Modern Physics Lab

INTRODUCTION

The laws of physics are based on experimental observations of the world around us. Although both theory and experiment are important components in developing our understanding of physics, it is only after a theory has been tested experimentally and found to be true over a wide range of conditions, that we consider it to be a law of physics.

Modern physics covers a very wide range of topics. This class will include labs in optics, nuclear and atomic physics, quantum properties, solid state physics, and other areas. The course will give you an opportunity to observe some of the concepts that were covered in the Modern Physics lectures as well as topics from Junior and Senior level lecture courses.

Experimentalists have many reasons for venturing into the laboratory. Experiments may be needed to test the validity of some theory or model. For an accepted theory, fundamental constants may need to be determined as accurately as possible. Sometimes the rationale is simply to explore the unknown - to find whether a relationship exists between two parameters and determine what that relationship might be.

Modern experimental science has advanced far beyond the simple world of wax, tape, and string (although all three are still very useful). Today's experimental laboratories often contain hundreds of thousands of dollars worth of equipment. As one of my theoretical colleagues has observed in comparing the cost of theoretical and experimental physics: "It is cheaper to just believe". When working with equipment in the lab, we need to be very careful. The equipment is by no means indestructible and the budget may not be available to replace or fix broken equipment. If you are ever in doubt, ASK!

Planning experiments

When entering the lab, it is important to have a good idea what you plan to do. Designing an experiment requires consideration of several factors. One obvious limitation is the equipment that is available to you. The accuracy desired in the measurement must be identified to determine whether you will be able to do the experiment adequately. Time may also be a factor. Some techniques require much more time than others. For large numbers of repetitive measurements, a short time is important. Time constraints from management are a frequent limitation in industrial laboratories.

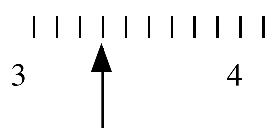
The equipment being used in the experiment should be well understood. Do the numbers on the LED readout mean what you think they mean? Is the equipment properly zeroed ? (Does it read zero when there is no input?) Is the equipment properly calibrated ? It is often worthwhile to check the zero and calibration of equipment by testing it with known inputs.

Data analysis

Significant figures

When making a measurement you are always limited in the number of digits you record. The equipment readout may be XXX.XX. This indicates that you know the number to the hundredths place. In any future calculations, you are limited to reporting your results to no better than the hundredths place. Calculators and computers often give you numbers to 8 or 10 decimal places, but only the smallest number of decimal places which you recorded during the experiment is significant. So you must round off your calculator result to the actual number of significant figures in your measurements. Typically if the next decimal place after your significant figures is < 5, you round down. If it is ≥ 5, you round up.

For non-digital readouts, you can estimate one decimal place beyond the actual scale. For instance, consider a ruler marked in millimeters.



You can estimate that a measurement at the mark is about 3.32. You now have two significant figures beyond the decimal point.

Mean value and standard deviation

When you repeat a measurement, you may (and, almost always, will) get different values for the quantity being measured. We can define the mean value, x, of the quantity as

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$

where N is the number of measurements make and x_i is the value recorded in the ith measurement. To measure the spread in the data about this mean value, we define the standard deviation, σ, as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \overline{x})^2}{N-1}}$$

For a large number of measurements (large N) the data can be approximated by a normal distribution.

The most likely value of the data in a normal distribution is the mean value. We can calculate that

68.0% of the data points are within σ of x
95.0% of the data points are within 2σ of x
99.7% of the data points are within 3σ of x

This information can be used to identify data points which may be resulting from instrumental or operator error. Since 99.7% of the data lies within 3σ of the mean, if a data point lies more than 3σ away from the mean it is probably a measurement error and not a true data point.

We usually report x, so we are interested in the deviation of the mean values. In other words, if we measured another data point, where would x move to. This quantity is the standard deviation of the mean, , and it is defined by

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

If we measure x a total of N times and N is large, we can be

68.0% confident that the actual value of x is in the range $\overline{x} \pm \sigma_m$
95.0% confident that the actual value of x is in the range $\overline{x} \pm 2\sigma_m$
99.7% confident that the actual value of x is in the range $\overline{x} \pm 3\sigma_m$

Experimental error

In discussing experimental error it is important to keep in mind the ideas of *accuracy* and *precision*. Accuracy is a measure of how close your measurement is to the actual value. Of course, you do not know the actual value or you would not be making the measurement. Precision is an indication of how reproducible your measurements are. A good analogy is arrows shot at a target. The accuracy measures how close to the bull's eye your arrows are. The precision measures how closely grouped on the target your arrows are to one another. Clearly you can have excellent precision but poor accuracy.

Two types of errors in experimental physics are *accidental* and *systematic* errors. Accidental errors are the random errors arising from uncontrolled factors. These are always present, even in the best experiments. The only way to reduce them is to design a better experiment. The other type of error, systematic error, involves factors which can be controlled. We can divide systematic errors into three types: instrumental, external, and observational. Instrumental errors involve problems with your equipment (not zeroed, not calibrated, not working). An example of instrumental error would be measuring lengths with a short meterstick. External errors are uncontrolled influences which tend to change your results in a non-random manner. An example of external error would be making length measurements with a meterstick in a hot room where the temperature has caused the stick to expand. Observational errors involve faulty methods of observation or bias of the observer.

