8

HOW TO WRITE A LAB REPORT

"… it was in plain, unaffected English, such as Mr. Knightly
used even to the woman he was in love with…"
--- *Emma*

8.1 INTRODUCTION

Science is fundamentally a communal process, in which individual scientists develop ideas and then seek through the medium of scientific journal articles to convince the scientific community of their validity. Learning how to communicate your ideas effectively is therefore a *crucial* skill for a working scientist (and is useful in many other callings as well).

Consequently, you need know how to describe the science that you do in a way that convinces the reader that your work is interesting and should be taken seriously. You may feel that comparing your lab work and the resulting report to "real" science that appears in journals is a bit pretentious, since we're probably not going to have you do much cutting-edge physics in an introductory laboratory. The purpose of the lab reports, though, is not so much to see if you did bold, original work as it is to give you practice in writing scientific reports, so that you'll be able to do it well when you *do* do bold original work.

Most articles in scientific journals (physics journals, at least) follow at least approximately a standard format, which looks something like this:

ABSTRACT

I. INTRODUCTION
   A. Motivation
   B. Summary of the experiment

II. THEORETICAL BACKGROUND

III. EXPERIMENTAL DESIGN AND PROCEDURE
   A. Description of the apparatus
   B. Description of the experimental procedure

IV. ANALYSIS
   A. Method of analysis
   B. Presentation of results
   C. Discussion of results
   D. (Optional) Suggestions for future improvements

V. CONCLUSIONS
   A. Summary of the results
   B. Pertinence of the results to the questions raised in the introduction

This format has evolved to answer the general questions a potential reader will ask:

What did you do?	(Procedure)
Why did you do it?	(Introduction, Theoretical background)
How did you do it?	(Procedure, Analysis)
What happened?	(Analysis, Conclusions)

The format also provides some shortcuts for busy (or lazy) people. Most scientific prose tends to be fairly dense, and readers like to find out in a hurry if a paper is actually of interest or importance to them. The **abstract** section provides a concise summary of the article and its most important results, so the reader only has to read a few sentences to determine if the entire article is relevant. The **introduction** and **conclusions** contain a little more information; usually the reader goes to the introduction for more information about the motivation and the method of the experiment, and the conclusion for more detail on the results summarized in the abstract.

Each of these report sections is discussed in a separate section of this chapter. You will probably find it helpful to read over the *entire* chapter the first time you are asked to write a lab-report section (to get some sense of how the pieces of a lab report fit together). At the end of the semester, when you will write a full report, you should go back and read the entire chapter again.

8.2 THE SHORT SECTIONS: The Abstract, Introduction, and Conclusions

Most published scientific papers are *not* read in their entirety by everyone who looks at them. It's not that they are poorly written (although some certainly are), and it’s not that scientists don't care; there are just so many hours in a day. The short sections of a technical paper -- the *abstract*, *introduction*, and *conclusions* sections -- identify the important results of your work, and persuade a reader that really reading the paper is worth the time. Typically a reader will look first at the abstract, to find out what the paper is about. If the abstract looks promising, the reader will look at the conclusions. If *they* look interesting (and especially if they're unexpected) the reader will then check the introduction to see if the experimental method looks good. If the introduction suggests that you knew what you were doing, *then* reader will read the rest of the article for the details.

8.2.1 *The Abstract*

An **abstract** is an extremely terse summary of the entire paper, about three to six sentences long, which in a journal appears in small print just below the article’s title and list of authors. (The abstract is also often published separately and distributed more widely than the article itself.) The purpose of an abstract is to provide readers with a brief glimpse into the subject of the article, to help them decide whether to read the whole thing. One of the first things that one does when beginning a research project is to search recent publications for articles that might be helpful: good abstracts make it possible to determine *quickly* which articles are relevant.

The structure of the abstract is essentially a miniature version of the structure of the article, except that each of the five major sections (*introduction, theory, experimental design, analysis,* and *conclusions*) might be represented in the *abstract* by only a sentence or even a phrase. Often the theory section is omitted completely from the abstract unless the paper is theoretical (which will not be the case for your lab reports!) Even so, the outline for the whole article is a pretty good starting point for the outline of the abstract as well. The abstract should *always* summarize the introduction and conclusion sections; this means that it will always include a short summary of what question you were seeking to answer, what your results were and what they imply. Although the abstract is the first section of a lab report, you may want to write it last because it *is* a summary.

In particular, a physics abstract *should* include a summary of any quantitative results you report in your conclusions. Apparently including quantitative results in the abstract is not standard in chemistry and biology articles (or so some chem and bio majors say when we criticize them for omitting this information), but it *is* standard in physics. Remember, the abstract is the "hook" you use to get people to read the rest of the paper, and you can best capture their attention with a nice juicy quantitative result with a promisingly small experimental uncertainty.

8.2.2 *The Introduction*

The **introduction** section is meant to provide the reader with the answers to two very important questions: *What is the question that your experiment is supposed to answer*, and *why* *is answering this question interesting* (and/or important)? In a published journal article, this section often begins with a brief summary of previous related research, a statement of a problem that this research has raised, and a brief description of the experiment in question and how it addresses the problem. Detailed descriptions are not appropriate in this section; the point is to provide a concise picture of your purposes and a broad survey of your approach. This section should capture the interest of your readers, provide them with some general orientation, and convince them that what you are doing is interesting and worth reading about.

After you motivate the experiment, you should give a brief summary of the experimental method you will use. This need not be extensive; the detailed description goes in the *procedure* section, which is separated from the introduction only by the theory section. You need to give enough information so that a reader who is interested primarily in your method, perhaps to duplicate your experiment or apply it to a related problem, can see if that method is appropriate.

8.2.3 *The Conclusions*

A **conclusions** section should, in one or two paragraphs, review the purpose of the lab and summarize the implications of your experimental results. That is, you should remind the reader of the basic question that the experiment was to address (as presented in the introduction), and then briefly explain how your results bear on that question or problem. This section should be a *summary* of information presented elsewhere rather than a place to present new information: the purpose of this section is to close the report with a review that highlights the most important results. As with the abstract, you should report quantitative results and their experimental uncertainties.

Students often ask, “What's the difference between the *conclusions* and the *abstract*?” The answer is, “Not much.” Both are summaries of the rest of the report, and both contain quantitative results. The main differences have to do with location: the abstract is the “hook” at the beginning, and should contain hints of the wonders to come. It also summarizes the *entire* report. The conclusion comes at the end, and should give some sense of finality or closure. It will emphasize your deductions from your data analysis, describing them in more detail than is given in the abstract. Both the abstract and the conclusions should report comparisons between predictions, presumably made in your theory section, and your measurements or their consequences.

8.2.4 *Appropriate Detail in the Short Sections*

By referring to the abstract, introduction, and conclusions sections as being the “short” sections, we imply that these three sections shouldn't be long enough to contain much detail. That's right. The abstract and conclusions sections in particular should be the least detailed, giving the broadest look at the purpose of the experiment and the implications of the results. The introduction should be a bit more detailed, but not much: its focus should be on a general statement of the problem to be considered and the experimental method used to study that problem. Too much detail in any of these sections will obscure the reader's view of the main issues in the report.

8.2.5 *A Checklist for the Short Sections*

(*All* checklists in this chapter are summarized on the inside front cover of this reference manual.) In your short sections, you should

- ☐ Summarize the entire paper in the abstract
- ☐ Discuss quantitative results in both the abstract and conclusions
- ☐ State the problem or question under investigation in the introduction
- ☐ Summarize the experimental procedure in the introduction

8.3 THE THEORY SECTION

The **theory** section is meant to provide the reader with enough mathematical or theoretical background to understand how the experiment works, what assumptions have been made, and how the experiment is related to the physics being studied. This section may be very short (or even non-existent) if the theory is well-understood and the connection between the theory and the measurements are straightforward and obvious. It can be quite extensive, however, if the experiment is complex or the actual measurements being made are related in a complicated way to the results being compared to the theory.

