Laboratory Guidelines

1 Instrumentation

Being both quantitative and experimental, physics is basically a science of measurement. A great deal of effort has been expended over the centuries improving the accuracy with which the fundamental quantities of length, mass, time, and charge can be measured.

It is important that the appropriate instrument be used when measuring. Ordinarily, a rough comparison with a numerical scale, taken at a glance and given in round numbers, is adequate. Increasing precision, though, requires a more accurate scale read to a fraction of its smallest division. The "least count" of an instrument is the smallest division that is marked on the scale. This is the smallest quantity that can be read directly without estimating fractions of a division.

Even at the limit of an instrument's precision, however, accidental errors— which cannot be eliminated—still occur. These errors result in a distribution of results when a series of seemingly identical measurements are made. The best value, known as the most probable value, is the arithmetic mean or average of the measurements.

Other errors, characteristic of all instruments, are known as systematic errors. These can be minimized by improving the equipment and by taking precautions when using it.

1.1 Length Measurement

Three instruments will be available in this class for length measurements: a ruler (one- or two-meter sticks, for example), the vernier caliper, and the micrometer caliper.

1.1.1 The Meter Stick

A meter stick, by definition, is 1 meter (m) long. Its scale is divided, and numbered, into 100 centimeters (cm). Each centimeter, in turn, is divided into 10 millimeters. Thus 1 cm = 10^{-2} m, and 1 mm = 10^{-1} cm = 10^{-3} m.

When measuring a length with a meter stick, different regions along the scale should be used for the series of measurements resulting in an average value. This way, non-uniformities resulting from the meter stick manufacturing process will tend to cancel out and so reduce systematic errors. The ends of the stick, too, should be avoided, because these may be worn down and not give a true reading. Another error which arises in the reading of the scale is introduced by the positioning of the eyes, an effect known as parallax. Uncertainty due to this effect can be reduced by arranging the scale on the stick as close to the object being measured as possible.

1.1.2 The Vernier Caliper

A vernier is a small auxiliary scale that slides along the main scale. It allows more accurate estimates of fractional parts of the smallest division on the main scale.

On a vernier caliper, the main scale, divided into centimeters and millimeters, is engraved on the fixed part of the instrument. The vernier scale, engraved on the movable jaw, has ten divisions that cover the same spatial interval as nine divisions on the main scale: each vernier division is $\frac{9}{10}$

the length of a main scale division. In the case of a vernier caliper, the vernier division length is 0.9 mm. [See Figure 1.]

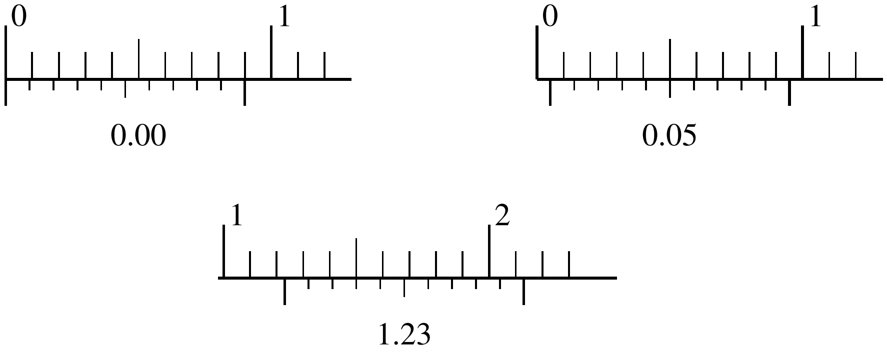


Figure 1: Examples of vernier caliper readings.

To measure length with a vernier caliper, close the jaws on the object and read the main scale at the position indicated by the zero-line of the vernier. The fractional part of a main-scale division is obtained from the first vernier division to coincide with a main scale line. Several examples are shown in Figure 1

If the zero-lines of the main and vernier scales do not coincide when the jaws are closed, all measurements will be systematically shifted. The magnitude of this shift, called the zero reading or zero correction, should be noted and recorded, so that length measurements made with the vernier caliper can be corrected, thereby removing the systematic error.

