PH 121 General Physics Lab Guidelines

Laboratory Practices and Procedures

There is a set of instructions for each laboratory session included in this handbook. Before you come to the lab, you should read the material for the day's lab and familiarize yourself with the specific approach and procedures to be used. For most labs the overall approach is based on carrying out one or more experiments, analyzing the data that you record, and writing some conclusions about the results.

You will work with lab partners, usually in groups of three, to carry out the experimental procedures. Each group of lab partners will have a separate lab station, which will be set up with the instruments and equipment you need. A laboratory instructor will be present to answer your questions and to help if you have difficulties with the equipment. You are encouraged to discuss the experiment as you work, but your analysis and conclusions should represent your individual effort.

Your lab report is expected to be complete, legible, and organized in such a way that your experimental results, analysis and conclusions can be clearly understood.

Although each lab session will have its own instructions and procedures, there are some common methods and principles that must be applied for all lab work. Some of these are discussed in the following pages. You are expected to use these principles consistently for all of your lab work.

Units

Physical quantities, such as length, mass, or time must refer to some system of measurement. For example, if a tank is said to have a capacity of 34, the description is clearly incomplete. Is it 34 gallons, 34 liters, 34 cubic meters, or something else? A number by itself is not enough to define a physical quantity, so it is very important to specify what units go with the number. Many units are named for scientists who made important contributions in a related field. There is an

interesting convention for the usage of names of units derived from proper names: If the unit is spelled out, the name is spelled without a capital letter (*curie*, for example), but if the unit is abbreviated, it is capitalized (*Cu* for curie). Units that are not derived from proper names are not capitalized in either case.

Combinations of units come from the definitions of quantities that connect simple measurements. For example, the density of a solid might be expressed in grams per cubic centimeter. The density ρ is calculated by dividing the mass m by the volume v. So the equation for density is

$$\rho = \frac{m}{v} \tag{i-1}$$

Equation (1) simply states that the density is the mass of a sample divided by its volume. In the example given, the mass is in grams, g, and the volume is in cubic centimeters, cm^3. (The abbreviation *cc* for cubic centimeters, sometimes used in medical applications and some others, is not properly used in physics. Since a cubic centimeter has a volume of 1 cm $\times$1 cm $\times$1 cm, it makes sense to abbreviate this volume by 1 cm^3.)

When two or more quantities are added or one is subtracted from another, they must have exactly the same units. Two apples and seven battleships cannot be added in any way that makes sense. Quantities appearing as exponents must be unitless. In expressions such as $y=Ae^x$, the exponent x cannot have any units associated with it. It must be a pure number, such as π or 7 or 0.1. Multiplication and division, however, may be carried out among quantities with differing units. Dividing 50 meters by 2.5 seconds results in the quantity 20 m/s.

If the units are combined in the same way that the measured quantities are related in equation (1), the density is given in g/cm^3, which is read “grams per cubic centimeter.” Comparing the right-hand side of the equation with the units shows that the quantities and the units have the same general form. Verifying that the units are consistent with the quantities in an equation is a useful way to check the form of the equation and to locate algebraic errors that may have occurred. This kind of test is called *dimensional analysis*.

Scientific Notation

Science is very often concerned with extremely large numbers (for example, astronomical distances or the number of molecules in a gram of matter) and extremely small numbers (the dimensions of atoms and molecules, the duration of very fast events). When writing down numbers for such quantities, it would be not only inconvenient, but also confusing to have to write and keep track of all of the zeros. For instance, a light year is a distance of about 9,447,000,000,000 km. The diameter of an oxygen molecule is about 0.0000000002 m.

A useful way to manage the zeros is simply to count them up and use a symbol to represent them. A ready-made mathematical symbol for this purpose is a power of ten, since we already know that

$10^2 = 100$

$10^3 = 1000$

$10^6 = 1,000,000$

$10^{19} = 10,000,000,000,000,000,000$

and so forth.

