Physics Laboratory Guide
Dr. Boucher, FGCU

A: Practical Advice for Successful Experiments

Included here are some helpful suggestions for planning, executing and recording the results of your experiments.

Lab Notebooks

In my physics courses I don't grade lab notebooks. Your lab grade is based solely on your lab reports. But, a dedicated lab notebook is still a very good idea.

For the laboratory, you should keep a notebook wherein you will record all of your raw data; tables, measurements, and of course the dates of each laboratory session. The notebook should be a permanently bound book that will prevent the inadvertent loss of pages of data (i.e. your hard work!). Somewhere in your notebook, preferably near the front, you should record your name[†], the names of your lab partner(s) and your lab section number. Since this is the only record of the experiments you have, you should make sure it is complete; never throw away pages containing data. If you *think* you have made an error in calculations or in the direct taking of data, simply cross out the supposed errors in a manner such that they may still be read. Occasionally, you will find that your mistake was not a mistake at all. Your lab book should be written in ink to prevent smearing and smudging. Although you **will not hand in** this notebook, it will be invaluable to you when you write your lab reports. It is a good idea to keep your notebook as tidy and complete as possible so that you can read and understand it even weeks after an experiment is performed.

You may also find that bringing a USB "jump" drive will help if you want to keep an electronic copy of any data files you may create while in lab. It may also be possible to use FGCU's computer-networked drives to do this or using the wireless network to connect to your email, but a backup plan is always a good thing.

Lab supplies you will need

There are no special pieces of equipment or safety gear to buy for physics lab. However, there are items you'll need on a regular basis so don't forget to bring them:

- Your lab notebook
- Your textbook and/or lecture notes Most often the experiments directly test some theory that you're learning about in lecture. It's very convenient to be able to refer to that theory during the course of the experiment and any analysis done in lab.
- A calculator We've seen so many groups struggle through data taking and calculations because of having to borrow or share calculators. You will need one often, so don't forget it.
- Graph Paper For some experiments, you will need graph paper, so you should buy a package (perhaps split costs with your lab partner). A practical type for physics labs is that with 1mm divisions, or about 20 divisions per inch. You can print this out from many online sources.

[†] Not a semester goes by without me finding a notebook in a classroom without the owner's name. How stupid! Think of the chaos thrown into your life by a notebook lost just before finals.

Plan ahead

Read the procedure long before you do the lab. You will find the recording of data easier (and faster) if you plan ahead and design tables for all measurements and all calculations. Also review (or preview) topics of experiments before doing the lab; you will then have a context in which to place the experience.

Ask questions

If physics were obvious and easy, this wouldn't be necessary. But it's not. Physics is a difficult subject. It is therefore likely that during a lab you will be confused about how to take certain data, how to understand the phenomena you are seeing, how to do some of the calculations and what errors you might have made in some preliminary calculations or analysis. ASK!

Our labs are also filled with heavy objects, sharp objects, high voltages, large forces, quickly moving bits of matter, extreme heat, blindingly bright lights and assorted other nasties harmful to the unprepared human. If you are in doubt about how to operate some device or how to complete some procedure that may be dangerous, ASK! Do not fear that the instructor will think you are stupid. Rather, the instructor will think that you are being safe.

It is also very tempting to leave lab as early as possible. It is often the last class of the day and you may be anxious to spend some time eating dinner, sleeping or having a life. Not so fast! It is a very good idea to make sure that you have all the data you need before leaving. Ask the instructor to review your data and any calculations before it's too late. The few minutes spent here will prevent hours wasted trying to write up a lab report based upon incomplete, incorrect or incoherent data.

Begin writing your lab report soon after the lab while things are fresh in your mind. This is especially important because if you encounter any difficulties you can ASK your instructor or lecturer for guidance.

Communicate and cooperate

You and your partner(s) should act as an efficient data gathering and processing team. Talk about a division of labor before lab. Have a plan as to who is going to do what and when. You should double-check each other's results on calculations and measurements. It is often helpful to confer with each other on the writing of lab reports, although this is not necessary.