If, for example, you were measuring the average velocity over some interval for your experiment, your theory section would be very short: you measure a distance and a time, divide the first by the second, and there’s your average velocity. Suppose, on the other hand, that your experiment was the determination of an acceleration in a situation where you couldn’t be sure the object was starting from rest. It is still possible to find the acceleration, but you have to measure two time intervals over two distances, and the connection between those measurements and the final result involves a fair amount of algebra. In that case, you would be expected to derive the connection for your theory section, which you could expect to be one or two pages long. You don't need to show each algebraic step, but you should show some intermediate results, especially if they involve complicated algebra, a substitution, or some trick of manipulation.

The amount of theoretical background that you provide also depends on the expertise of your intended audience. For the purposes of this course, you should imagine your typical reader to be a classmate (not a professor or a lab assistant), who for some reason has not done the lab in question and knows nothing about it. This situation is analogous to that of a researcher whose audience has quite a bit of general knowledge about physical principles and experimental techniques, but no experience with the specific experiment.

For this semester, at least, you should start your theory section with first principles, or at least the equation (such as the law of conservation of momentum or energy) that defines the phenomenon you'll be studying. In a journal article you wouldn't go this far back, because starting from first principles to get to the result would take up too much space. Doing so in the introductory lab is a good idea, though, because you're probably just learning how to write a theory section. And since you're doing experiments that are usually close to the basic principles, starting with those principles helps you to examine your assumptions carefully.

8.3.1 *Writing down equations*

Theory sections tend to involve equations. There are three general rules about equations in text.

Rule 1: *Don't write equations in the body of the text*. Give each equation a line of its own. (Set aside three or four lines in your printout if you write in equations by hand.) You may break this rule for very simple equations you will not need later. For example, “When $L = 1.0$ m, the period of a pendulum is about 2 s.” Setting equations apart from the text makes the text read more smoothly, and also signals to the reader that it's time to go into Math Mode. You also get more room for writing the equation.

Rule 2: *Give every equation a number* (except the simple ones mentioned in Rule 1). This way you and the reader can find them easily later on.

Rule 3: *Don’t try to typeset equations without an equation editor*. If your word processing software doesn’t have a integrated equation editor that will let you typeset equations in standard form, *don't* try to type in an equation or parts of it; instead write the *entire* equation in by hand, instead. Faked Greek letters are almost never recognizable, and the time required to get fractions to print out correctly isn't worth it. Most readers don't instantly recognize “**” or “^” as meaning exponentiation, either, and they look terrible. You *can* get "$\underline{+}$" by underlining the "+" sign; don't use "+/-," because it looks terrible, too.

If you *do* write in equations by hand, don't forget to enter them after you print out your report! Missing equations are a sure tip-off that you forgot to proofread your report. People seem especially prone to forgetting the Greek letters and special symbols in partially typeset equations, whereas they usually notice those big blank spaces set aside for entire equations.

(Note: Recent versions of Microsoft Word, WordPerfect, and many other word-processing programs for both the Mac and Windows operating systems have integrated solid equation editors, and one can buy good stand-alone equation editors relatively cheaply. Dr. Moore likes MathType, which is easy to use and can be used with any word processor: see www.mathtype.com. There is therefore no excuse any more for attempting to typeset equations without an equation editor. Writing equations in by hand, however, is perfectly acceptable and will not lower your report grade.)

Look at the class text for examples of good style regarding equations: the book was typeset according to McGraw-Hill’s professional standards for science texts (as described in a long document that Dr. Moore has). Note in particular that **variables should always be set in *italics*:** this helps set them apart from the text and identifies them as variables as opposed to just letters.

8.3.2 *Checklist for a Theory Section*

Your theory section should:

- ☐ Start with the basic defining equations
- ☐ Show all non-obvious intermediate algebraic steps
- ☐ Clearly describe any assumptions and/or approximations involved in the model
- ☐ Display each equation on its own line
- ☐ Give each equation an equation number

8.4 THE PROCEDURE SECTION

Your job in the *procedur*e section is to convince your reader that you carried out an experiment carefully and knowledgeably enough that the reader should take your experimental results seriously. In describing your experimental procedure, you should think of the reader as someone who is unfamiliar with the particular experiment you are doing but who *is* familiar with the pitfalls of working with the equipment you will be using. Furthermore, to keep you on your toes, you should think of this reader as being someone who is inclined to be skeptical about your results and hence will be picky about your procedure. (This doesn't sound very friendly, but professional scientists act just this way reading other authors’ papers, especially about experiments they wish they'd thought of doing, or about experiments they were about to do themselves.)

Consider, for example, an experiment you will do later, measuring the period of a pendulum as a function of several variables. Simply saying, “We measured the pendulum period as a function of mass hanging from the end” doesn't do justice to what's really a rather elaborate procedure. Making this measurement carefully requires multiple measurements, timing several periods for each measurement, and choosing a particular starting and stopping point in the swing, all to reduce the uncertainty in your results, and you should say so. You should also explain why you went to all that trouble; doing so enhances your credibility with the reader, providing evidence that you thought carefully about the experiment. (It also justifies going to all that trouble.)

Most procedure sections have a fairly standard format, which (as usual) you should feel free to modify. A typical description of experimental procedure starts with a list and description of the equipment. The equipment description should state the precision to which measuring devices read. Anything that isn't a standard device should be described somewhat quantitatively. (For example, in the pendulum experiment you would give the approximate length of the string, and say something that would tell the reader whether to look in the stockroom for lightweight fishing line or big, hefty twine for wrapping packages.) Identify your lab station by its number if it has one. Large pieces of equipment should be identified by manufacturer's name, model, and serial number, which you should have written down in your lab notebook. Giving this information in your report tells the reader what performance is possible from the equipment you used.

It is very important that you also give the reader a sketch of the apparatus. A good and complete sketch may be able replace a text list of equipment, and if so, it should be used instead. Sometimes this sketch will be schematic in nature, like a block diagram or a circuit diagram; in that case, a computer-drawn sketch is fine. In cases where you need to show fine detail, or where it's important to show the geometry accurately, a carefully hand-drawn sketch is usually better (and takes much less time to do well). Unless you are very skilled or have very good drawing software, computer drawings don't normally look enough like the objects they represent to be useful.

The list and/or sketch of the apparatus tell the reader what equipment was available to you, and to some extent whether you set it up in an appropriate fashion. Next, you tell what you did with the equipment. You should do this in a logical order, but not be too "step-by-step" about it. Specifically, avoid a numbered list of steps, which are difficult to read and hence inappropriate except for the rare reader who intends to repeat your experiment exactly. At the other extreme, you should avoid narratives like this: "First we did (whatever), but that didn't work, so then we tried (something else) to fix the problem with the first measurements." Refine your procedure to remove these false steps, and present it in enough detail so that the reader can clearly understand what you did without being overwhelmed by irrelevant tiny details.

If you've made some revision in some seemingly obvious procedure that significantly improves the accuracy of your results, though, make sure you take credit for it. For example: “At the longest pendulum lengths ($L > 1$ m), the pendulum frequently hit the wall before completing ten swings. For those lengths we only timed five swings. This gave satisfactorily consistent results."

You can also refer to the lab manual if its description of the procedure is sufficiently detailed (many articles in professional journals refer to other papers for details regarding equipment or procedure), but be *especially* sure to include a complete description of any procedural details that *do not* appear in the lab manual! In referring to a lengthy source like the lab manual, state the author, title, year of publication, and page number. (For example, a reference to this booklet should look like: Moore and Zook, *Laboratory Reference Manual for Physics 51a*, 2001, p. 16.) A reference to a journal article would state the author, journal name (but not the article title), volume number, number of the first page, and year of publication. Instructions from the lab instructor or lab assistant can be cited as A. C. Zook, 1999, private communication. (This format is used in journal articles to refer to a conversation, unpublished letter, or e-mail message from the person cited.)

You might also consider the following questions as you write this section:

1) How did you determine the experimental uncertainties that you chose?
2) What (if anything) did you do to reduce them?
3) Did you experience any difficulties with the apparatus? If so, how did you resolve them?
4) Did you encounter any problems or difficulties in following the lab manual's procedure? If so, how did you resolve them?
5) Did you modify that procedure in any way, and, if so, how and why?

Standard techniques, such as the correct use of a stopwatch or a vernier caliper, need not be described in your procedure section. Unless you've given us some reason to be wary of your ability to use a device that you’ve presumably either used before (for example, the stopwatch) or received some instruction about (for example, a caliper) we'll assume that you used it correctly.