It is not quite so obvious that *negative* powers of ten can be used, but they are perfectly valid, as can be seen using logarithms. More directly, they are required for algebraic consistency. Here are some examples of negative exponents:

$10^{-1} = 0.1$

$10^{-3} = 0.001$

$10^{-7} = 0.0000001$

The alert reader will notice that the power of ten is the same as the number places the decimal point is shifted, left or right depending on algebraic sign, from the position immediately following the 1. The general principle of scientific notation is to write one digit before the decimal point and leave off any trailing zeros after the decimal. The result is multiplied by a power of ten to indicate the position of the decimal point. For example, using this notation, we can write the distance of light year as 9.447×10^{12} km, and the diameter of an oxygen molecule as about 2×10^{-10} m.

Arithmetic Operations

When numbers in scientific notation are multiplied, the exponents on the powers of 10 simply add, as in the following case. First, just rearrange and regroup.

$$[3.0 \times 10^4] \times [1.5 \times 10^3] = 3.0 \times 1.5 \times 10^4 \times 10^3$$

$$= (3.0 \times 1.5) \times 10^{4+3}$$

$$= 4.5 \times 10^7$$

When negative exponents are included in the multiplication of two quantities, the exponents are still just added algebraically. You can easily verify, by writing out the zeros, that,

$$[2.1 \times 10^9] \times [3.2 \times 10^{-4}] = 6.7 \times 10^5$$

By similar logic, when numbers in scientific notation are divided, the power of ten in the denominator is subtracted from the one in the numerator. Thus

$$\frac{7.7 \times 10^7}{7.0 \times 10^4} = \left(\frac{7.7}{7.0}\right) \times \left(\frac{10^7}{10^4}\right)$$

$$= \left(\frac{7.7}{7.0}\right) \times 10^{7-4}$$

$$= 1.1 \times 10^3$$

Caution! When two numbers written in scientific notation are added or subtracted, they *must* have the same power of ten attached. In the following example, notice how this is accomplished:

$$1.73 \times 10^6 + 3.225 \times 10^8 = 0.0173 \times 10^8 + 3.225 \times 10^8$$

$$= 3.242 \times 10^8$$

You may be tempted to rely on your calculator to manipulate large numbers, but we encourage you to work through calculations by hand as far as possible. This will help you to develop a feel for the quantities involved and to verify that the result you get from your calculator is reasonable.

Significant Figures

The way the numerical value of a physical quantity is written implies the accuracy of its measurement. For example, if a length is given as 1.32 cm, the actual length could be anywhere between 1.315 cm and 1.325 cm, so the implied accuracy is within ± 0.005 cm. It cannot be assumed that the measurement was any more precise than that. The number 1.32 in this example is said to be accurate to *three significant figures*. If there are no zeros in the quantity, the number of significant figures is simply the number of digits, as in the previous example. But if a string of zeros is included, as in 186,000 or 0.0000437, we require rules to determine their significance.

Zeros before the decimal point

If a number includes an *unbroken sequence* of zeros to the immediate left of the decimal point, and nothing to the right of the decimal point, those zeros are not counted as significant. So the number 186,000 is accurate to only three significant figures. (The decimal point is implied.) A number such as 310,005 has 6 significant figures, because the last digit before the decimal point is non-zero, and therefore requires including all digits that appear to its left.

Zeros after the decimal point

If a number includes an *unbroken sequence* of zeros to the immediate right of the decimal point and preceding the first non-zero digit, those zeros are not counted as significant. The number 0.0000437 mentioned above has only three significant figures. Zeros *following* any non-zero digits are counted as significant. So 0.004550 has 4 significant figures.

Tip: The best way to remember the above rules is that zeros used to set the position of the decimal point are not significant. If a number is properly expressed in *scientific notation* then all expressed digits are significant, since the position of the decimal point is set by the accompanying power of ten. For example, 2.715×10^9 has four significant figures, as does 6.934 and 3.290×10^{-14}.