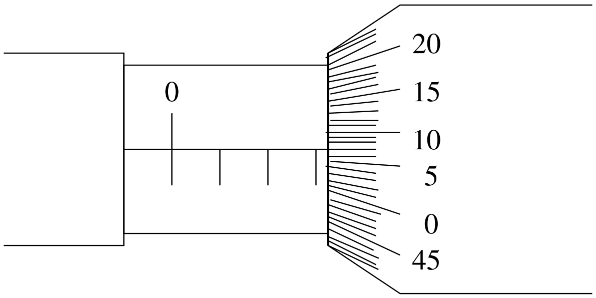
1.1.3 The Micrometer Caliper

A micrometer caliper is an instrument that allows direct readings to one hundredth of a millimeter and estimations to one thousandth of a millimeter or one millionth of a meter (and, hence, its name). It is essentially a carefully machined screw housed in a strong frame. To measure objects, place them between the end of the screw and the projecting end of the frame (the anvil). The screw is advanced or retracted by rotating a thimble on which is engraved a circular scale. The thimble thus moves along the barrel of the frame which contains the screw and on which is engraved a longitudinal scale divided in millimeters. The pitch of the screw is 0.5 mm, so that a complete revolution of the thimble moves the screw 0.5 mm. The scale on the thimble has 50 divisions, so that a turn of one division is $\frac{1}{50}$ of 0.5 mm, or 0.01 mm.

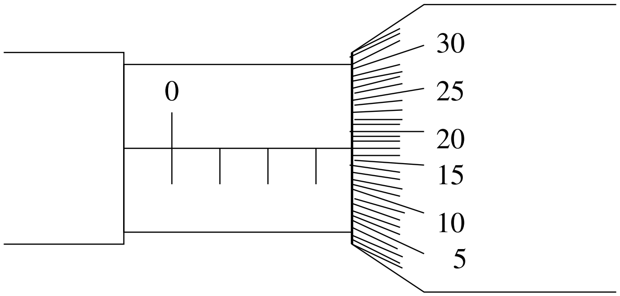
Advance the screw until the object is gripped gently. Do not force the screw. A micrometer caliper is a delicate instrument.

To read a micrometer caliper, note the position of the edge of the thimble along the longitudinal scale and the position of the axial line on the circular scale. The first scale gives the measurement to the nearest whole division; the second scale gives the fractional part. It takes two revolutions to advance one full millimeter, so note carefully whether you are on the first or second half of a millimeter. The result is the sum of the two scales. Two examples are shown in Figure 2.

As with the vernier caliper, the zero reading may not be exactly zero. A zero error should be checked for and recorded, and measurements should be appropriately corrected.



0.307 cm



0.367 cm

Figure 2: Examples of micrometer readings.

1.2 Mass Measurement

Three kinds of instruments will be available to determine mass: a digital scale and two types of balances. The operation of the first instrument is trivial, and so will not be explained here.

Please understand that with each of these instruments we are really comparing weights, not masses, but the proportionality of weight and mass allows the instruments to be calibrated for mass.

1.2.1 The Equal-Arm Balance

The equal-arm balance has two trays on opposite sides of a pivot. The total mass placed on one tray required to balance the object on the other gives the mass of the object. Most equal-arm balances have a slider, as well, that can move along a scale and allow for greater precision than the smallest calibrated mass available. Typically, this scale has 0.5 g divisions.

1.2.2 The Triple-Beam Balance

The triple-beam balance, so-called because of its three slider scales, can be read to 0.1 g and estimated to half that. With an object on the tray, the masses of the different scales are slid to notches until balanced. Get close with the larger masses first and then fine-adjust with the smallest slider.

1.3 Time Measurement

Time measurements in this course will be made either with a computer or with a stop watch. This first is out of your control.

1.3.1 The Stop Watch

The stop watches you will use in class have a time range of from hours to hundredths of a second. There are two buttons at the top: a stop/start button and a reset button. The operation of these should be evident, although once the watch is reset, the reset button also starts the watch (but doesn't stop it). Please be aware of this feature.

1.4 Charge Measurements

The magnitude of charge is among the most difficult measurements to make. Instead a number of indirect measurements are undertaken to understand electric phenomena. These measurements are most often carried out with a digital multimeter.

1.4.1 The Digital Multimeter

The digital multimeters available for laboratory exercises have pushbutton or knob control to select five ac and dc voltage ranges, five ac and dc current ranges, and six resistance ranges. The ranges of accuracy are 100 microvolts to 1200 volts ac and dc, 100 nanoamperes to 1.999 amperes ac and dc, and 100 milliohms to 19.99 megaohms.