One detail you *should* definitely include, at this stage in your career, is the number of times you repeated any given measurement. Every year, we’re surprised at the number of students who don't seem to remember the importance of repeated measurements. Remember that repeating repeatable measurements is essentially the only way to determine the measurement’s uncertainty! Although you will formally calculate the experimental uncertainty in the analysis section, it's good to mention the uncertainty ranges of your basic, unprocessed measurements in the procedure section, or at least state whether a given measurement was repeatable or not.

Finding the appropriate level of detail is difficult. You don’t need to tell the reader *everything*, but you do have to say *enough*. The ideal procedure section is one that provides just enough so that the reader to go into the lab stockroom, pick out the right equipment, repeat the experiment, and get results consistent with yours based only on the information in your report and the lab manual. Providing just the right amount of detail requires practice, and probably the most aggravating comments you'll get on your lab reports will be in this section.

8.4.1 *A Few Comments on Style...*

Procedure sections are right up there with theory sections for putting the reader to sleep. In procedure sections, the culprit is usually excessive use of the passive voice. (“The ball was hit by the batter” rather than “The batter hit the ball.”) In the natural sciences, we have this fond hope that the identity of the experimenter should not affect the result of the experiment, except insofar as one person may be a more skilled than another. Writing in the passive voice became standard in the scientific community partly to move the experimenter one step back. Unfortunately, the passive voice is really boring to read, partly because it wordier and partly because it dilutes the sense of action.

The procedure section is a place where the historical convention *especially* required the passive voice. In other parts of the report, the spring exerts a force, or some results suggest an inverse-square law; since you’re out of the picture, the active voice was acceptable. But in the procedure section, *you* describe what *you* did, except that *your* identity isn’t supposed to important.

However, the times are changing! We here at Pomona are not the only people who have trouble staying awake reading technical literature, and we’ve noticed that authors of scientific papers are more often saying things like “*We* observed NGC 253 on seven consecutive nights looking for supernovae,” and even (gasp) “*I* measured the activity of the radioactive sample at 15-minute intervals.” So go ahead, be on the cutting edge -- every so often, admit that human beings with names and faces make those measurements. If you're describing a division of labor, the standard phrase seems to be “One of us (TAM) calibrated the Heisenberg compensators while the other (ACZ) carried out the tachyon-beam efficiency measurements.”

8.4.2 *Checklist for a Procedure Section*

Your procedure section should:

☐ Provide a sketch or schematic diagram of experimental setup
☐ Provide a textual list and/or descriptions of equipment (when needed for clarity)
☐ Describe all measurements, in roughly the order in which they were made
☐ Describe any departures from procedure described in the lab manual, if any
☐ Describe any steps taken to reduce experimental uncertainty
(the last two descriptions should follow the description of the measurement in question)

8.5 ANALYZING YOUR DATA AND WRITING AN ANALYSIS SECTION

8.5.1 *Data Reduction*

The general task you have to accomplish in an **analysis** section is this: You start with a *bunch* of numbers (your measurements). You want to wind up with a *few* numbers (maybe only one) that characterize those measurements. Those few numbers in turn presumably tell you something about a theoretical prediction you or someone else has made; typically you have to make a decision about the validity of a theory based on your results.

You get to the few numbers from the many numbers through your data analysis. In your analysis section, you show the reader how you got from the many numbers to the few, in enough detail that the reader can decide if you used the appropriate methods and carried them out correctly. Then you present your case for the implications of your numerical results. For example, in the first lab you measured the time it took sound to move through a long tube. Presumably you made several measurements of the time, and you must have made at least one measurement of the length of the tube. Then you made some calculations and came up with a result for the speed of sound. Human nature being what it is, you probably compared your result to the accepted result.

8.5.2 *Graphing*

Your analysis section could more accurately be called your “data presentation and analysis” section, because the first thing you must do in an analysis section is display the data you are analyzing. You should *not*, however, display your original or “raw” data (the numbers you wrote down in your lab notebook) in tables in your report, because it's very difficult to pick out data trends from a large table. Instead, you should present your data *graphically*, plotted on Cartesian paper. Even this graph (or set of graphs) will probably not simply be a graph of your unprocessed data: you will more likely plot averages (or means) of sets of data with appropriate uncertainty bars. (See Chapter 4, *Presenting Data Graphically*, for details about setting up graphs.)

Just drawing the graph isn't enough, though. You must tell the reader that it exists, what it’s about, and where it is. A typical first sentence in an analysis section reads something like this: “The dependence of falling time on distance from the initial position is given in Figure 1.” (Obviously you should give the dependent and independent variables for the experiment you're actually describing!) Notice that you have identified the graph both by the data being displayed and by stating a figure number. Identifying the graph by the data tells the reader why this graph is part of your logical argument about the meaning of your data and results. Identifying the graph by a number makes it easy to find, especially if you put all your graphs at the end of your report. If your word processor lets you display a graph on the *same* (or at worst the *next*) *page* as the text discussing the graph, then do that; the next best thing is to put all your graphs at the end. Either way, the reader knows exactly where to look for them, which is better than having a figure located at the nearest convenient empty space several pages away. (A word of caution about positioning graphs: you can use up an enormous amount of time trying to put a graphic in just the right location while keeping section and page breaks where you want them. If you find your word processor driving you mad while positioning figures, a particular problem with Word for Windows, put all your figures at the end. It is OK to do this, really!)

You must, of course, show error bars on your graphs, unless they’re too small to be visible. If this is the case, say so explicitly so that your reader does not assume that you have simply forgotten about them (which could have deleterious effects on your grade). If your error bars are large enough to be visible, you should also state explicitly whether they represent one standard deviation, the 95% confidence interval, or some other range. (The 95% confidence range is standard.)

The details of your analysis from here depend on exactly what question you are trying to answer with your data. Often in your theory section you have worked out an expected relationship between the variables that you are measuring. If the expected relationship is linear, you can check that the data you have graphed are consistent with that prediction. If the expected relationship is *not* linear, you will generally have to draw another graph of your data using one of the linearization techniques described elsewhere (Chapters 5, 12 and 13) to *make* the expected relation linear. If this second graph is necessary, refer to it by title and number in your report. It's usually a good idea to put the linearized plot right after the Cartesian plot, and comment briefly on the relation between the Cartesian and non-Cartesian plots in the report. For example, in a write-up of a pendulum lab, you might say something like this: "The curve in Figure 1 and the predicted $L^{1/2}$ dependence suggest a power-law relation between pendulum length and period. Figure 2 shows a log-log graph of the data of Figure 1. The data in Figure 2 lie on a straight line, indicating that period and pendulum length are in fact related by a power law."

The result you are after in an experiment is often related to the slope and/or intercept of this final straight-line graph. Early in the semester you may find the slope and intercept by eyeballing the best-looking straight line. (You may also use this method later when you want a quick estimate of the slope.) If you do this, indicate on the graph the two points you used for the slope and intercept calculations, and give the numerical results in your Analysis section. Later on, after you become familiar with a technique known as linear regression (see Chapter 10), you will use that method, usually with the program called *LinReg*.

If you did some calculations to extract the value you want from the slope or the intercept of your final graph, please go through these calculations in enough detail that the reader can duplicate your work if necessary. If you have to do a series of very similar calculations (and they're more complicated than dividing by 2 or π), show one such calculation in some detail as an example and then state that the other calculations are similar.

8.5.3 *Experimental Uncertainty*

An essential part of any analysis is a discussion of experimental uncertainty. Careful treatment of uncertainty is essential if you are to draw meaningful conclusions from your data. If you have to *estimate* the uncertainty of any measured quantities, describe how you did your estimate, unless you already did this in your procedure section. If you *computed* the uncertainty of a value, describe how you did that calculation and show an example calculation. Also make sure that you specify explicitly (where relevant) whether the uncertainty you are quoting is the uncertainty of a single observation or the uncertainty of the mean.

Report uncertainties with units and in the same form and to the same precision as your results: for example, 3.98 ± 0.07 N, not 3.98 ± 6.8×10^{-2} N. If you are reporting a result (with uncertainty) whose magnitude requires the use of scientific notation, report both numbers written with the same exponent: $(1.10 \pm 0.06)\times 10^{-6}$ meters, not $1.10 \times 10^{-6} \pm 6.2 \times 10^{-8}$ meters. Comparing the precision of your uncertainty to your result is much simpler with the preferred format.