Format

Your reports must be prepared using a word processor (i.e. *MS-Word,* etc.). Alternatively, they may be prepared on a typewriter, though few students these days have ever used one. (Take it from me, you're not missing much!) The report should be brief (no more than a few pages) and should contain:

1. No cover sheet. Save a tree!
2. Procedure: brief, indicating not what the lab procedure *told* you to do, but rather what you actually did, focusing primarily on any deviations from the standard procedure due to human error, equipment malfunctions, etc. Therefore, ***only go into detail if your actual procedure differed from that stated in the lab manual***.
3. Measured data and computed results. Make sure to include a few sample calculations to show how you obtained your analyzed results.
4. Discussion: A comparison with accepted values of the measured quantity (or predictions of a physical law), possible explanations for any discrepancies, and other relevant observations. Often, you're asked to answer some questions or solve some problems as part of the lab report; include these in the discussion section.
5. Usually, the data, calculations and discussion will be separated into different sections of the lab report, pertinent to questions and analyses on different sections of the procedure. Please keep your report organized into sections when asked to do so.
6. Neatness, grammar, spelling and organization count!
7. Staple in the upper left-hand corner. Paper clips are evil, as they grab other papers when shuffled about; papers like an important memo from my boss. Shun the evil clips.

Show Your Work

Also important for your homework problems as well as on quizzes and tests, make sure you show all of the important steps in your mathematical reasoning. This is crucial for two reasons:

- So that corrections can be made from which it is possible for you to learn.
- Partial credit!!!!

For lab reports, mathematical reasoning should also be shown. In the case of repetitive calculations, for example doing the same calculations on ten distinct sets of similar data, you need only show a single representative "sample calculation."

For word-processed lab reports, showing equations can be very tedious. Therefore, it is acceptable to insert *neatly* hand-written equations into your final printed report. The same applies to diagrams and graphs.

If you want to try a completely electronic approach using Microsoft's Word simply choose Insert→Object→Equation Editor. The Editor is cumbersome at first but allows a wide range of mathematical symbols and structures to be created. It is not always installed on all computers, so don't be surprised if you have to re-install your software with this option. All campus PC's should have this option installed. If this is not the case, let me know and I'll try to get it fixed.

Using Tables for Data, Results

For labs requiring many trials of similar data, a table is best for summarizing what you measured. It's good for you as it lets you see your data in an organized manner that allows trends to be seen easily and errors to be easily spotted. It's good for the instructor for the same reasons. Searching for data buried within paragraphs of florid prose is difficult and tedious. This is annoying to instructors.

Label all tables, graphs and computer printouts
Well, now that you've included that table (or graph, etc.) label it clearly. I expect the labels to be dull but useful; "Data for Part 1," "Trial 2 for first configuration in part 1," etc.

Also important for tables are that the *units* used in columns or rows of data should be clearly marked; "height (m)," "time (s)," "bomb yield (megatons)," etc.

C: Measurements and Error Analysis

Some numerical statements are exact: Mary has 3 brothers, and $2 + 2 = 4$. However, all *measurements* have some degree of uncertainty; the complete statement of a measured value should include an estimate of the level of confidence associated with the value. Properly reporting an experimental result along with its uncertainty allows other people to make judgments about the quality of the experiment, and it facilitates meaningful comparisons with other similar values or a theoretical prediction. The process of evaluating the uncertainty associated with a measurement result is often called *error analysis.*

When we make a measurement, we generally assume that some exact or **true value** exists based on how we define what is being measured. While we may never know this true value exactly, we attempt to find this ideal quantity to the best of our ability with the time and resources available. As we make measurements by different methods, or even when making multiple measurements using the same method, we may obtain slightly different results. So, how do we report our findings for our best estimate of this elusive *true value?* The most common way to show the range of values that we believe includes the true value is:

Measurement = (measured value $\pm$ error in value) units

Scientifically used, an error is different from a mistake. When using a meterstick to measure a distance, for example, error (uncertainty) would be related to how accurately you can read the meterstick or how accurately you can align the meterstick to whatever you are measuring. If the meterstick is graduated in millimeters, you can probably accurately read to within 1mm, so all of your measurements will be subjected to an uncertainty of + or − 1mm. You would thus report a measurement of 45.2 cm as 45.2 $\pm$ 0.1 cm.

A mistake with the meterstick, on the other hand, could be one of the following; reading the wrong side (usually in inches, horrors!), using it backwards (i.e. measuring 30cm rather than 70cm), or misaligning the zero end so that every measurement is off by some amount.