To perform a DC voltage measurement, select the DCV function and choose a range maximum from one of 200 millivolts or 2, 20, 200, or 1200 volts. Be sure the input connections used are V-Ω and COMMON. The same is true for AC voltage, regarding range and inputs, but the ACV function button should be selected.

For DC current choose DC MA (for DC milliamperes), while for AC current choose AC MA. Your choices for largest current are 200 microamperes or 2, 20, 200, or 2000 milliamperes. Check that the input are connected to MA and COMMON.

There are two choices for resistance measurement: Kilohms (KΩ) and Megohms (20MΩ). The input connectors are the same as when measuring voltage, namely V-Ω and COMMON. The range switches do not function with the Megohm function, but one of the range buttons must be set. The maximum settings for Kilohm readings are 200Ω or 2, 20, 200, or 2000kΩ.

2 Recording Data

When performing an experiment, record all required original observations as soon as they are made. By "original observations" is meant what you actually see, not quantities found by calculation. For example, suppose you want to know the stretch of a coiled spring as caused by an added weight. You must read a scale both before and after the weight is added and then subtract one reading from the other to get the desired result. The proper scientific procedure is to record both readings as seen. Errors in calculations can be checked only if the original readings are on record.

All data should be recorded with units. If several measurements are made of the same physical quantity, the data should be recorded in a table with the units reported in the column heading.

3 Errors and Uncertainties

Any measurement has an associated uncertainty. In general, if two or more measurements are made of the same physical quantity, they differ. The difference between a measurement and the true value of the physical quantity is the error in the measurement. The true value lies somewhere within a range of values near the measured value. This range of values is called the uncertainty of the measurement. Therefore the error is likely to be less than or equal to the uncertainty. The experimenter's goal is to reduce the error as much as possible while recognizing and specifying the appropriate uncertainty.

The term "error" as used in science should not be confused with "mistake." Errors are inherent in measurements and cannot be avoided. Mistakes can, and should, be avoided.

3.1 Types of Errors

There are two types of errors: random and systematic. A systematic error usually repeats itself with the same sign. That is, all the measurements are either too large or too small. A poorly calibrated instrument, such as a meter stick, voltmeter, or thermometer, will introduce systematic errors. Other types of systematic errors are also possible. For instance, if you tend to always hold your head to one side of a scale, you may introduce a systematic parallax error.

Random errors are associated with fluctuations in repeated measurements of the same physical quantity. These errors are just as likely to be positive as negative. Therefore the effects of random errors tend to cancel when you average the results of repeated measurements. For this reason the average of repeated measurements is assumed to be less uncertain than a single measurement.

"Human error" is not a class of scientific error, and the term should never be used.

3.2 Precision and Accuracy

The precision of a set of measurements of the same quantity refers to the amount by which they differ. If the measurements are very close together the precision is high, while the precision is low if they scatter over a wide range.

Accuracy refers to how close the measured value is to the true value. It is possible for a high precision measurement to have low accuracy if a systematic error is present.

As an example, consider a game of darts between two students, Ryan and Ashley. They each throw three darts resulting in the distributions shown in Figure 1. Ryan's darts show high precision because they are close together, but low accuracy because they are far from the bull's eye. On the other hand, Ashley's darts have lower precision than Ryan's because they are farther apart, but have higher accuracy because they are scattered around the bull's eye.