This might be a good place to point at that "uncertainty analysis" or "error analysis" does not mean, "Explain what went wrong and how you'd do it differently next time." Certainly, if in analyzing your data you realize that you carried out some part of the procedure in a way that gave poorer results than you had expected, and you don't have the time do redo that part of the experiment, you should say so: thinking carefully about your procedure after you've done the experiment is an important part of improving your experimental technique, and can be critical for eliminating systematic errors from your results. The term "uncertainty analysis," however, refers to the *quantitative estimation of the experimental uncertainty in your numerical results*.

8.5.4 *Results*

Earlier we said that you should not give tables of your *raw* data in your analysis section (or anywhere else). There are occasions, however, when reporting *processed results* in tabular form is appropriate, when a graph is difficult or meaningless. Suppose, for example, that you repeated the collisions experiment in a number of different ways (using magnetic pucks that repel each other, using velcro to make the pucks stick together, using pucks with varying masses), and generate from class data the mean ratio of the total momentum magnitude after the collision to that before the collision in each case (and its uncertainty). In this case, there is no independent variable to plot these results against, so a tabular display of these processed results would be appropriate.

At some point you will draw some conclusions about whether the data you have obtained are consistent with the expected relationship between your variables. If you predicted a straight line in your theory section and your experimental results support your prediction, you should say so. You should, however, avoid comments like, “Our results prove that the theory is correct.” You can never *prove* a theory; to do so, you would have to perform all possible experimental tests of that theory, and you don’t have time for that in a three-hour lab period. On the other hand, it is possible to *disprove* a theory with a single contradictory measurement (provided that the experiment has been done correctly, which may be a matter of debate!). The accepted phrase in both cases is less rashly assertive: "Our results are *consistent* (or *inconsistent*) with the theory.

Often your discussion of the implications of your results will be straightforward; if you're working with a well-known physical system and you follow the treatment in a textbook to develop a theory, your results will be probably consistent with the theory. We have tried to slip in a few curve balls just to keep the lab from being “verify what's in the book,” though. Your discussion of the implications of unexpected results will show your strength as a physicist most clearly. You should be creative, but also *very* careful. Don't allow yourself to indulge in empty speculation about an unexpected result; *test* your speculations. If you come up with an explanation, try to show that it could indeed have caused an effect of the same magnitude and in the same direction as the effect you observed. That is, if your explanation predicts a greater-than-expected measurement, you'd better *observe* a greater-than-expected measurement if your explanation is to be valid.

8.5.5 *Checklist for an Analysis Section*

Your analysis section should

- ☐ Briefly describes the data
- ☐ Include a Cartesian (unlinearized) graph of data
- ☐ Includes linearized graphs of data, if appropriate
- ☐ Discusses consistency or lack thereof with any theoretical predictions
- ☐ Discusses how you calculated the slope and intercept of any linear graphs
- ☐ Shows the calculation any derived quantities from slope or intercept
- ☐ Completely discusses all uncertainties involved, showing sample calculations if needed
- ☐ Discusses the results and their implications

8.6 PUTTING IT ALL TOGETHER

8.6.1 *Proofreading*

In principle, if you write the various sections of your report using the guidelines above, you should be done. Before you turn in that masterpiece of scientific prose, though, you need to make sure that it all hangs together. That is, do the links between sections that you imply in one section actually appear in another? For example, did you test in your analysis section the equation that you derived in your theory section? If you made assumptions in your theory section, did you include tests of those assumptions in your procedure section? Did the measurements you describe in the procedure appear as graphs in analysis? Do your quantitative results support your discussion and your conclusions? Is it clear that your theory and your procedure are about the same experiment?

You should really read your report over twice. The first time through is for proofreading, a step we find people often omit. That word-processed output from the laser printer may look wonderful at first glance, but it has to stand up to a careful reading. Remember, the computer may not going to catch your mistakes in punctuation, and the spelling checker will probably not distinguish between “there” and “their,” or “it’s” and “its.” (Now is a good time for you to make sure that *you* know the difference between *it’s* and *its*.) It also won’t notice that you’ve left out the equations. (Indeed, using a spelling checker with technical writing can be pretty annoying, as it chokes on every technical word, symbol, and equation number.) Our experience with grammar checkers suggests that they are not up to college-level English, so don't slavishly follow every instruction your grammar checker makes, either. We're not suggesting that you turn your backs on some benefits of modern computer technology and not use your spelling and grammar checkers at all, but you should recognize that they have their limitations.

The second reading is for sense and continuity. Do the steps of your procedure follow each other logically? Is the same true for your analysis? Do the sections of your report relate to each other as described above? If you can stand it, and if you can get yourself to write your report well ahead of time (a good intention with which the road to hell is no doubt liberally strewn), get someone else (preferably *not* your lab partner) to read your report. The lab assistants will be prepared to read over your reports for just such considerations as we've described above.

8.6.2 *More on Good Writing Style*

The mechanics of your presentation are arguably its least important aspect. Nevertheless, a sloppy presentation can add to your reader’s difficulty in getting through your report, and hence lower your credibility. (If you didn’t care enough about your report to run it through your spelling checker, how much effort could you have gone to on the parts that needed some real work?) You are presumably already familiar with the need for correct spelling and punctuation; here are some mechanics of presentation that may be less familiar.

- Set apart the different sections of your report (abstract, introduction, etc.) with blank lines.
- Avoid breaking a section between the heading and the first paragraph; that is, don’t leave a section heading dangling at the bottom of a page with the text of the section beginning at the top of the next page.

You will be expected to write good, clear, English in your lab reports, using correct grammar in complete sentences. The days when someone in a science course could wail, “But this is a physics course, not an English course!” are, thanks to the concept of writing across the curriculum, long gone (if in fact they *ever* existed at classy liberal-arts colleges like Pomona). Remember that the point of any report is *communicating* with someone else. If you keep distracting your readers with grammatical mistakes or unclear prose, you will make it difficult for them to concentrate on the meaning. You *will* be graded partially on the quality and clarity of your writing. As a general guide to a good prose style, we recommend Strunk and White's *The Elements of Style*. It is a small paperback, usually available at the bookstore. We think it will be a useful investment for several of your classes. Also keep handy your copy of Hacker, *A Writer’s Reference* from your ID 1 course; the lab staffers are likely to refer to it when pointing out grammatical mistakes.

In spite of what Strunk and White say, however, you should use "inclusive" pronouns rather than the generic "he." That is, you should use constructions like, "When physicists make measurements, *they* ..." rather than, "When a physicist makes a measurement, *he* ..." Strunk and White wrote their book before inclusive language became standard. It's almost the 21st century now, usage changes, and it's time to get with it. (You might also count the members of the lab teaching staff who are left out by the generic "he" and think of inclusive language as simple self-defense.)

You should also avoid certain words and expressions. "Readings" (as in, "We took five readings for each distance") belongs on *Star Trek*, where it's used to avoid using the technical terminology that a 23rd-century scientist would use, since the screenwriters don't have any idea what that terminology might be. You're using 20th-century equipment and a 20th-century vocabulary, and you can describe exactly what you're *measuring*: "For each distance between the source and the timer, we *measured the time interval* for the sound wave to travel that distance five times."