Error Analysis
In most of the labs you'll do in this course, error will be determined by running several trials of a situation and averaging them. The average value will be your reported value and the error will be the maximum and minimum values for that situation. Let's take several measurements of the descent time of a cart down an inclined plane, made by a person with a stopwatch:

13.71 s13.65 s 13.89 s 13.75 s 13.77 s

These average out to 13.75 s. Reporting your results as *average, minimum and maximum* gives a good summary of the experiment:

Min. 13.65 s   Ave. 13.75 s   Max. 13.89 s

Assuming the error is random, that is, as likely to be overestimated as it is underestimated, we can take a worst-case scenario approach and report the maximum deviation from the average as the error. In the case of the above data, 13.89 is farther from the average than 13.65, so we might report the error as the difference between 13.89 and 13.75, or 0.14. Thus, 13.75 ± 0.14 s.

We will primarily use the max/min method as a measure of the uncertainty in a series of measurements, but alternatively, the standard deviation could be used. The latter, however, is a more representative estimate when you have a large amount of data. The quality of our measured results can be quantified using one of the two methods below.

Fractional Uncertainty

The fractional uncertainty is a measure of how well a result can be determined and the degree of consistency and agreement among independent measurements of the same quantity. It is also the reliability or reproducibility of the result.

$$\text{Fractional Uncertainty} = \text{uncertainty in measurement} / \text{measured quantity}$$

The smaller this number, the more precise are your measurements.

Relative Error

The relative error is used to state the closeness of agreement between a measured value and a true or accepted value.

$$\text{Relative Error} = \frac{|\text{ expected value} - \text{measured value}|}{\text{expected value}}$$

The relative error x 100 gives you a percent error; the smaller this number, the more accurate you measurements.

The uncertainty in our measurements may come from a variety of sources. Our strategy is to reduce as many sources of error as we can, and then to keep track of those errors that we can't eliminate. Many times, an estimate of the uncertainty will need to be made based purely on the judgment of the experimenter.

Common Sources of Error in Physics Laboratory Experiments:
- **Instrument resolution** – All instruments have finite precision that limits the ability to resolve small measurement differences. For instance, a meter stick cannot distinguish distances to a precision much better than about half of its smallest scale division (0.5 mm in this case).
- **Incomplete definition** – One reason that it is impossible to make exact measurements is that the measurement is not always clearly defined. For example, if two different people measure the length of the same rope, they would probably get different results because each person may stretch the rope with a different tension. The best way to minimize definition errors is to carefully consider and specify the conditions that could affect the measurements.
- **Failure to account for a factor** – The most challenging part of designing an experiment is trying to control or account for all possible factors except for the one independent variable

that is being analyzed. For instance, you may inadvertently ignore air resistance when measuring free-fall acceleration or you may fail to account for the Earth's magnetic field when measuring the field of a small magnet. The best way to account for these sources of uncertainty is to brainstorm with your peers about all the factors that could possibly affect your results. Sometimes a correction can be applied to a result after taking data to account for an error that was not detected.

- **Failure to calibrate or check zero of instrument** – Whenever possible, the calibration of an instrument should be checked before taking data. When making measurements with a micrometer, electronic balance, or an electrical meter, always check the zero reading first. Re-zero the instrument if possible, or measure the displacement of the zero reading from true zero and correct any measurements accordingly. It is a good idea to check the zero reading throughout the experiment.
- **Environmental factors** – Be aware of errors introduced by your immediate working environment. You may need to take account for or protect your experiment from vibrations, drafts, changes in temperature, electronic noise or other effects from nearby apparatus.
- **Physical variations** – It is always wise to obtain multiple measurements over the entire range being investigated. Doing so often reveals variations that might otherwise go undetected.
- **Parallax** – This error can occur whenever there is some distance between the measuring scale and the indicator used to obtain a measurement. If the observer's eye is not squarely aligned with the pointer and scale, the reading may be too high or too low.
- **Instrument drift** – Most electronic instruments have readings that drift over time. The amount of drift is generally not a concern, but occasionally this source of errors can be significant and should be considered.
- **Personal errors** – These come from carelessness, poor technique, or bias on the part of the experimenter. The experimenter may measure incorrectly, or may use poor technique in taking a measurement, or may introduce a bias into measurements by expecting (and inadvertently forcing) the results to agree with the expected outcome. Gross personal errors, sometimes called mistakes or blunders, should be avoided and corrected if discovered. As a rule, gross personal errors are excluded from the error discussion because it is assumed that the experimental result was obtained by following correct procedures. The term human error should be avoided in the discussion since this term it too vague to be useful.

