A Sermon on the Labs

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Adapted from an earlier sermon by
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What is this handout for?

This is a "sermon." Here I will try to articulate an ideal for the physics labs. I will try to do so by persuasion rather than by dictating policies. You can get all the policy stuff from the Introduction to this manual. Here I want to make an attempt to persuade you that the labs are worthwhile and that they have a central point. One of the things I will try to do is really emphasize this central point; I ask all of the lab staff to do this emphasis as well. Hopefully, when students have a better sense of what the purpose of the labs are in the context of their overall physics education, they will find the labs more enjoyable—or at least less painful.

Also, this document will serve as my introduction. I want to make some additional remarks about the labs, so as to put my own "spin" on some of the issues. This might help you to get to know me.

What is the purpose of the labs?

At CWRU, physics labs are administered as a component of the regular physics lecture courses—not as separate courses. However, the labs are organized and administered by department staff and faculty who are not the same as for the lectures. As a result, sometimes students perceive something of a "disconnect" between the lectures and the labs. This perception is unfortunate because, in fact, care has been taken to provide a lab component that complements and supports the lecture component of the course. Students who find the labs difficult or unpleasant often do not have a clear picture of the intended purpose of the lab.

In my opinion, the primary purpose of the physics labs is to reinforce the central notion that physics as a discipline depends entirely on *experimental verification*. In other words, it does not matter how clever or beautiful your idea of physics is. If it does not actually match what is seen in the lab, it's wrong.

More specifically, everything we deal with in physics is based on representing physical systems as mathematical *models* or *theories*. These models of theories are the "laws of nature" that we write down as equations that allow us to describe reality and predict phenomena.

In the laboratory (student labs as well as cutting edge research labs) experiments are conducted to actually measure the behavior of physical systems to determine if that behavior is well-described by the mathematical model or theory we want to test. In every lab experiment there is one (and only one) central question we want to address:

Do the experimental measurements support the underlying physics theory to within the uncertainties associated with the measurement?

In other words, do the *data* support the *model* to within the *error bars*? This is the central question you must address and answer on every lab that you do. There is no more important thing that you need to do for you lab. Compared to this question, everything else in the lab is merely for your enrichment.

The reasons we need to do this in lab are because:

1. seeing is believing,
2. experimental verification is generally ignored in the context of introducing theoretical and problem solving techniques in lecture, and
3. going through the process will provide students with a wide range of experimental approaches, techniques, and

mathematical methods that are widely applicable in a variety of technical disciplines.

Plotting the data

Okay, in practice how does answering the central question work? In most labs, you will find yourself taking data and plotting something vs. something else on a graph. *Graphing your data is very important in the labs*. Suppose you find yourself plotting velocity vs. time. Maybe your data plot looks like Figure 1:

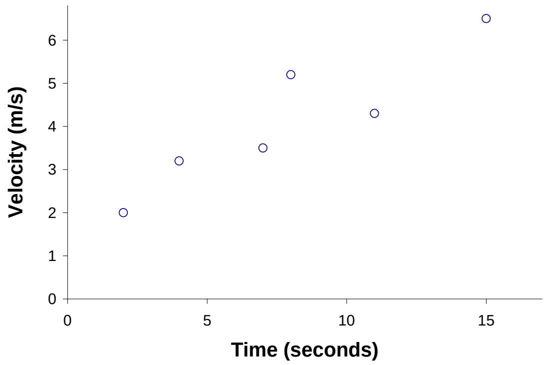

Figure 1: Plot of sample data.

Well, that's nice. It looks sort of linear. Now you need to consider the *model*. It's very important that each time you take data, you consider what the model is that you are trying to verify or test. For instance, in this example, perhaps you are trying to verify that the velocity is changing according to what we expect for constant acceleration due to a constant applied force. In this case, our model would be the equation for velocity in constant acceleration:

$$v = v_0 + at$$

Note that the issue is not determining the value of v_0 and a. The issue is determining whether this *model* can be supported by the data. In general, if we are plotting v as a function of t the model predicts that v will vary *linearly* with t. so this is what we want to know: Do the data fall into a straight line? If yes, then the model is verified. If no, then the model is refuted.