Other words and phrases that people often use incorrectly are:

- ***Defined as,*** in the sense of "found to be" or "may be described empirically by." You can *define* the length of a pendulum as "the distance from the pivot to the center of mass of the bob," if that is the correct definition, but you *find* or *measure* it to be 1 meter long.
- ***Calculated value,*** in the sense of "number we calculated from our measurements." Usually the *calculated* value (or the *theoretical value)* is one you derive from some theoretical calculation, and the *measured* value (or the *experimentally-determined value)* is the one you calculate from your measurements.
- ***Approximate*** for "estimate" (as a verb). Estimates (as nouns) usually *are* approximations, in the sense that you typically know them to one significant figure. But you *estimate* a number (that is the process), and end up with an *approximation* (or better, *estimate* [noun]) of its value.
- ***Correlation*** for "simple relation." Saying that two quantities are "correlated" only means that they seem to be related in some way, so that if one changes, the other one changes as well. The relationship between variables in many disciplines of natural and social science can be extremely complicated, and although we often assume that some underlying cause is responsible for the relationship, this is often *not* the case: *correlation does not imply causation*. In physics, however, the variables that we generally will look at will be clearly related by some simple relation. Saying that two quantities are "correlated" in physics is usually too *weak* a statement: *describe* the relationship.
- ***Calibration.*** People really like this term, because it sounds so technical. It refers specifically to the comparison of one measuring instrument either against another or some reference standard, to make sure the instrument is working correctly. If this is *not* what you're doing (and you rarely will do this in this lab program), you are not "calibrating."
- ***Prove*** meaning "support." We talked about this already, but it's worth repeating. You can't *prove* a theory with one experiment, although you can *disprove* a theory with one. Results can only *support* or *be consistent with* a theory.
- ***Correct value*** in the sense of "a value published in a book." In some experiments, you might be measuring a value (like the speed of sound) whose value we can look up in a reference, and you may be tempted to call the value in the book the "correct" value. It is not the correct value: it is the (currently) *accepted* value. The values of physical constants published in books are summaries of experimental results, and new experiments can (and often do) lead to modifications in these accepted values.

An episode from the history of optics illustrates the last point. Albert Michelson (1852-1931) was the first American to win the Nobel prize in physics, for his precision measurements in the field of optics. He invented the Michelson interferometer, used in the famous Michelson-Morley experiment to demonstrate (unexpectedly!) that the speed of light is the same in all inertial reference frames. He also made several measurements of the speed of light using a method very similar to the one you will use later on this semester, although with considerably longer baselines. (One of his measurements was made between Mt. Wilson and Mount Baldy [no lie!], and Baseline Road in northern Claremont was surveyed accurately as part of this measurement.) His last measurement, made in an evacuated tunnel about a mile long (on what was then the Irvine Ranch) was accepted as the standard for decades, and probably most physicists thought of his result as the "correct" one. A 1941 review of fundamental physical constants (R.T. Birge, "The General Physical Constants," in *Reports in Modern Physics*,**8**, 90, 1941) weights this result the most heavily in coming up with a weighted average of several contemporary measurements of the speed of light.

You can guess what's coming. Later measurements, mostly made in the 1950s, consistently got results that disagreed with Michelson's. The disagreement wasn't very large, about 17 km/s (out of 300,000 km/s). Their result and Michelson's differed by more than the sum of the experimental uncertainties, though. Eventually a partial explanation for the discrepancy surfaced. Michelson died shortly before the experiment was actually performed, although he did see the apparatus installed. His collaborators made the measurements (almost 3,000 altogether) at night, to reduce temperature variations and human activity in the area as sources of experimental uncertainty. The baseline distance was measured during the *day*, though, and only two or three times. (It's difficult to survey distances of more than a few tens of meters at night.) Apparently the thermal expansion and contraction of the ground itself with temperature was large enough to have a systematic effect on the speed of light they deduced from their measurements.

Lest Michelson's collaborators seem inept, we should mention that they were quite alert to some even more obscure possible sources of systematic error. In reporting their results, they mentioned an apparent weak dependence of the measured speed of light on the tides, but since they couldn't identify the cause of this dependence, they couldn't figure out how to correct for it, or even whether they should! The cause of this systematic effect is unclear even now. Michelson's collaborators and the authors of the review article from which most of this historical summary is taken, mindful that "correlation doesn't imply causation," all hesitated to claim that the tides were directly responsible for the apparent variation in the measured speed of light. (For more details, see E.R. Cohen and J.W.M. DuMond, "Fundamental Constants in 1965," *Reviews of Modern Physics*, **37**, 537, 1965, and the references therein.)

The moral of this tale, of course, is that there are no "correct" results in science, only *accepted* ones. Even prominent scientists forget sources of systematic error, or run into systematic error where do one would have expected it, or someone comes along with better equipment. It is true that you're not likely to hit the frontiers of physics in an introductory laboratory, but you should get into the habit now of regarding every scientific result as only one carefully designed experiment away from revision.

8.6.3 *How Long Should a Lab Report Be? (and Stuff to Leave Out)*

A typical scientific journal article might be about ten pages long. Your full lab reports will probably be shorter; try to limit yourself to the equivalent of four or five single-spaced typewritten pages of text, not counting graphs or diagrams. This means that few of the five major sections (the ones with Roman numerals on the outline) will exceed a page in length, and some may be shorter.

There are also some items you should leave *out* of a lab report. Please don't complain about the equipment; we already know that if we had an infinite budget, we could buy really frictionless gliders and opto-electronic timers good to a microsecond. You won't have an infinite budget in real life, either. Even if your equipment budget is large, you will always be making measurements that require care and ingenuity to make; sometimes the equipment you would like doesn't even exist! Experimental physics isn't about making really precise measurements so much as it is about making the best measurements you can with the equipment you have. By practicing with the admittedly limited equipment available now, you prepare yourself for those later measurements when you can't improve the data simply by spending more money.

Don't editorialize about an experiment being a “success” or “failure” in the context of agreement with accepted results or theories. It’s true that we have some expectation that your results will be in agreement with established laws of physics, because normally you won’t be dealing with particularly exotic (that is, poorly understood) physics in an introductory course. We also expect that in the full report, in which you do write a draft for which you have presumably analyzed your data, that if your results are in gross disagreement with established laws of physics, that you will make some attempt to figure out the cause of that disagreement *and fix it.* You do, after all, have most of that second lab period to collect more data if that should seem appropriate, and that’s exactly why we arranged the lab schedule the way we did. In evaluating your work, though, we look primarily for evidence that you understood how the equipment worked, how the measurements you made were related to the theory discussed, and generally that you were thinking about what you were doing. Some real physical effect could be present that the designers of the lab overlooked, or have left in to keep you on your toes. (This happens more often than you might think.) If you have been careful about your work, be confident in presenting what you have observed. (The confidence *should* follow from being careful, though, and if the lab staff identify some systematic effect in data collection that you overlooked, *go take more data!*)

8.6.4 *Example Lab Reports*

Two sample lab reports are provided as appendices to this chapter. Each is *mostly* well-written, but has problems with specific sections, as discussed in the exercises below. Except for these problem sections, though, you can use these reports as examples of good report style.

Note again that a summary of all checklists appears on the inside front cover of this manual.

EXERCISES

Exercise 8.1

Read the lab report entitled “The Speed of Sound.” This report (which describes an older version of the experiment you did during the first week of lab) is mostly well-written except for the *abstract* and *procedure* sections. See what *you* think is lacking in these sections (according to the checklists and other information in this chapter) and then compare with the comments on the last page of this chapter. (There is no penalty for not spotting everything: just do the best that you can.) Write your comments on the report itself.

Exercise 8.2

Read the lab report entitled “Gravitational Potential Energy”. This report is mostly well-written except for except for the *analysis* section (where little superscripted numbers indicate problem areas). See if you can figure out what these numbered problems are, and then check the answers provided on the last page of the chapter. (There is no penalty for not getting everything just right: just do the best that you can.) Write your guesses in the margin of the report itself.

APPENDIX 8.1: FIRST SAMPLE LAB REPORT

Torrin Hultgren
Partner: Alix Hui
9/10/98

The Speed of Sound

Abstract:

In this lab we determined the speed of sound by timing the interval that it took for a loud bang to echo off a surface a known distance away. Our average time interval was 1.28 s, and the distance was 440 m, so our calculated value for the speed of sound was 343.8 m/s. This is consistent within our experimental uncertainty with the accepted value at 30°C, which is 349.7 m/s.

Introduction:

The speed of sound has many practical applications, such as determining the distance from lightning, knowing when jets will break the sound barrier, designing acoustical facilities like concert halls and auditoriums, and literally thousands of others. The phenomenon of an echo is familiar to most people, and it is a relatively easy way to measure the speed of sound.

We used two blocks of wood to create a loud and sharp bang. We determined the distance using a counting wheel whose circumference we measured and we used hand stopwatches to time the echo. We repeated the time measurement 20 times to reduce experimental uncertainty. We calculated the speed of sound by dividing the distance measurement by the time measurement. In addition, because the speed of sound varies with the temperature of the air through which it propagates, we measured the temperature with a mercury thermometer in order to calculate the accepted value for the speed of sound.