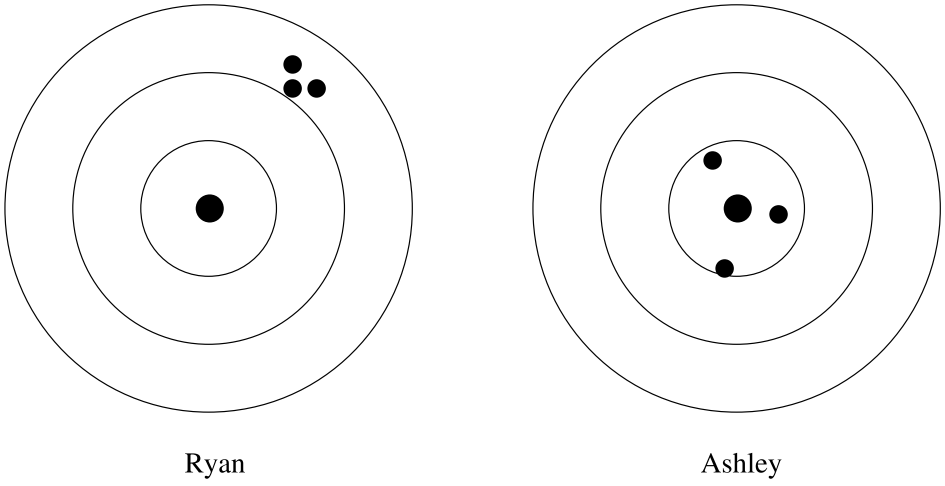


Figure 3: The results of one round in a game of darts between Ashley and Ryan. Ryan's distribution has higher precession but lower accuracy than Ashley's.

3.3 Significant Figures

A laboratory worker must learn to determine how many figures in any measurement or calculation are reliable, or "significant" (that is, have physical meaning), and should avoid making long calculations using figures which he/she could not possibly claim to know. All sure figures plus one estimated figure are considered significant.

The measured diameter of a circle, for example, might be recorded to four significant figures, the fourth figure being in doubt, since it is an estimated fraction of the smallest division on the measuring apparatus. How this doubtful fourth figure affects the accuracy of the computed area can be seen from the following example.

Assume for example that the diameter of the circle has been measured as $0.526\underline{4}$ cm, with the last digit being in doubt as indicated by the line under it. When this number is squared the result will contain eight digits, of which the last five are doubtful. Only one of the five doubtful digits should be retained, yielding a four-digit number as the final result.

In the sample calculation shown below, each doubtful figure has a short line under it. Of course, each figure obtained from the use of a doubtful figure will itself be doubtful. The result of this calculation should be recorded as 0.2771 cm^2, including the doubtful fourth figure. (The zero to the left of the decimal point is often used to emphasize that no significant figures precede the decimal point. This zero is not itself a significant figure.)

$$(0.526\underline{4}\ \text{cm})^2 = 0.277\underline{09696}\ \text{cm}^2 = 0.277\underline{1}\ \text{cm}^2$$

Very large or very small numbers should always be recorded using scientific notation. For example, the proper way to record the area calculated above in $\text{m}^2$is $2.771 \times 10^{-5}\ \text{m}^2$. All of the figures, including the zeros, are significant in a measurement properly recorded using scientific notation.

There are several rules that must be kept in mind when determining the appropriate number of significant figures to record in reporting a result:

1. In multiplication and division, a calculated result should contain the same number of significant figures as the least that were used in the calculation.
2. In addition and subtraction, do not carry a result beyond the first column that contains a doubtful figure.
3. Zeros that serve only to locate the decimal point are not significant.

3.4 Expressing Uncertainties

An experimental determination of the quantity x that has a mean (or average) value $\overline{x}$ and an uncertainty Δx should be expressed as

$$x = \overline{x} \pm \Delta x. \tag{1}$$

For example, suppose you measure the diameter, D, of a circle with a meter stick and get 3.42 cm. The "2" is a doubtful digit because it was obtained by estimating between the smallest divisions (mm) on the scale of the meter stick. In the absence of additional information, the measurement must be assumed to have an uncertainty of at least 0.01 cm and the measurement would be recorded as

$$D = 3.42 \pm 0.01\ cm. \tag{2}$$

In a later section we will discuss more sophisticated ways of finding uncertainty from multiple measurements of a physical quantity.

3.5 Propagation of Uncertainties

Often in the laboratory you will use a measured quantity to calculate another quantity and you will have to determine the error associated with the calculated quantity due to the error in the measured quantity. The uncertainty in the calculated quantity can be determined using calculus.

In general, if a physical quantity f is a function of x,

$$f = f(x), \tag{3}$$

then the uncertainty Δf in f is defined as

$$\Delta f = \frac{df}{dx}\Delta x, \tag{4}$$

where Δx is the uncertainty in x.

