/difficulties in setup or procedure, (3) imprecision in the measuring devices, and (4) physical effects neglected in the model. It's clear how to address (1): if your equipment is not working, get someone to troubleshoot or replace it. (Be aware that this does happen sometimes; if you're getting results that don't make sense, check your equipment rather than just charging ahead.) If you think (2) is an issue, don't just cite "human error." While it is almost certainly true that humans made errors in the lab, that statement is too vague to be useful. Be **specific** in your discussion: e.g., "We couldn't get the center of the basketball exactly aligned with the motion detector," or, "It was difficult to maintain constant speed when moving the cart by hand." If the "human error" is something you can easily fix, do so, and repeat the experiment to get better results.

Your text discusses (3) in the context of sig figs: any measuring device has a limited precision, giving rise to uncertainties in measurements. For example, with an ordinary ruler, you can measure lengths to within about $\pm$ 1 mm. It is also important to **calibrate** measuring devices (for example, zeroing force and voltage probes); failure to do this properly will result in inaccurate data. (4) is the most interesting type of error, I think. In physics, we make models to describe nature–but nature is complicated, so we simplify the models by neglecting some effects. All the physical theories you will learn are approximate in this way; the question is, when is the approximation appropriate? In labs, we may, for example, neglect friction, or consider a string to be massless. If the results are not what you expect, think about how friction, or the mass of the string, would affect your result. Should it make your measurement too high, or too low? Is that what you saw?

Thinking about and discussing errors in this way is often useful. It's even better to try to figure out how to fix or minimize the errors, and repeat the experiment to improve your results. This is an essential part of the job for an experimental scientist.

**Graphs:** For most labs, your printed graphs will be worth 10 points. Things to keep in mind: (1) Attach the graphs neatly, in the correct order. (2) Give each graph a descriptive title using "Printing Options." (3) **Rescale** your graphs so that the area of interest is clearly visible, and irrelevant areas are excluded. (4) If you are making a graph in event mode (using the "keep" button), make sure the graph shows individual points rather than trying to connect them. (You can do this by unchecking "connect points" in the Graph Options menu.)