Procedure:

We used the following pieces of equipment to do the lab.

- Two small blocks of wood
- 2 stopwatches
- 1 measuring wheel
- 1 meter stick
- Thermometer
- A small piece of masking tape

We set up on the concrete bench closest to the grass on Marston Quad. We chose this spot because it lined up with the small wall at the end of Stover Walk (which we could see through the trees) which gave us an easy reference point for beginning our distance measurement. One of us held the stopwatch and the other hit the blocks together. Because we could see the blocks coming together we could anticipate when they would hit. Then we stopped the stopwatch when we heard the echo, without anticipating it. This gave us a slight delay in timing the echo because of our reaction time, but we were able to correct for this as described below. Both of us made 10 time measurements and hit the blocks together 10 times.

To account for the reaction time delay we devised this procedure. I started both stopwatches at the same time. I then handed one stopwatch to Alix and kept the other. Behind my back she simultaneously stopped her stopwatch and hit one of the blocks against the concrete bench. When I heard the sound I stopped my stopwatch. The difference between the two times on the stopwatches was my reaction time. We repeated this measurement for each of us five times.

To calibrate the measuring wheel we put a small piece of tape at the edge of the wheel. We put the meter stick on the ground and lined this piece of tape up with one of the ends of the meter stick. We then rolled the measuring wheel along the ground next to the meter stick until the piece of tape had traveled one full revolution. The point that it lined up with was our value for the circumference of the wheel.

For the distance measurement we began at the wall at the beginning of Stover Walk that lined up with the place where we had taken our time measurements. We walked the measuring wheel down the middle of Stover Walk, using the sidewalk lines to make sure we were traveling in a straight line and not zigzagging excessively. We continued across the street, and then used the sidewalk lines to line up perpendicularly so we could move over and roll the measuring wheel across the wood chips and right up to the face of Carnegie that we believed the sound was echoing off of. We then doubled this measurement to arrive at the total distance the sound had traveled.

Analysis:

The average of the measurements I took was 1.55 s, with a standard deviation of s = 0.05 s. The uncertainty of this measurement, using the Student t-value, is

$$st = 0.05 \text{ s} \times 2.09 = 0.10 \text{ s} \tag{1}$$

This measurement therefore had a fractional uncertainty of

$$\frac{0.10 \text{ s}}{1.55 \text{ s}} = 0.064 = 6.4\% \tag{2}$$

The similar values for Alix's measurements, which were different because she had a different reaction time, were 1.43 s ± 0.13 s for a fractional uncertainty of 9.1%. Both of these fractional uncertainties seem reasonable for the type of measurements we were doing. My average reaction time was 0.27 s ± 0.02 s, and her average reaction time was 0.20 s ± 0.03 s. Our actual calculated times of flight were therefore 1.28 s ± 0.082 s and 1.23 s ± 0.11 s.

Our measurement for the circumference of the wheel was 0.587 m. Our measurement for the number of rotations of the wheel was 374.3. The distance from us to Carnegie was therefore

$$374.3 \text{ turns} \times 0.587 \frac{\text{m}}{\text{turn}} = 220 \text{ m} \tag{3}$$

Doubling this we arrived at a total distance of flight measurement of 440 m. We generously estimated our uncertainty to be ± 1.0m. This gives us a fractional uncertainty for the distance measurement of 0.2%. Compared to the uncertainty of the time measurement, this is tiny.

My calculated value for the speed of sound was

$$\frac{440\ \text{m}}{1.28\ \text{s}} = 344\ \text{m/s} \tag{4}$$

Propagating uncertainty using the weakest-link rule, my calculated uncertainty was ± 22 m/s. Alix's value was 355 m/s ± 32 m/s.

The formula for the speed of sound as it varies with temperature is

$$v_s = 331.3\,\frac{\text{m}}{\text{s}} + \left(0.6\,\frac{\text{m}}{\text{s}\cdot\text{C}^\circ}\right)T \tag{5}$$

where T is measured in Celsius degrees. Our measured value for the temperature was 30°C. Plugging this into the above formula gives us an accepted value for the speed of sound of 349.3 m/s. This value lies well within both of our experimental uncertainties.

Conclusion:

We measured the time it took for an echo to travel a measurable distance. Using our separate time and mutual distance measurements we calculated two values for the speed of sound: my result was 344 m/s ± 22 m/s and Alix's was 355 m/s ± 32 m/s. These values for the uncertainty are a reasonable fractional amount. Our calculated accepted value for the speed of sound based on the observed temperature was 349.3 m/s. This value lies well within the experimental uncertainty of both our measurements.

COMMENTS ON THIS REPORT:

Short sections:

These are fairly good, except that the abstract should include an estimate of the uncertainty in their measurement of the speed of sound, not just their measured value. The introduction should provide a clearer statement of the particular experimental question to be resolved here (that is, that the goal of the experiment is to measure the speed of sound by measuring the round-trip time of an echo from a distant object and compare the result with an accepted formula for the speed of sound).

Theory:

The Theory section is missing! This is obviously a simple experiment based on very simple theory, but at the very least the author should state explicitly that he is assuming that the speed of sound is constant, and give the appropriate equation for finding the speed from distance and time measurements.

Procedure:

The equipment list does not include their stopwatch number or the number of the measuring wheel. Consequently, if they needed to check their calibration of the wheel (or the accuracy of the stopwatch, which is less likely), they would have no way of identifying it.

The procedure section does provide an equipment list but not a sketch or diagram. However, this lab is a case where an equipment list is probably more useful than a sketch for helping the reader understand how the lab works. Even though the guidelines strongly suggest that one should include a diagram, the guidelines should not be followed slavishly if a diagram does not really add much to the reader's understanding. Do whatever makes things most clear to the reader!

It might have been nice to briefly discuss that the author is assuming that the "actual" flight time of the echo that he will use to calculate the speed of sound is his measured flight time of the sound minus his reaction time. This is implicit but should be stated more explicitly.

The calibration of the measuring wheel needs more discussion. For example, the piece of tape mentioned presumably has a finite width, probably about 1 cm. If they weren't careful to identify a particular reference point on the tape (such as a penmark on the tape, or one of the two edges), this would introduce a systematic error into their calibration, which would carry over into a systematic error in their value for the distance.

The author also doesn't state the precision of their measurement of the circumference of the measuring wheel. Without this, the reader has no way of knowing if the later estimate in the uncertainty of the distance is reasonable. It is also unclear if they repeated the circumference measurement or the distance measurement.

Analysis:

The main problem with this section is the uncertainty analysis. To begin with, the author mentions combining the uncertainties of their average time measurements for the echo time and the reaction time, but does not identify the method used to combine the uncertainties. Next, no uncertainty estimates are given for either the measurement of the wheel's circumference or the number of revolutions of the wheel. Finally, the author invokes the weakest-link rule in finding the uncertainty in the final value for the speed of sound, but does not justify the use of the weakest-link rule by explicitly locating the weakest link in the calculation and then showing a sample calculation using that weakest link.

APPENDIX 8.2: SECOND SAMPLE LAB REPORT

GRAVITATIONAL POTENTIAL ENERGY

Maria Goeppert-Meyer
(Lab partner: Irene Curie)
Sept. 26, 1995

ABSTRACT

In this experiment, we determined the change in the gravitational potential energy V of the system consisting of the earth and a dropped plastic slab as a function of the distance h through which the slab falls. We found this change in potential energy to be consistent with the expression $V_i - V_f = mgh$, where m is the mass of the object and g is the gravitational field strength. We found the value of g to be 9.81 ± 0.02 m/s^2, consistent with results obtained in other laboratories.

INTRODUCTION

Consider the change $V_i - V_f$ of the gravitational potential energy of a system consisting of the earth and a falling object, where V_i is the system's initial potential energy, V_f is its final potential energy after the object has fallen a certain distance h. In section C7.4, the text *claims* that this change in potential energy is given by $V_i - V_f = mgh$, where m is the object's mass and g is the gravitational field strength near the earth, a constant that is *purportedly* equal to 9.8 m/s^2.