This may be extended to physical quantities that are functions of several variables. If a physical quantity f is a function of two variables x and y, for example, then

$$f = f(x, y), \tag{5}$$

$$df(x, y) = \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy, \tag{6}$$

and

$$\Delta f = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial y}\Delta y. \tag{7}$$

In many cases the uncertainties Δx and Δy will be uncorrelated and Eq. (7) will yield an overestimate of the uncertainty in f because Δx and Δy can compensate for each other. Therefore, it is usually best to add the terms in quadrature and determine the uncertainty in f using the expression

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial f}{\partial y}\right)^2 (\Delta y)^2}. \tag{8}$$

The relative uncertainty is the ratio of the magnitude of the uncertainty to the magnitude of the quantity (e.g. $\Delta f / f$). The percent uncertainty is just the relative uncertainty $\times$ 100%.

As an example, suppose you measure the diameter, D, of a circle to be 2.00 ± 0.02 cm and you want to calculate the area of the circle. First, notice that the relative uncertainty in the diameter is 0.01 and the percent uncertainty is 1%. The area of the circle is

$$A = \pi r^2 = \pi \left(\frac{D}{2}\right)^2 = \frac{1}{4}\pi D^2 = \frac{1}{4}\pi(2.00\,cm)^2 = 3.14\,cm^2. \tag{9}$$

To find the uncertainty in the area, we apply the technique described above:

$$\frac{dA}{dD} = \frac{1}{2}\pi D \tag{10}$$

$$dA = \frac{1}{2}\pi D dD \tag{11}$$

or

$$\Delta A = \frac{1}{2}\pi D \Delta D = \frac{1}{2}\pi(2.00\,cm)(0.02\,cm) = 0.06\,cm^2. \tag{12}$$

So, the final result for the area would be recorded as

$$A = (3.14 \pm 0.06)\,cm^2. \tag{13}$$

This gives us a relative uncertainty in the area of about 0.02 or a percent uncertainty of about 2%.

3.6 Statistical Analysis

Any measurement is an intelligent estimation of the true value of the quantity being measured. To arrive at a "best value" we often make several measurements of the same quantity and then analyze these measurements statistically. The results of such an analysis can be represented in several ways. Those in which we are most interested in this course are the the mean, standard deviation, and standard deviation of the mean.

3.6.1 Mean

The mean is the sum of a number of measurements of a quantity divided by the number of such measurements, which is just the arithmetic mean or the so-called average. For a group of N measurements, x_i, the mean, $\overline{x}$, is defined by

$$\overline{x} = \frac{\sum x_i}{N}. \tag{14}$$

It represents the most probable value of the measurement.

3.6.2 Standard Deviation

The standard deviation, σ, is a measure of the spread of the data about the mean value. The equation for calculating the standard deviation is

$$\sigma = \sqrt{\frac{\sum_i \left(x_i - \overline{x}\right)^2}{N-1}} \tag{15}$$

where x_i are the individual measurements, $\overline{x}$ is the mean, and N is the total number of measurements.

3.6.3 Standard Deviation of the Mean

A related quantity is the standard deviation of the mean, σ_m, defined as

$$\sigma_m = \frac{\sigma}{\sqrt{N}}$$

where $\sigma$is the standard deviation and N is the number of measurements. If the distribution of the measurements is normal (i.e. Gaussian), then there is a 68% chance that the true value falls within the interval $\overline{x} \pm \sigma_m$. While few measurements sets are truly normal distributions, this is a reasonable approximation for bell-shaped distributions. In this course we will assume that the uncertainty in a quantity determined from a set of measurements is the standard deviation of the mean, σ_m, and that the measured value should be reported as $\overline{x} \pm \sigma_m$.

3.6.4 Standard Deviation of the Mean of a Function

Some physical quantities are not measured directly, but rather are computed from other quantities which are directly measured. The following is a general prescription for calculating the standard deviation of the computed quantity from the standard deviations of the measured quantities.

Let z be a function of x and y,

$$z = f(x, y), \tag{16}$$

where x and y are directly measurable. Suppose x and y have been measured several times each, and that their mean values, $\overline{x}$ and $\overline{y}$, and standard deviations of the means, σ_{mx} and σ_{my}, have been computed. The mean value of z can be calculated using

$$\overline{z} = f(\overline{x}, \overline{y}), \tag{17}$$

and the best estimate of the standard deviation of z is computed from

$$\sigma_{mz} = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 \sigma_{mx}^2 + \left(\frac{\partial z}{\partial y}\right)^2 \sigma_{my}^2}. \tag{18}$$

The final result should be reported as

$$z = \overline{z} \pm \sigma_{mz}. \tag{19}$$

The extension of this procedure to functions of more than two variables is straightforward.