Fitting the data

Okay, so we look at the data and perhaps we can say that it looks like it might be close to falling in a line. What we want to do next is put down a *model* on our plot. In other words, if we say the data are supposed to represent a line, we want to *fit* a "best line" to the data.

In fact, there are several mathematical descriptions of the best way to fit a line (such as a linear regression). Some scientific calculators will do this regression for you. The *Origin* software package will do this for you. Lots of this stuff is described in wonderful detail in the appendices. There are many wonderful and sophisticated mathematical techniques for finding the best fit and inferring the values of the fitted parameters. That's great. But as far as I'm concerned, spending an inordinate amount of time and effort on developing the best fit model is sort of besides the point for these labs. In my opinion, for the purposes of the introductory labs, *it does not matter what method you use to fit a line (or any other model function) to the data so long as you make it clear in your report what you did*. For these labs, it is perfectly acceptable to simply place a ruler on the plot and "eyeball" the best line to the data. Just make it very clear in your notebook and/or your lab paper that this is what you did. If you are more comfortable plugging the coordinates into your calculator or *Origin* and doing a regression, this method is fine too. (Note: using *Origin* will usually be the easiest way.) Just so long as you can describe the line (the *model*) in terms of a mathematical function ($y = mx + b$) so that you have a model that you can test against your data.

In Figure 2 I have taken the data and have fit a "best" line using the ruler and eyeball technique. Not so bad really:

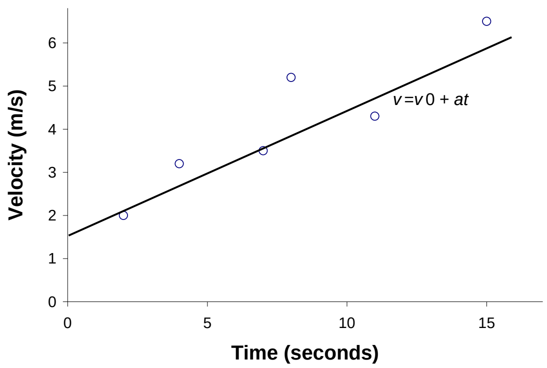

Figure 2: Sample data with "eyeball" fit.

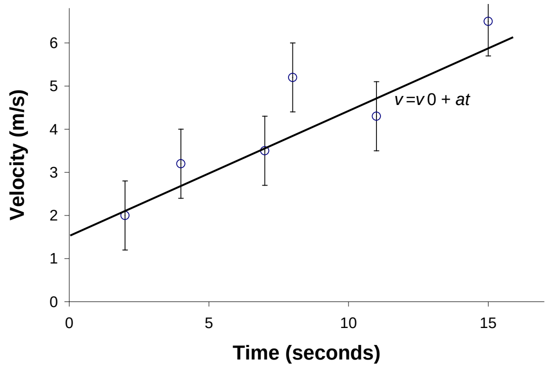

Figure 3: Sample data with large error bars

The absolute importance of error bars

So now we have data and model as shown in Fig. 2. Are we ready to answer the main question of the lab: *Do the data support or refute the model?* Well unfortunately the answer is not yet clear. The data indeed line up *close* to the model, but the data do not fall exactly on a single, straight line. There is that annoying point at x = about 8 seconds that is kinda high above the line. Is this okay? Or is this a problem? Simply guessing just won't cut it. *We cannot address our central question until we add a critical missing piece to the plot: error bars.*

What are error bars? They are graphical indication of the approximate uncertainty in the individual measurement value of each point. In a nutshell, the answer to the central question depends entirely on the size of the error bars. If we determine that the error bars look like Figure 3, then it's pretty clear that the data support the model to within the approximate error bars for most of the data points:

Note that in Fig. 3, the error bars "catch" the line at nearly every point. (One or two points missing by a relatively small amount is okay.) If you went ahead and calculated the chi-squared per degree of freedom (see Appendix VIII, Least Square Fitting) you would get a value of approximately 1, as expected for a good fit. When nearly all the points match within the error bars and at most one or two points miss and then only by a small amount, the data support the model to within the errors. We can answer the central question and we can say that the answer is "Yes, the data do support the model to within the uncertainties."