This result, which is stated without justification in the text, is a basic and important result that subsequently used many times in the text. It would be valuable, therefore, to supply the empirical foundation for this assertion. Our goals in this experiment were to demonstrate for a specific object interacting with the earth that (1) for a given value of h, the value of $V_i - V_f$ does appear to be proportional to m, (2) for a given value of m, the value $V_i - V_f$ increases linearly with h, and (3) the value of g is what it is purported to be.

In this particular experiment we dropped a plastic slab (released from rest at a known initial height) past a photodetector connected to a computer. A series of equally-spaced opaque bands painted on the slab interrupted the light falling on the photodetector, and the computer measured the time that it took each band to pass the photodetector. From this information, we could determine slab's speed as each band passed the photodetector, and thus determine its kinetic energy after it had fallen whatever distance h was required to bring that particular band past the photodetector. Given the object's kinetic energy as a function of h, we could find $V_i - V_f$ as a function of h. By attaching various weights to the bottom of the slab, we could vary the mass of the falling object and thus check how $V_i - V_f$ depends on mass.

THEORY

As the plastic slab drops under the influence of the gravitational interaction between it and the earth, the total energy of the earth-slab system must be conserved:

$$K_i + K_{E,i} + V_i = K_f + K_{E,f} + V_f \tag{1}$$

where K_i and K_f are the initial and final kinetic energies of the slab, $K_{E,i}$ and $K_{E,f}$ are the initial and final kinetic energies of the earth, and V_i and V_f are the initial and final gravitational potential energies of the system. According to the argument presented in section C7.3 of the text, we can consider the earth to be essentially at rest throughout the experiment (since it is so much more massive than the slab) and thus $K_{E,i}$ and $K_{E,f}$ are negligible. If we drop the slab from rest, then $K_i = 0$ also, and equation (1) becomes simply

$$V_i - V_f = K_f = \tfrac{1}{2} m v_f^2 \tag{2}$$

So, to measure the system's potential energy change $V_i - V_f$ after the slab has fallen a distance h, all that we have to is measure the slab's mass m and its final speed v_f. We can easily measure its mass using a balance. We can measure its final speed as follows. Imagine that we paint an opaque band across the width of the slab perpendicular to the direction that the slab falls. As the slab falls, imagine that this band interrupts a horizontal beam of light between a light source and a detector. We can use a computer to register the time Δt that the beam is interrupted. If the height of the band is Δd, then the speed of the slab as the band crosses the beam is approximately given by:

$$v \approx \Delta d / \Delta t \tag{3}$$

This most closely approximates the slab's speed halfway through the time interval and thus roughly as the *center* of the band passes the light beam. This speed, therefore, can be used to determine the slab's kinetic energy after it has fallen a distance h equal to the change in the slab's position from its release point to the position where the band is centered on the photocell beam.

Finally, note that the *claim* is that $V_i - V_f = mgh$, where m is the slab's mass and g is the constant gravitational field strength. *If* this is true, then plugging this into equation (2) yields

$$mgh = \tfrac{1}{2} m v_f^2 \quad \Rightarrow \quad gh = \tfrac{1}{2} v_f^2 \tag{4}$$

Therefore, if $V_i - V_f$ is proportional to m as claimed, the slab's final speed after falling through a given distance h should be completely *independent* of its mass, which should be easy to check. Also, if this is true, the slab's mass is not really relevant and we do not need to measure it.

PROCEDURE

In this experiment, our falling object was a clear plastic slab about 1.1 m tall and 8 cm wide, with five opaque bands 5.0 cm tall and vertically separated (center to center) by 20 cm. We could vary the mass of the slab by attaching one to four weights to the bottom of the slab. We dropped this slab past a photogate consisting of a paired infrared light source and a photodetector mounted on a lab table so that the line connecting the source and detector was horizontal (perpendicular to the motion of the slab). The output of the photodetector was connected to a small box which in turn was connected to a Universal Lab Interface (ULI) circuit board (sold by Vernier Software, Inc.), which processed the signal for the photogate before passing it on to a Macintosh Centris 610 (serial number 3255967). A program called *ULI Timer* (also from Vernier Software) monitored the output from the ULI and displayed time intervals on the computer screen (see Figure 1 for a sketch of our experimental setup.) The program was configured to display the length of time that each of the five dark bands on the slab blocked the photogate beam as the slab fell past it.

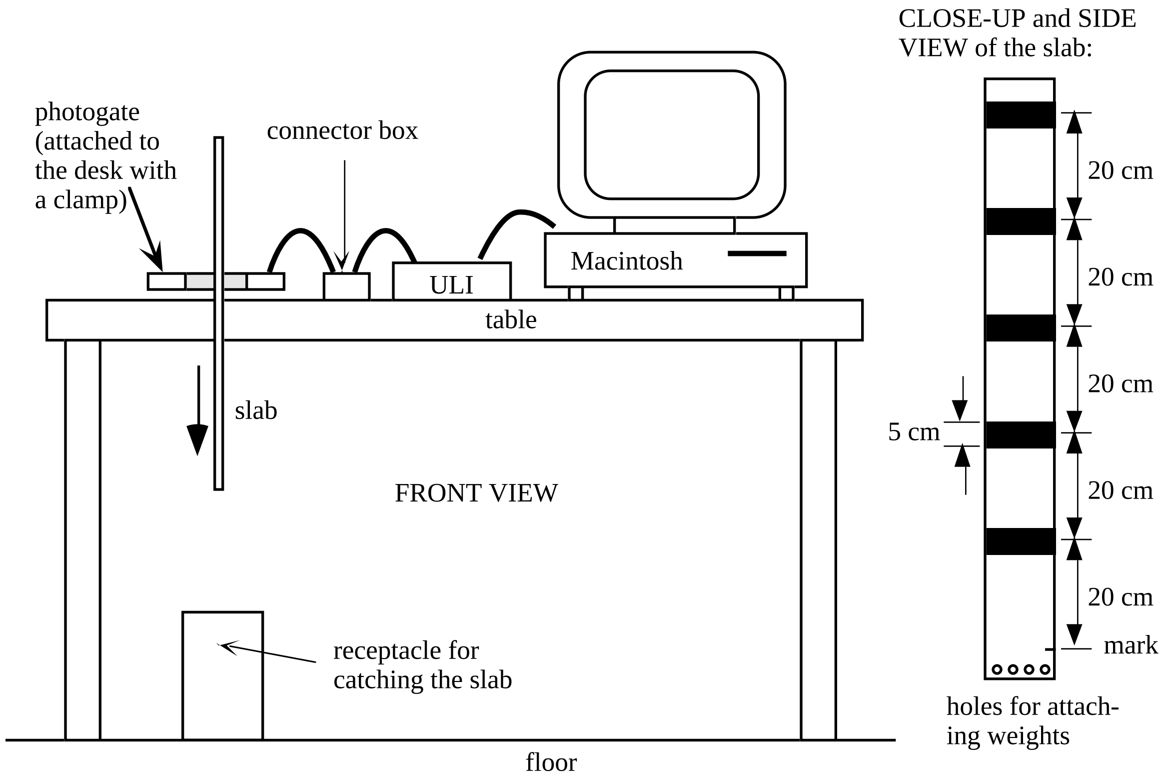

Figure 1: Sketch of the apparatus

After our lab instructor gave a brief demonstration of the equipment, each of the seven lab teams in our particular afternoon session did a run. When our turn came, one of us (M-G.M.) held the center of the upper end of the slab between his thumb and forefinger and adjusted its vertical position until a certain mark inscribed on the slab edge was aligned precisely in the middle of the photogate as reported by IC. We waited until the slab had stopped swinging back and forth and was completely at rest. I.C. then triggered the *ULI Timer* program to start taking data and M-G.M. dropped the slab. The computer then automatically recorded and displayed the time Δt that it took each of the five opaque bands to pass the photogate. We wrote these five numbers on the blackboard, filling in a table already started by other teams.

Once all the data was taken, *each* pair of lab partners calculated the means and uncertainties of the mean (using the techniques in chapters 3 and 5 of the lab reference manual) of the results for Δt for each of the five bands. We discussed the results as a class and decided that these results appeared to be uncertain by very roughly ± 0.002 s.

While we were calculating the means and uncertainties, our pair of partners took turns doing a total of seven more runs, three runs with two weights attached to the slab and four runs with four weights attached to the slab. These runs were also recorded on the blackboard.