Whenever you make a measurement you should report an error range for the result. If you made enough repetitive measurements you can use σ or σ_m as an error estimate. If not, estimate your error from the limitations of your instrument. For instance, in the example of the meterstick measurement earlier of 3.32 cm. We might estimate our error as $\pm$ 0.01 cm.

If you measure several different parameters and have a different error for each parameter, and now need to calculate a number from those parameters, there are specific rules for combining the errors to arrive at the error in your final calculated value. Suppose you measure the parameters B and C with errors δ_B and δ_C. You use them to calculate a final value A with an unknown error δ_A. The following rules apply for finding A and δ_A.

Addition:	$A = B + C$	$\delta_A = \delta_B + \delta_C$
Subtraction:	$A = B - C$	$\delta_A = \delta_B + \delta_C$
Multiplication:	$A = B \times C$	$\delta_A/A = \delta_B/B + \delta_C/C$
Division:	$A = B/C$	$\delta_A/A = \delta_B/B + \delta_C/C$
Powers:	$A = B^n$	$\delta_A/A = n\, \delta_B/B$
Logarithms:	$A = \log B$	$\delta_A = \delta_B / B$
Exponents:	$A = e^B$	$\delta_A = \delta_B\, e^B$

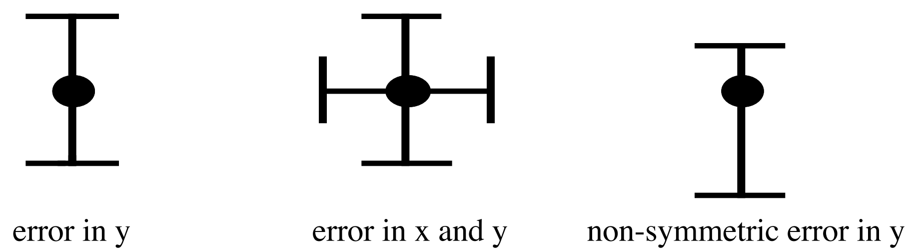
These formulas assumed that some systematic errors might still be present. If you manage to eliminate systematic errors (so all errors are random), you can do slightly better. For random errors:

Addition and Subtraction: $\delta_A = \sqrt{\delta_B^2 + \delta_C^2}$

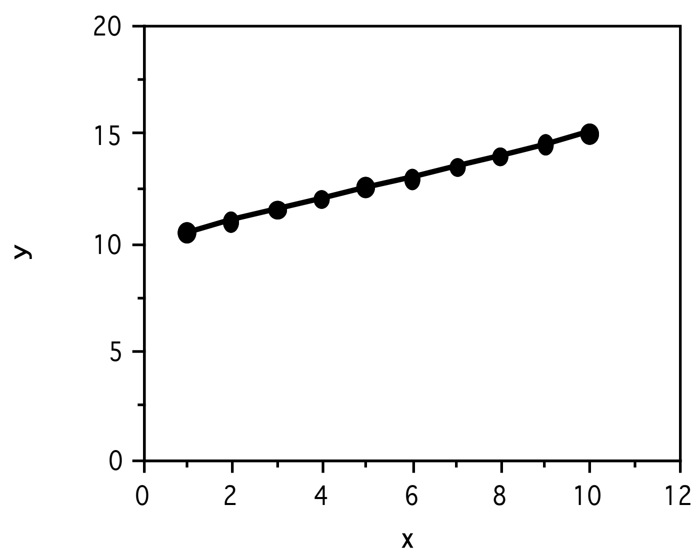
Multiplication and Division: $\frac{\delta_A}{A} = \sqrt{\left(\frac{\delta_B}{B}\right)^2 + \left(\frac{\delta_C}{C}\right)^2}$

graphs

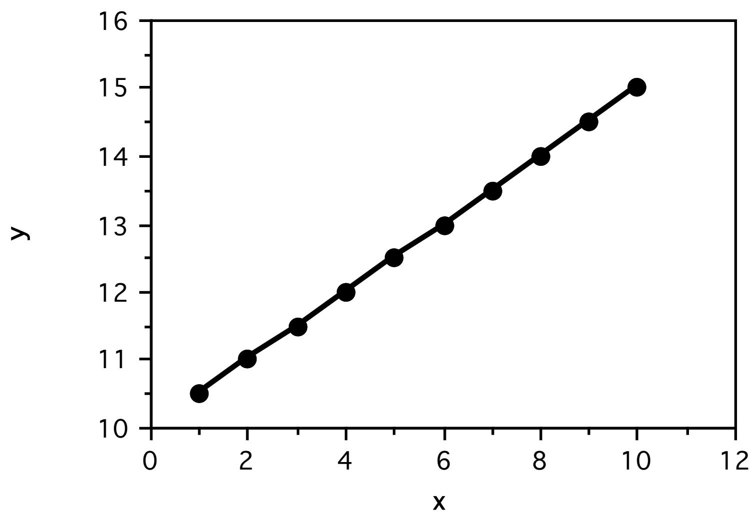
The best way to convey a series of measurements is often in the form of a graph. When plotting points on a graph be sure to make them large enough to see. The error in the data should be represented by error bars. Often these will be just in the y axis direction - but sometimes errors in both x and y need to be included. Often the error bars are symmetric, but they do not have to be.



Graphs should always fill the paper. Adjust the scales on the axes to make optimum use of space.



This graph wastes quite a bit of space by plotting regions where no data exists.



This graph is preferred. It clearly shows the trend without much wasted space on the graph.