On the other hand, if the error bars look like Fig. 4 below, then it's pretty clear that the experimental data are in rather harsh disagreement with the model:

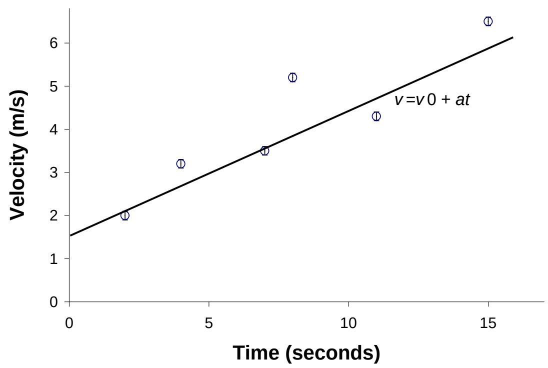

Figure 4: Sample data with small error bars.

In Fig. 4, at least four of the six points do not catch the line in the error bars. The point at 8 seconds is several error bars away from the line—clearly inconsistent with the model. If you were to calculate the chi-squared per degree of freedom you would get a number that is rather larger than 1. In this case we can also answer the central question and we can say that the answer is "No, the data do not support the model. The data are inconsistent with the model given the specified uncertainties."

So a central and important task for each lab is to determine an estimate of the errors on the measurement because you need to have this estimate in order to determine if the model is supported or refuted by the experiment. Your lab is a success if you indicate a "yes" *or* "no" answer to the central question. Your lab is failure if you cannot.

Note that in general when we do an experiment, we try to use methods to make the error bars as small as possible. The smaller the error bars, the more precise and meaningful the experiment is. If the error bars are small and the data supports the model, the experiment shows the model to be accurate to a high precision. If the error bars are small, the experiment is able to detect any small but real deviations of the real world from physics theory, even if they are small. Such deviations are typically the stepping stones to more sophisticated and accurate physical theories. For example, when the motion of the planet Mercury was measured carefully with precision instruments (which yielded small error bars) in the 19th century, a tiny but significant deviation from the orbit predicted by Newton was measured. This deviation could not be explained by Newton's classical physics; it took the development of Einstein's Theory of General Relativity to explain the data.

Estimating Error Bars

There are many fine points for determining uncertainties in measurements and propagating these uncertainties in calculations. Some of these statistical techniques can be mathematically sophisticated. For introductory physics, you have plenty of resources (in the appendices) on handling and propagating uncertainties. At the end of the day, however, you really need to have some method for making the case that the error bars on all your points are realistic. Your goal is to make some *justifiable estimate* of the measurement uncertainty for each point on your plot. You should be very clear in your lab paper how you determined this estimate—even if this estimate is rather crude.

However, in any case, you should be able at least to discern and consider the difference between random (or *statistical*) errors and systematic errors as follows:

Random errors are those that result from the inherent spread of expected measurements. There is nothing very profound about determining the random error. *The simplest way to determine the random error of any measurement is to repeat the measurement several times.* If you want, you can calculate the mean and standard deviation according to the equation in Appendix V. The standard deviation is a very good estimate of the size of an error bar due to random errors. However, for this class, it is just as good to make a rough estimate of the random error by making a simple histogram or plot or inferring the spread directly from the values. For example, if I was to repeat a measurement of the diameter of a styrofoam ball and got numbers like 4.43, 6.31, 4.14, 6.11, and 4.76 cm, I could calculate the formal standard deviation, or I could just say that by looking at the numbers the average value is about 5.5 cm and the spread is about $\pm$ 1.0 cm. This method is crude, but much better than nothing, and really worth doing while you are actually taking data so that you can see before you leave the labs if everything looks reasonable. *If you are simply taking data and you are not checking the values against your expectations as you go along in the lab you are missing the whole point of the labs and are headed for disaster.* If you have the time and inclination to calculate a formal standard deviation as you go, then great. If not, at least take a few measurements and call the observed spread in these numbers an estimate of the uncertainty. Use this technique in lab to see if you are getting the results you expect and to see if you have everything in place to address the central question.

One final little point—in our plots we need error bars on every point (x, y), not just one. In the ideal world we would repeat the entire experiment several times at every x, y point on our plot. This procedure is what real physicists often do in real research labs. However, in the few hours you have, it is acceptable to get an estimate of the error by repeating the measurements at any *one* point on your plot and then assuming that this estimate can be used for the other points as well.

Systematic errors are much more problematic for experimenters at all levels. These are errors due to miscalibrated equipment or neglected but significant interfering phenomena. No matter how many times you repeat the measurement, you will still get a slightly "wrong" answer if your ruler is manufactured to be too short or your assumption that air resistance is negligible isn't justified. Systematic errors are much harder to estimate as a rule. You should consider any potential sources of systematic error in your lab paper, and it cannot hurt to make a guess as to the size and direction of the error, but unless you have some particular good reason where you feel you can justify a numerical estimate of the systematic errors, it is best to *not* include these in your error bars. As a rule, unless specifically stated otherwise, error bars on plots represent random errors only.

Summary of key points

In summary then, for every lab you will make one or more plots. The plots are the most important part of the labs because they address the central question for each lab. For each plot you need to have the following:

- The data points (x, y),
- Error bars on the data points,
- An explanation for how you determined the error bars,
- A "best fit" model that you want to test, drawn on the plot, that is based on some theory of physics that you are exploring in your course work,
- An explanation for how you determined the "best fit," and
- A statement—based on all of the above—as to whether the data *does* or *does not* support the model to within the errors on the data points.

The items above are the most important things in lab. Everything else is important too, just not as important as the stuff in the list above. Of course it would be good to have cleanly labeled axes on your plots with units. And it would be a good idea to discuss potential sources of systematic error. Etc.

This leads to one last point. Obviously, introductory labs are designed to "test" laws of physics that have in fact been experimentally verified for over a hundred years. Our expectation is that in most labs you will demonstrate to yourself that, yes indeed, your experiment has also verified the model or theory once again. Tada! Good for you. But what happens if at the end of the day your measurement appears to contradict or refute the expected model? Don't panic. *It is not the policy of the lab staff to down-grade auto-*

matically just because you did not get the accepted answer. Such a policy would be antithetical to the purpose of the labs and would make for poor physics. If you and your partner analyze your data and find that it appears inconsistent with the expected result consider these possibilities:

- First, review carefully your measurement technique. Are you sure that your equipment is operating correctly? Have you skipped a step in the procedure somewhere? Did you misread a measurement? If you have time, repeat the measurement. This is what real physicists do. Repeat, repeat, repeat. (It's one of the reasons it's called *re*search.) We only believe a surprising result after it has been shown to be true experimentally over and over.
- Perhaps there is some systematic error that is really messing you up that you are not taking into account. Can you try to determine what this error is? Is there any way that you can provide some evidence that this is the case? For example, if you suspect air resistance is causing a problem, can you demonstrate that air resistance would change the result in the direction that you observe?
- If you are still stuck and you are convinced that your data are inconsistent with the laws of physics and you cannot envision a likely source of systematic error, then make this clear in your paper but report your results as you see them. *Under no circumstances should you consider fudging, adjusting, doctoring, omitting, discarding, or otherwise manipulating your data so as to indicate a better match between you data and the expected model.* Students who are caught doing these things will be harshly penalized for scientific and academic dishonesty. Your job is to do the experiment as accurately and carefully as you can so that when you have a final answer, you can stick to your guns experimentally. Honest, careful, and clear results that include one or two missteps or other mistakes will be graded much more leniently than sloppy or self-contradictory results that appear to be ambiguous or manipulated so as to more closely support the accepted values.