Finally, each pair worked individually to analyze the data. As we did this, we passed the slab from pair to pair so that each could check that the opaque bands were 5.0 cm tall and separated from center to center by 20 cm. We did this using an ordinary meter stick turned on its edge so that the scale was right next to and perpendicular to the bands. We estimated that the height of the bands was equal to 5.0 cm to within ± 0.05 cm and that the distances between the centers of the band was 20.0 cm to within ± 0.1 cm (we actually measured these from bottom edge to bottom edge).

ANALYSIS

A table of the mean values of the time intervals appears below:[1]

Band Number	Δt (no added weight)[2]	Δt (one added weights)[2]	Δt (four added weights)[2]
1	0.0252	0.0250	0.0256
2	0.0179	0.0181	0.0179
3	0.0146	0.0149	0.0144
4	0.0126	0.0124	0.0126
5	0.0112	0.0113	0.0110

It is clear from these results that the speed of the slab *is* independent of its mass[3], so (as we argued in the theory section) $V_i - V_f$ must be[4] directly proportional to the slab's mass m.

From the values of Δt for the slab with no added weight, we calculated $\frac{1}{2}v_f^2$ for each of the heights[5]. Figure 2 shows a graph of these results. According to *LinReg*,[6] the slope of the line is 9.81023 and the intercept is 0.012865.[7] This proves[8] that $V_i - V_f = mgh$ (though our value of g is a bit high due to experimental error).[9]

CONCLUSION

In this experiment, we showed that the final kinetic energy per unit mass $\frac{1}{2}v_f^2$ of a plastic slab dropped from rest through a distance h is independent of the mass of the slab and seems to be proportional to h (within experimental uncertainty), with the constant of proportionality being equal to $9.81 \pm 0.03\ \text{m/s}^2$. These results are completely *consistent* with the assertion made in the text that $V_i - V_f = mgh$, where $g = 9.8\ \text{m/s}^2$.

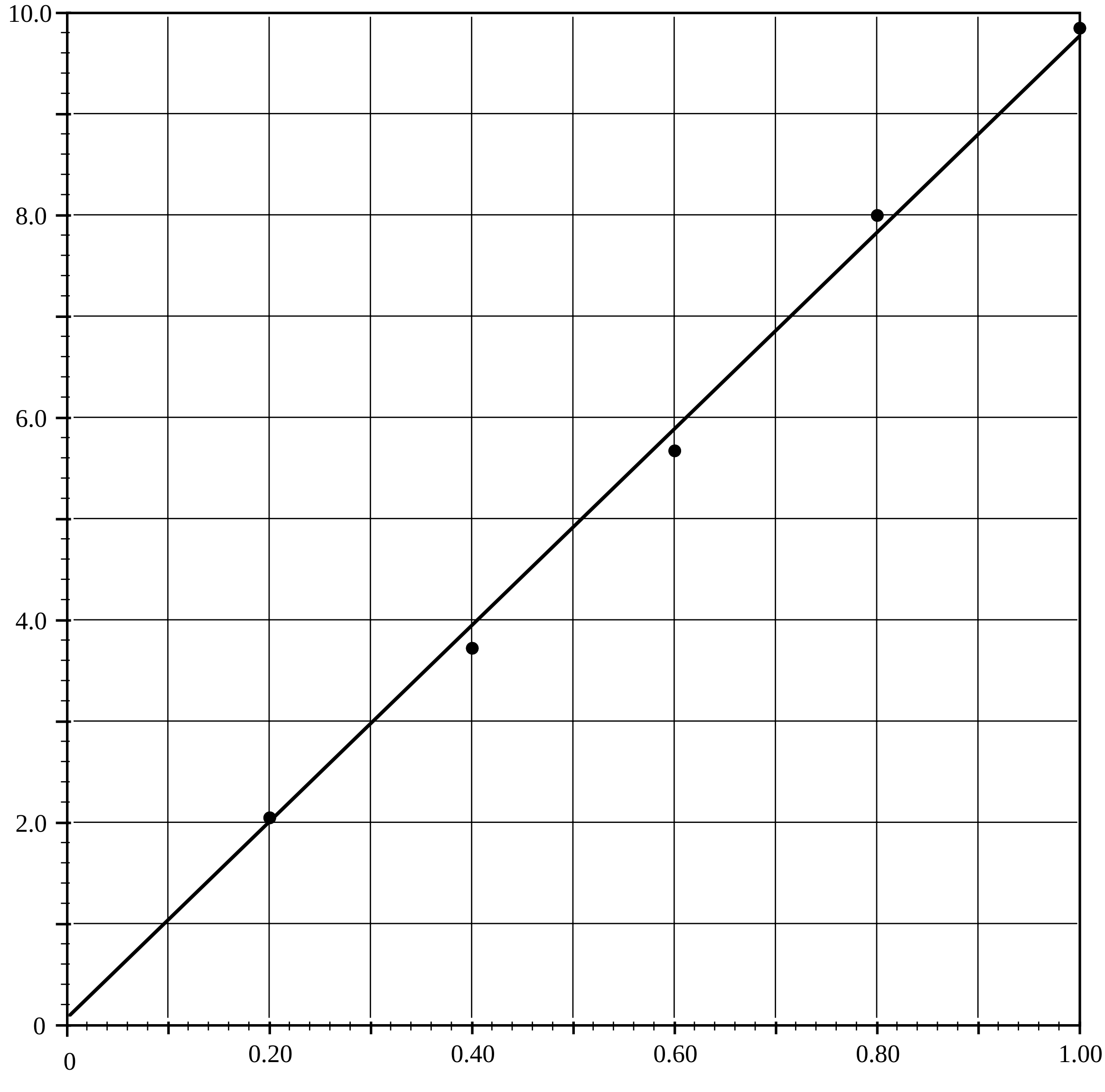

Figure 2.10

COMMENTS ON THE ANALYSIS SECTION

In general, the problem with this section is that it is far too short and thus does not provide us with some information that we need to understand the results and how the authors analyzed them. There are also several statements made that are not or cannot be supported by the data.

Here are specific comments about the places in the analysis section where specific errors were flagged with numerical superscripts. (The simulated errors in this report reflect the *most common* types of errors that people make when writing analysis sections.)

(1) This table is nicely laid out, but a table of processed data like this should state the *units* of the quantities and state the *uncertainties* of the means as well as the means themselves. The writers should have also included a description of how many measurements went into calculating the mean and how the uncertainties were calculated. Also, if the uncertainties are really on the order of ±0.002 s (as stated in the procedure section), then the last digit in the tabulated data is totally meaningless. Are the uncertainties really more like ±0.0002 s (this would be consistent with the variation appearing in the table data)?

(2) One could include the units of the data in the column heading like this: "Δt in seconds".

(3) *Is* this really clear? Without knowing the uncertainties, the small variations in the values are impossible to interpret.

(4) We really can't say that $V_i - V_f$ *must* be independent of m, only that our data is consistent with this interpretation.

(5) This needs to be explained in much more depth. *How* did the writers calculate $\frac{1}{2}v_f^2$ from this data? What are the uncertainties of these speeds, and how were *they* calculated (one has to use something like the weakest link rule)? How were the heights determined and their uncertainties estimated? It would have also helped *greatly* if the writers had listed the calculated values and uncertainties for $\frac{1}{2}v_f^2$ and h for each row of the table (or better yet, on a separate table).

(6) A brief description of *LinReg* and what it does would be appropriate here.

(7) The quantities quoted here have units and uncertainties: what are they? Also what is the significance or meaning of the slope and the intercept here?

(8) An experiment can never *prove* that any theoretical assertion is true. The best that we can say here is that our results are consistent (or inconsistent) with this assertion. See the conclusion for better language.

(9) How is g is related to something we have calculated in this lab? Also, the value is a bit high compared to what? Saying that the difference is due to "experimental error" says nothing. What *kind* of experimental error? Is the result within our uncertainties or not? If so, what does it mean to say that this is "a bit high"?

(10) What are the experimental uncertainties of the data points? Are they not shown because they are too small to appear on the graph or did the writers simply forget about them them? What is being plotted against what here? (The axes should be labeled.) What is this graph about? (It should have a title!) What are the *units* of quantities displayed? What does the line mean? This graph is missing many of the features that a higher-level graph should have.