Physics 201 Lab 1: Methods for Experimental Physics

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Errors and Precision

There are two different sources of error in all measurements. The first is called *precision*. Precision refers to how fine your measurement scale is. A general rule of thumb is that you can measure to within 1/2 of the finest division on your measuring device. Thus, for example, if your measuring stick has divisions of 1 mm, your precision is ± 0.5 mm. You should not apply this rule mindlessly, however; Even if your measuring stick has 1 inch divisions, you can probably measure things more precisely than ± 0.5 in.

The second is called *measurement error*. It refers to your intrinsic ability to make the measurement with the tools at hand. For instance, even if your ruler were demarked in microns (10^{-6} m), you couldn't measure something to that precision if you had to use your naked eye to do it—you simply couldn't see that well. There are many possible causes for measurement error, and there are no simple rules to tell you how big it is. Usually, you simply have to use your own judgement to estimate it.

When reporting values, the number of significant digits you use should reflect your estimate of the uncertainty (combined precision and measurement error) in your measurement.

Measuring and Scaling an Area

Suppose that you must measure a reasonably large area such as that depicted in figure 1. In this figure, the area is divided up into a square grid, with some remainder in the length and width. If you had a big enough measuring stick, you could measure it directly. But a simpler procedure, and one that is possibly more accurate as well, would be to count the number of whole squares along the length and width, and add in the appropriate remainders.

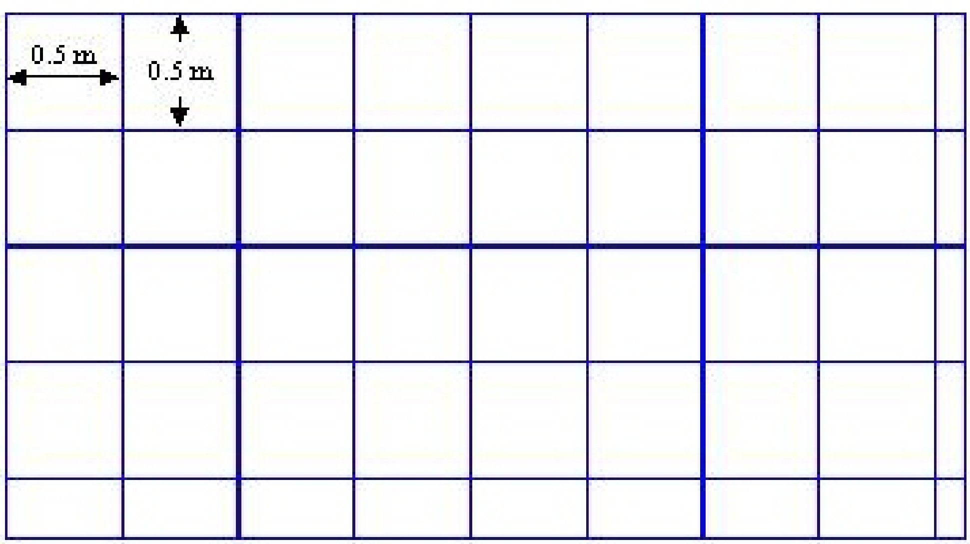

FIG. 1: How to measure and scale areas

For instance, in the figure shown, there are 8-$\frac{1}{4}$ squares along the length, and 4-$\frac{1}{2}$ squares along the width. Since each square is 0.5 m to a side, the length is $l = (8.25)(0.5) = 4.125$ m. Similarly, the width is found from $w = (4.5)(0.5) = 2.25$ m. What about the uncertainty? Suppose you have measured the squares to an accuracy of 2 mm. Since your length contains 8-$\frac{1}{4}$ squares, the uncertainty in the length is

$\Delta l = (8.25)(0.002) = 0.0165 = 0.017$ m. We have left off the final digit (5) because the total uncertainty for 8-$\frac{1}{4}$ squares cannot be specified more precisely than the uncertainty for one square. The uncertainty in the width is $\Delta w = (4.5)(0.002) = 0.009$ m. Note that the number of squares is a whole number, and just because it contains only 1 decimal place, it does not increase your uncertainty, because whole numbers are *exact* numbers. Thus you should report the dimensions of the length and width as $l = 4.125 \pm 0.017$ m and $w = 2.250 \pm 0.009$ m.