Accounting for significant figures in measurements and calculations

As suggested above, the number of significant figures written down as a result of a measurement expresses the accuracy of the measurement method and equipment. It is usually not difficult to

determine about how accurate a measurement is. If the experimenter uses a meter stick with closest marks 1 mm apart and measures as carefully as possible by directly viewing the meter stick against the object to be measured, an accuracy within about 0.5 mm can reasonably be assumed. Weighing an object on a digital scale can be assumed as accurate as the digital value displayed.

When calculations involve two or more measured quantities, it is not quite so clear how many significant figures should be included in the result. As a general rule, the "weakest link" criterion applies. That is, the quantity that is most limited in accuracy or precision will normally determine the number of significant figures in the result. The procedure for carrying out the calculation is to include all digits in the computation, and then round the result to the smaller number of significant digits in the input numbers.

Examples

The following calculations illustrate how to treat significant figures for addition of numbers in decimal notation and multiplication in both decimal and scientific notation.

$$36.2 + 1.362 = 37.6$$

$$0.00023 \times 3.1415926535898 = 0.00072$$

$$[3.68\times10^{14}] \times [2.71828\times10^{-12}] = 1.00 \times 10^{3}$$

Notice that in the last example, if we had written the number 1.00×10^3 in the form 1,000 we would imply that only one significant figure is justified, although when it is written in scientific notation it is clearly good for three significant figures. This is an example in which the result cannot be expressed unambiguously without using scientific notation.

Measurements and calculations must be done with proper use of significant figures. Using too many indicates a higher degree of accuracy or precision than can be justified, and using too few gives results that are not accurate enough.

Two final notes:

- Numbers that are purely mathematical (as opposed to results of measurements) such as π, integers that come from a theoretical equation, or conversion factors (sec/min, cm/m, etc.) may be considered absolute and *do not* limit the number of significant figures in a result.
- Calculators and computers usually don't give results in the proper number of significant figures. If, for example, you measure the radius of a circle and use that number to calculate its area, it is practically certain that the calculator will give a result that contains far too many significant figures. You will have to round it to the right number yourself.

Accuracy and comparison

Quantitative comparison of numbers is often required in experimental work. If two or more measurements of a single quantity are made, the reliability of the results can be supported by a close agreement in their numerical values. Two measured quantities can be compared in terms of the difference between the values as a percentage of their average. For two measurements A_1 and A_2, the *percentage difference,* $\Delta_{\%}$ is defined as

$$\Delta_{\%} = \frac{A_1 - A_2}{\left[\dfrac{A_1 + A_2}{2}\right]} \times 100\% \qquad \text{(i-2)}$$

The denominator in this equation is just the average of A_1 and A_2, so the percentage difference is the numerical difference divided by the average value. The factor of 100%, numerically equivalent to 1, converts the result to a percentage.

Note that, ideally, two determinations of the same quantity should be very similar, in which case their average should not differ substantially from either value. In that case, simply dividing by either will give a satisfactory result. Indeed, if two values agree to within some small amount, then taking their difference reduces the number of significant figures to the point where it does

In some experiments the result needs to be compared with an established standard. For example, if the circumference C of a large circular object is measured by wrapping a string around it, and the diameter D is measured with a meter stick, then it would be expected that dividing C by D would result in a number approximating π. The accuracy of the experiment can be determined by calculating the *percentage error, E%*, which is defined as the difference between the measured value M and the established standard value S, divided by S, and, as above, multiplied by 100%.

$$E_{\%} = \frac{M - S}{S} \times 100\% \qquad \text{(i-3)}$$

For the example given, the value found by measurement is C/D and the established standard value is π. Whenever your laboratory instructions direct you to compare two or more quantities, or to evaluate the error in a result, the only correct response is to calculate a percentage error or a percentage difference, whichever is appropriate for the specific case.