As an example, suppose we have made several measurements of the length l and radius r of a cylinder and we want to calculate the volume, V. Four measurements of the length yielded 16.45, 15.95, 17.02, and 16.00 cm, and six measurements of the radius gave 3.29, 3.17, 3.19, 3.62, 3.43, and 3.28 cm. Calculations of the mean and standard deviation of the length measurements yield $\overline{l}$ = 16.4 cm and σ_{ml} = 0.1 cm, and for the radius measurements we get $\overline{r}$ = 3.33 cm and σ_{mr} = 0.03 cm. We can calculate the average volume using the formula for the volume of a cylinder

$$\overline{V} = \pi\overline{r}^2\overline{l} = 571\,cm^3 = 5.71 \times 10^2 cm^3. \tag{20}$$

The standard deviation of the volume can be calculated using

$$\sigma_{mV} = \sqrt{\left(\frac{\partial V}{\partial l}\right)^2 \sigma_{ml}^2 + \left(\frac{\partial V}{\partial r}\right)^2 \sigma_{mr}^2}, \tag{21}$$

where

$$\frac{\partial V}{\partial l} = \pi r^2 = 34.8\,cm^2, \tag{22}$$

and

$$\frac{\partial V}{\partial r} = 2\pi r l = 343\,cm^2, \tag{23}$$

so that

$$\sigma_V = \sqrt{(34.8cm^2)^2(0.1cm)^2 + (343cm^2)^2(0.03cm)^2} = 11\,cm^3. \tag{24}$$

Thus, the final result for the volume is

$$V = (5.7 \pm 0.1) \times 10^2 cm^3. \tag{25}$$

4 Comparing Measured and Accepted or Predicted Values

Often one wishes to compare the value of a quantity determined in the laboratory with the best known or "accepted value" of the quantity obtained through repeated determinations by a number of investigators or with a value predicted by theory. A quantitative way to do this is to calculate the percent difference. The % difference is calculated by subtracting the accepted value from your value, dividing by the accepted value, and multiplying by 100. If your value is greater than the accepted value, the % difference will be positive. If your value is less than the accepted value, the % difference will be negative. The % difference between two values in a case where neither is an accepted value can be calculated by choosing one as the accepted value.

It is also often appropriate to state whether the accepted or predicted value lies within the uncertainty of your measured value. If not, there may be a systematic uncertainty present that has not been taken into account.

5 Lab Reports

Formal lab reports should follow a standard format with several clearly marked sections. The first page should contain the title, your name and the names of your lab partners, and the date. The rest of the report should have the following sections, in order: Abstract, Introduction, Experimental Procedure, Results, Discussions/Conclusions, and References. You should assume that your readers are at the same level in physics as you, but that they have not read your lab manual or handouts.

5.1 Sections of the Lab Report

5.1.1 Abstract

Summarize your experiment in one short paragraph. State the purpose, the experimental method, and the result. Be concise–for example, often just giving the name of the method is sufficient. If you have made a quantitative measurement of some quantity, state the result of the measurement, with uncertainty. Remember to include the appropriate units on any results that you present. The abstract should be self-contained and there should be no references to figures or tables in the main body of the report.

5.1.2 Introduction

Discuss any relevant theory and/or motivation for the experiment. This section serves primarily to help the reader understand the significance of the experiment and all the issues that are later addressed. The main questions to be addressed in this section of the report are "Why are you doing this experiment?" and "What do you hope to find?"

If the experiment is designed to test a particular physical theory discussed in class, you should describe both the general theory and the particular prediction you're attempting to check in the Introduction. This section is often the most difficult to write, and you may want to try writing this section last, since you want to be sure to introduce any important concepts that are needed for your discussion in later sections.

5.1.3 Experimental Procedure

Describe your experimental set-up (drawings are usually needed) and the method used. Do not just restructure the instructions in the lab handout, and do not assume that your reader has read the lab handout.

Make sure you describe the apparatus before referring to parts of it. A Procedure section which starts out "We moved the cart back and forth on the track and recorded the position with the sensor" will be incomprehensible to a reader who was not in your class. You need to tell the reader that the apparatus consisted of a cart, a track, and a sensor, and also what kind of cart, track, and sensor you used. Including a sketch of the apparatus is not sufficient description; you must also describe the apparatus briefly in words.