What about the area? The area itself is easy: $A = (4.125)(2.25) = 9.2813$ m^2. What about the uncertainty in the area? Concievably, you could have been off in your determination of the area by as much as $\Delta A = l\Delta w + w\Delta l = (4.125)(0.009) + (2.25)(0.017) = 0.075375$ m^2. We could round this either to $\Delta A = 0.08$ m^2, or to $\Delta A = 0.07$ m^2. In the first case, we might overstate our uncertainty; in the latter we might understate it. Therefore, we choose to include the second figure to be more precise about our uncertainty, so that we take $\Delta A = 0.075$ m^2. It doesn't make any sense to be more precise than this. Since you are uncertain in the area by at least 0.075 m^2, it makes no sense to report the last decimal (3) of your area, because your uncertainty is much larger than this. In general, you should report your result to the same precision as you report your uncertainty. Therefore, you would report your area as

$$A = 9.281 \pm 0.075 \text{ m}$$

This involves a lot more thinking than simple rules about how many digits to keep, but it is a more precise rendering of your state of knowledge of the area, and that is what other scientists reading your results need to know.

Graphing Data

In this course, you will be making all of your graphs by hand. For this reason, you must purchase a supply of graph paper for use in lab and bring this paper with you to every lab. When graphing data, there are some simple, but very important rules and conventions that you should always follow.

Conventions: The horizontal axis (sometimes called the"x-axis") is known as the *abscissa*. The vertical axis (sometimes called the "y-axis") is known as the *ordinate*. The reason that it is preferable to use the terms abscissa and ordinate rather than "x-axis" and "y-axis" is that sometimes we might wish to plot a variable called x on the vertical axis or a variable called y on the horizontal axis. Rather than saying "Plot x on the y-axis.", or "Plot y on the x-axis", it is less confusing to say "Plot x on the ordinate." and "Plot y on the abscissa." If you are comfortable enough with the idea of variables to use x-axis/y-axis language, then that's fine, but in this lab we will use the terms abscissa/ordinate or horizontal/vertical just so there is no confusion.

The instructions "Plot the mass vs. the frequency" and "Plot the mass as a function of frequency" both mean the same thing: Plot the mass on the ordinate (vertical axis) and the corresponding values of the frequency on the abscissa (horizontal axis).

Rules: You must always label the graph axes so that anyone viewing your graph can readily apprehend what you have plotted. Your labels should include the units associated with the quantities plotted on each axis. Your graph should also include some kind of title that describes the relationship between the quantities plotted on the graph. In addition, you must properly scale your axes so that the relationship your graph explores is apparent to the viewer.

Scaling your graph: You should always adjust the scale and starting point of your axes so as to use as much of the page as possible. If all of your data is scrunched up into a tiny corner of your graph, you will not be able to see significant features of the data; the way one variable depends on the other, for instance.

Properly scaling your data is easy. Note that it is not necessary to use the same scale for both axes; in general you will use different scales. Neither is it necessary for both scales to have the same origin, nor is it necessary for either scale to include the zero point. For each axis, you should:

- Determine the lowest and highest values for your data.

fat content grams/liter	population change %
520	-3.2
590	-1.0
680	1.1
770	2.7
850	5.2

TABLE I: Effects of dietary fat on wallabee population

- Choose the lower and upper limits of your scale so that the lower limit is smaller than the lowest value of your data and the upper limit is larger than the highest value. You should also choose the limits so that the difference between them is an easy number to divide up.

As an example, consider Table 1, which gives the yearly percentage change in population of a group of wallabees (on a wallabee farm) as a function of fat grams per liter in the wallabee feed they are given.

In order to determine the functional relationship between population change and dietary fat, I might plot the population change vs. feed fat content. I would scale the abscissa axis so that it goes between 500 and 900 and the ordinate axis so that it runs between -3.5 and 5.5. The resulting graph is shown in figure 2

FIG. 2: How to plot data

Finding the equation describing linear data: If the data you plot on your graph seem to follow a straight line, it may be that a linear relationship exists between the variable on the ordinate axis and the variable on the abscissa. If we call the ordinate variable q and the abscissa variable t, then the equation of the line relating q and t is

$$q = at + b$$

where the parameter a is called the *slope* of the line and the parameter b is called the *intercept*. Oftentimes the physics information in an experiment can be extracted by determining these two parameters. There are three steps:

1. *Draw the "best" straight line through the data.* The best straight line through your data is *not* a line through the endpoints. In fact, the best straight line may not even go through *any* of your data points. The best straight line is the line that, on average, is closest to all of the points. There are many ways to interpret this last statement. Most computer programs interpret it by performing a least squares regression on the data; the least squares regression defines "closest on average" as the line that minimizes the sum of the squared distance between the data and the line. Since you are doing all your graphs *by hand*, you will draw the best straight line *by eye*.

2. *Determine the slope.* The slope of a straight line is defined as the ratio of the rise—or change along the ordinate axis—to the run—change along the abscissa—for any segment of the line. The larger a segment of your line you use, the more accurate will be your determination of the slope. Remember that the units of the rise and run are the same as the units used on the ordinate and abscissa axes, respectively. Figure 3 shows a best straight line through the wallabee population data, along with a calculation of the slope.