Grades for labs

We strive to have consistent and objective grading on the labs. This is a challenge for the staff since the range of organizations and styles in submitted lab papers is very large. Here are some things that can impact the lab score:

- Advanced preparation is important. Sometimes it's pretty obvious to the TA that the student has not even glanced at the lab manual prior to coming to the lab. Running out of time is a classic problem for students who are not prepared for the labs.
- You should record your laboratory experience in a proper bound lab notebook with grid-ruled paper for drawing plots and tabulating data. Regular spiral-bound notebooks and/or loose leaf are not acceptable.
- Neatness counts. We realize that sometimes during a lab you will have false starts and make mistakes that you subsequently catch and correct. Do not make messy erasures or white-outs. The proper procedure when you realize that a result is wrong in a lab notebook is to *cross out* the mistake in the book with a large "X" and write a note as to what the problem was. For example, you might write something like "This data is corrupt because we forgot to level the dynamics track."
- Set up a table to take data. Don't just scribble random numbers into your notebook. Make a table with headers and units

on each column. It should be obvious to the TA which tables represent your raw data.

- Explain what you are doing at each step of the lab. Indicating the time is helpful. In your notebook you should say words like "3:45 PM. Now we proceed to measure the velocity of the cart after we increase the mass by 20 grams." Your lab notebook should tell the story of what you did, what results you found, and how you did your analysis.
- You often have to do a bit of calculation to get numbers for your plots. Make it very clear in your notebook what is going on in these calculations. What formula are you using?
- Remember the presentation of your plots is most important. You cannot get full credit for the lab if your plots are missing model or error bars. You need to explain how you determined these items.
- You need to demonstrate clearly in the notes that you hand into the TA that you understand the purpose of the lab. You should present a final conclusion statement summarizing the experimental result.
- Make the most of your time. There are several things that can be done once you have completed the standard procedure. Several labs have extra steps in some sections. You will get more points for doing these. Another area where there is always more to do is in the determination of error. If you repeat various measurements you will get an increasingly accurate estimate of the statistical error. With extra data taken you can calculate the standard deviation more precisely. For any given lab it might be very nice to determine the chi-squared as a statistical estimate of the match between data and model. Or perhaps you can consider a test to determine possible sources of systematic error. Perhaps you can come up with a minor modification to the experimental procedure that would reduce the influence of systematic error. We reward creativity here. These are some ideas of things you can do beyond the standard lab. Check with the TA. Just remember, your time is limited.

One last thing—a disclaimer of sorts

I am constantly trying to improve the lab program and have made numerous changes, both big and small, to the program over the last year. Sometimes the changes to a program do, in fact, improve it. On occasion, trying something new doesn't work quite the way it's intended. I ask the students to bear with me and the staff as we test these changes. In addition to changes in the laboratory program, there are several other issues:

- Although we have done the best we can with proofreading, I am sure that there will be some text, some equations, and some other details that are missing, garbled, or wrong in the lab manual. I will do everything in my power to make corrections and bring these to the attention of students in advance of each week's lab. If you notice an error in the lab manual, please do not hesitate to bring it to my attention.
- Some of the lab sections are really oversubscribed. This fact means that scheduling lab swaps, etc., is going to be quite tricky, and some labs will be filled to capacity. Please arrive to lab on time, prepared and ready to work. Contact me as soon as possible if you know you have some scheduling issue. I am happy to do what I can but if a student comes to me at the last minute or (worse) after the fact, there is little I can do to help.

Very good. I look forward to working with each of you this semester.

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