Do not include unimportant details, such as where a particular switch is, what combination of keystrokes and mouse-clicks you use to do something in Science Workshop, or how you line up your head to see that something is aligned. In particular, you do not need to include steps like "Then we made a graph of position vs. time and printed the graph out"– inserting the graph of position vs. time in the lab report is sufficient. It's also not necessary to identify the software packages used to generate graphs and tables, though it is important to identify the software used to acquire data. For example, "We recorded the position as a function of time using the Science

Workshop package" is important, while "We entered numbers into a data table in Microsoft Excel" is not.

Explain what you did in the course of the experiment, but don't write the procedure section like an instruction manual. Use the most direct descriptions possible, writing in past tense and active voice. For example, it's better to write "We measured the length of the track using a meter stick" than "The length of the track was measured with a meter stick" or "Use a meter stick to measure the length of the track."

Include measurements that are related to the limitations of the experiment, such as a measure of the amount of error in a particular measurement. You will discuss these errors in more detail in the Results section, but how you measure them and what you measure them to be is relevant to the procedure and so needs to be discussed in this section. They belong in this section because they give a quantitative measure of the accuracy and reliability of the results.

5.1.4 Results

The Results section is where you present your data and calculations, and is the meat of your report. Begin by presenting the raw data. Numerical data should be listed in a table and the table referred to in the text; graphical data (for example, position vs. time plots from Science Workshop) should be presented as figures and referred to in the text. Be sure to include uncertainties in any measured quantities.

After presenting the raw data, discuss any calculations that you made from that data. If there are results of calculations that would be best presented in a table, make sure they are clearly distinguishable from the raw data, either by putting the processed data in a separate table, or by clearly labeling the columns. If there are results that would be best presented in a figure, label the figure clearly, and be sure to refer to it in the text. Be sure to label the tables and figures and to refer to them in the text by name (e.g. "Figure 1", "Table 2"). Don't include a figure without discussing it in the text. Explain the relevance of the figure, and what it tells you about the experiment.

Be sure to include an uncertainty with every measurement. In general the discussion of the measurement of the uncertainty (that is, how you determine the value of the uncertainty) is given in the experimental procedure section, but you still need to give the uncertainty (after a plus-minus sign) when presenting the results. Say "We measured the mass of the cart to be 1.02 ± 0.03 kg," not "The mass of the cart was 1.02."

Discuss your errors in this section. Discuss the sources of error, both random and systematic, and how the errors affect your results. Do not put off the discussion of the error until the Conclusion section.

5.1.5 Discussion/Conclusions

If there are further interpretations of the results or significant implications to be discussed, such a discussion should occur in the Discussion/Conclusions section. You must also summarize the main results of the experiment.

This is where you should discuss the implications of the comparison between experiment and theory (Does your measurement agree with the theoretical prediction? If so, what does that tell you? If not, why not?), or between two different methods of measurement (If you measured the same quantity in two different ways, which measurement was more accurate?). Address any additional ideas you have about the experiment, such as improvements that could be made, or how the experiment relates to the material discussed in class.

5.1.6 References

References should be listed in the order in which they are cited in the report. They should be numbered in square brackets and the numbers should be used when citing the references in the body of the report. For example, to reference the book on experiments in modern physics by Mellissinos and Napolitano you might say "Melissinos and Napolitano [1] have shown that ..." in your report, and list in the reference section "[1] Adrian C. Melissinos and Jim Napolitano, *Experiments in Modern Physics*, Second Edition, Academic Press, 2003." References to journal articles should have the following format: [number] Authors, journal, volume number in bold faced type, page number, (year). For example, "[2] B. A. Mecking *et al.*, Nucl. Instrum. Methods Phys. Res., A **503**, 513 (2003)."

5.2 Additional Guidelines

5.2.1 Figures and Tables

A very common (and annoying) mistake made by students is neglecting to label the figures and tables and/or not referring to them in the text. Figures and tables are crucial components of a science paper and should be able to stand by themselves. They should include a short caption written using complete sentences telling the reader what is being presented. If multiple quantities are plotted in a single figure, the different data sets should be clearly distinguished (using different symbols or line styles, with a key to the symbols or styles included in the caption or on the figure itself). Figures and tables should also be referred to at the appropriate points in the text, to be sure to draw the reader's attention to the data.