D: Technical Tips and Suggestions

Equations and Special symbols

For word-processed lab reports, showing equations can be very tedious. Therefore, it is acceptable to insert *neatly* hand-written equations into your final printed report. The same applies to diagrams and graphs.

If you want to try a completely electronic approach using Microsoft's Word simply choose Insert→Object→Equation Editor. The Editor is cumbersome at first but allows a wide range of mathematical symbols and structures to be created. It is not always installed on all computers, so don't be surprised if you have to re-install your software with this option. All campus PC's should have this option installed. If this is not the case, let me know and I'll try to get it fixed.

If using MS-Word, you can insert special symbols by using the "Symbol…" selection under the "Insert" menu. That is Insert→Symbol… You will be prompted to browse a menu and can simply click on the symbol you want. If you don't see the symbol you need, try selecting a different "Font" in the white box at the top of the Symbol menu. The "Symbol" font is usually the one you want but often the "normal text" font is the one that comes up on the screen by default. If you are working on your personal computer, you can also assign a shortcut key to a symbol to avoid the steps above. To do so, in the "Symbol" window, select the "Assign Shortcut Key", enter in the shortcut of choice and choose "Assign". For example, I use the combination Alt+o to insert the degree symbol.

Also in MS-Word, subscripts$_{\text{like this}}$ and superscripts$^{\text{like this}}$ are very easy. For subscripts, type the letter or word preceding the script and then press and hold the Ctrl key and press the "=" key; you are then typing a subscript until you repeat the Ctrl-"=" sequence, which returns you to normal text. Superscripts are done the same way but with a Ctrl-"+" sequence (Ctrl-Shift-"=").

If you have any trouble with word processing the instructors are glad to help. We are all thoroughly familiar with the evil creations of Micro$oft!

Data Tables

For labs requiring many trials of similar data, a table is best for summarizing what you measured. It's good for you as it lets you see your data in an organized manner that allows trends to be seen easily and errors to be easily spotted. It's good for the instructor for the same reasons. Searching for data buried within paragraphs of florid prose is difficult and tedious. This is annoying to instructors.

Simple tables can be inserted in MS Word using the Table → Insert command. You will be prompted for the number of rows and columns. Be sure to include the appropriate number of rows and columns to include headers and units. Tables may also be imported from MS Excel.

Once you have included your table, you should label it clearly. This is especially important for computer printouts because they can get shuffled around so in the lab. I expect the labels to be dull but useful; "Data for Part 1," "Trial 2 for first configuration in part 1," etc. Also important for tables are that the *units* used in columns or rows of data should be clearly marked; "height (m)," "time (s)," "bomb yield (megatons)," etc.

Graphs

All real physicists love graphs, so you will be asked to make many. These are not mere busywork for you. If you are asked to make a graph rest assured that there is a *reason* why the graph is needed. The reason is usually that the graph will show some relationship between data that will be useful in forming conclusions about the phenomena studied. First, let's consider making the graphs.

Y versus X
The first step in making a graph is determining what numbers go on what axis. The convention is Y (ordinate) versus X (abscissa). If you reverse the axes the graph may make little or no sense and any conclusions drawn from it are likely to be wrong.

Slopes
A slope is a number. If asked for the slope of a graph, do not respond with "big" or "positive." Calculate the rise/run - $\Delta Y/\Delta X$ for any two points along the straight line of your graph. Is your graph *not* a straight line? If so, it has no single slope! (Hint: if a slope is asked for, a straight line is expected! Remember $y = mx + b$ is the general equation for a straight line.)

Also important are the *units* of the slope. Suppose you are graphing speed (units m/s) versus time (s) for a given object and the graph ends up being linear. The slope, $\Delta Y/\Delta X$, has units (m/s)/s or m/s^2. That is important because the physical interpretation of that slope would be an acceleration; its units are that of acceleration.

Also important is whether to include the origin in your graph. This is a decision based upon the physics at hand. For example, if you were graphing time of fall vs. height of fall for a dropped object, you would include the origin. This is because it would take an object zero time to drop zero distance.