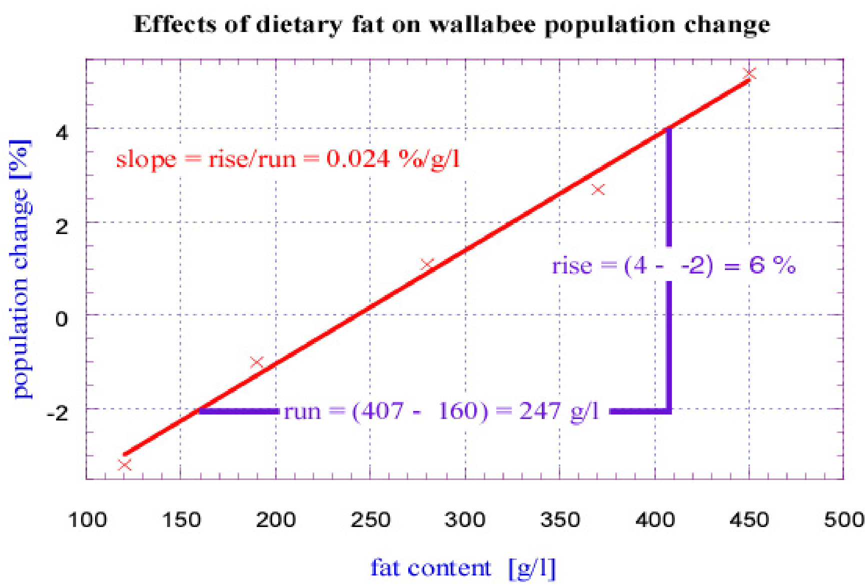

FIG. 3: How to find the slope of a straight line

Finding Means and Deviations

The mean: To find the *mean* or *average* value of a number of measurements, add all the values and divide the result by the number of measurements you are adding together. For example, if you made three different measurements of the length of a piece of pipe, and the values were $l_1 = 10.4$ cm, $l_2 = 10.2$ cm, and $l_3 = 10.5$ cm, then the average of your measurements is

$$\langle l \rangle = \frac{l_1 + l_2 + l_3}{3} = \frac{10.4 + 10.2 + 10.5}{3} = 10.4 \text{ cm}$$

Note that the number of significant digits in the average is the same as the number of significant digits in the measurements themselves.

The root-mean-square (rms) deviation: The rms deviation is the standard statistical measure of how alike different measurements of the same quantity are. It is equal to the square root of the average of the squares of the differences between each individual measurement and the measurement average. Using the example in the previous paragraph of the three measurements of a length of pipe, the rms deviation is equal to

$$\sigma = \sqrt{\frac{(l_1 - \langle l \rangle)^2 + (l_2 - \langle l \rangle)^2 + (l_3 - \langle l \rangle)^2}{3}} = \sqrt{\frac{0.00 + 0.04 + 0.01}{3}} = 0.13 \text{ cm}$$

Note that the rms deviation has the same units as the mean.

The fractional deviation: The fractional deviation between any two numbers is equal to the absolute value of their difference divided by their average. Suppose that the predicted (theoretical) mass of a certain subatomic particle is $m_{\eta_{\text{the}}} = 548.800 \text{ MeV}/c^2$ and the measured (experimental) mass is $m_{\eta_{\text{exp}}} = 550.100 \text{ MeV}/c^2$. Then the fractional deviation between the two determinations is equal to

$$\Delta_{m_\eta} = \left| \frac{\left(m_{\eta_{\text{the}}} - m_{\eta_{\text{exp}}}\right)}{\frac{1}{2}\left(m_{\eta_{\text{the}}} + m_{\eta_{\text{exp}}}\right)} \right| = \left| \frac{-1.3}{549.45} \right| = 0.0024 = 0.24\%$$

In this laboratory, as in the world of professional science, we do not give preference to theoretical predictions over experimental measurements. The fractional deviation is a *value-free* method of expressing the difference between the two, or between any two determinations which are equally likely to be correct. The fractional deviation is dimensionless, meaning that it has no units.

Experimental Procedure

1. Measure the length of three different Hot Wheels cars. Use a metric ruler.
2. Measure the length of three bolts of differing lengths. Use the calipers.
3. Find the mass of the three bolts whose length you measured, using the mass balance.
4. Calculate and report the average length of the cars. Calculate and report the rms deviation of the cars' lengths.
5. Plot the mass vs. length for the bolts. Find and report the slope of the best straight line through your data.
6. Estimate the area of the lab room by measuring and counting the squares on the floor.