Figures and tables should be assigned numbers according to the order in which they appear in the text, and should be referred to by number (e.g., "A graph of velocity vs. time is shown in Figure 1" or "The data for the second trial are shown in Table 2."). Tables and figures are numbered separately–the first figure is "Figure 1," and the first table is "Table 1" regardless of where they appear in the text.

The figure caption should be a short (one or two complete sentence) description of what is in the figure. If multiple quantities are plotted, the caption should identify the symbols used for each. Figures which show the arrangement of experimental apparatus should mention the most important components in the caption, and if curve fits are used, the relevant fit parameters should be mentioned in the caption (e.g.: "The solid line is a linear fit to the data. The slope of the line gives the mass of the cart, m=1.007 ± 0.003 kg.")

5.2.2 Equations

Equations that appear in the text should be put on their own line, and centered in the text. When multiple equations are used in a report, you should number them according to the order in which they appear, and refer to them by number (e.g., "As we see from Equation 1, the force is proportional to the acceleration.").

When you introduce a new equation, you should be sure to define all the symbols in it. For example, if I want to refer to Newton's Second Law, I would write: "The motion of an object is determined from Newton's Second Law,

$$\overrightarrow{F}_{net} = m\overrightarrow{a} \tag{26}$$

where $\overrightarrow{F}_{net}$ is the net force acting on an object, m is the mass of the object, and $\overrightarrow{a}$ is the acceleration of the object."

5.2.3 Writing Counts

Part of the grade for each lab report will be based on the general quality of the writing. This includes elements like grammar, spelling, and proofreading.

As a scientist, you can go into the lab and take data worthy of a Nobel Prize, but if you can't explain the results of your experiments clearly and concisely in written form, you may as well not have done them. The key to all of modern science is reproducibility–for a result to be accepted as the correct result, other experimenters need to be able to reproduce the result. For that to be possible, you need to be able to explain to other researchers all around the world what your results were, how you got those results, and why those results are important. If you can't write clearly, you'll never succeed in communicating your results well enough to get the credit you deserve.

In a similar vein, an engineer is expected not only to design and develop useful technology, but also to convince people that his or her designs are the best. You can have a wonderful design for a cell phone that turns into a submarine, but if you can't explain in writing how it works, what it's good for, and why your cellular submarine design is superior to all other cellular submarine designs, you'll never get anyone to buy it. All the technical skill in the world is useless without the ability to communicate your results to others.

The key to good writing is organization. A lab report, like a scientific paper or an engineering proposal, should have a clear and logical flow of ideas: first explaining the motivation of the experiment, then the procedure, then the results, then the conclusions drawn from those results. The reader should be led smoothly from one idea to the next, not tugged erratically back and forth between procedure, results, motivation and conclusions.

On a finer level, each sentence and each paragraph should have a clear point, and serve to advance the argument being presented. Writing is more than simply stringing together a disjointed collection of unrelated thoughts. "Stream of consciousness" lab reports are confusing and difficult to read, and create the impression that you don't actually know what you're talking about. Such an impression would be disastrous for a scientific paper or an engineering proposal, and will accordingly be marked down in a lab report.

An even more basic element of good writing is proofreading. There is no better way to make yourself look foolish than to turn in a written document with a huge, glaring spelling error in the first paragraph (especially in the current age of automatic spelling checkers in word-processing programs). Before you hand a lab report in, read it over, or have your lab partner read it over. Make sure the report makes sense, and that all the words are spelled correctly and used correctly.

5.3 Academic Honesty

You will work on the lab experiments in groups, and you are always free to discuss your results and the interpretations of those results with your lab partners. Indeed, you are encouraged to discuss your results, and even discuss how best to present the results.

What you hand in as your lab report, however, must be your own work, and only your own work. You are not allowed to copy sections of a report from another person, or to write sections of a report with or for another person. You can proofread your partners' reports, and ask your partners to proofread your report, but any changes made to the text must be made by the person who will hand the report in for grading (i.e., you can neither offer nor accept verbatim re-writes of paragraphs in your report).

Lab reports that are wholly or partly identical will receive a grade of zero, and be referred to the Deans as plagiarized. If you have any questions regarding the limits of acceptable collaboration on lab reports, ask your lab instructor.