Error bars, horizontal, vertical and double
Error bars are a way of visually indicating the error (uncertainty) of a measurement. Again, suppose you are graphing velocity versus time. If you know the error in the velocity is +/− 1 m/s (that is your measurement could be over or underestimating by as much as 1 m/s). Your measurement, say, 14 m/s at 1.75 seconds would be represented by a dot on a graph. The error in the velocity would be represented by lines above and below the dot, connected together by a short line through the dot:

This gives one an immediate sense of how uncertain the data is.
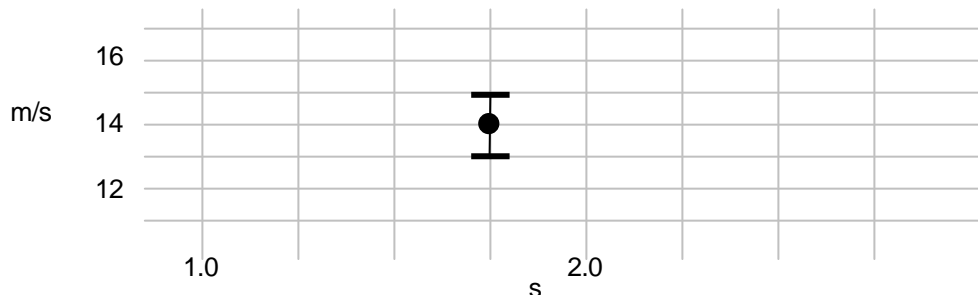
We could add a horizontal error bar to indicate an uncertainty in the time measurement. Let's say that the error in time is +/− 0.25 s. Our new double-error-bar graphed point would look like:
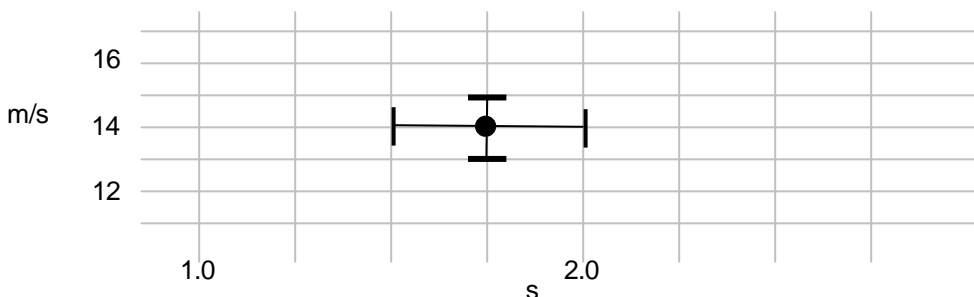
Any lines or curves drawn through the data (e.g. an approximate "best fit" line) would have to stay within as many of the error bars as possible.

Error bars will often be determined by the minimum and maximum values in a particular data point (see **Error** above). In this case, the error bars might not be symmetric about the data point.

Mathematical shape

Unless you are trying to place a best-fit straight line through your data, it is very difficult to determine what mathematical functional form some curve might have. $y = \sqrt{x}$ looks very similar to $y = \sqrt[3]{x}$ or $y = 1 - e^{-x}$ or any number of other functions. One trick is to plot y versus, say, $\sqrt{x}$ rather than x. If y is proportional to $\sqrt{x}$ then the resulting graph will be a straight line.

Another way is to use a computer graphing program to "fit" a mathematical formula to your data. This can work, but you often have to use trial and error to find the best fit function.

A safe bet when asked to comment on possible mathematical relationships is to consult the textbook or lecture notes which may hint at what type of behavior to expect.

Using Microsoft Excel for graphing

Microsoft Excel is a "spreadsheet" program that is installed in all of the student and faculty computers across campus. It is useful for making some simple scientific graphs, but it is not easy to prod it in that direction. Bear in mind that this program was written for accountants and business types, so you have to wade through a lot of garbage to get to what's scientifically useful.

A few things to note:
- A graph in Excel is called a "chart". You will need to know this when consulting the so-called "help" files.
- Just about the only type of graph, um… excuse me, chart that is useful to science types like ourselves are "XY (scatter)" graphs. These will place data on a traditional Cartesian coordinate system.

- A mathematical fit to your data is called a "trendline" and can be initiated by using the Chart→Add trendline command. To display the actual *function* that fits the data, you have to check the "Display equation on chart" box in the Trendline→Options menu.
- See my web site for some useful Excel files that you can download and adapt to your needs.
- Don't hesitate to ask your instructor for help with Excel. If something in the program frustrates you because it doesn't seem to make sense, chances are it *doesn't* make sense. We'll show you how to jump through the illogical hoops necessary to get done what needs to get done.