Introduction to Measurements

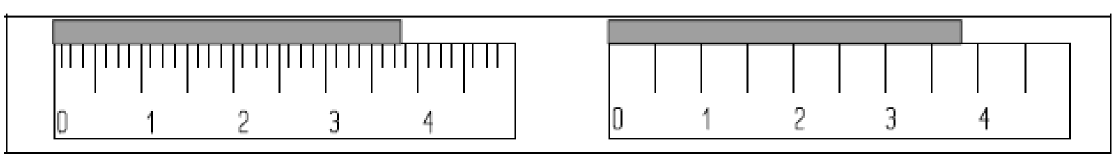
Objectives: To introduce basic measurements and experimental statistics

Equipment: Metric ruler, balance scale, vernier calipers, Pasco density set.

Physics is largely a quantitative science; that is, a science that is concerned with measurement. Anytime we take data in an experiment we would like to know both how accurate our numbers are and what useful information may be gleaned from them. To do this we must determine several things about our data: the degree of precision in our measurements; the difference between our measurements and other measurements obtained in similar experiments; what predictions could be based on our measurements; what statistical patterns our measurements follow. Each of these criteria is important in answering the question, "how good is our data." This is a question that you will have to answer many times throughout this course. The following introduction will acquaint you with the fundamentals of data collection and analysis.

Part 1. Significant Figures

Whenever we take any measurement in an experiment we must first decide upon the precision available with the measurement. The value recorded for a particular measurement generally includes all of the digits that we are sure of plus one additional digit that we estimate (assuming the use of analog equipment requiring an estimate of greatest precision as opposed to digital devices that give a discrete numeric reading). As an example, consider the figure below:



The measurement taken from the scale on the left might be recorded as 3.73 centimeters. The measurement taken from the scale on the right might be recorded as 3.7 centimeters. In the first measurement we are sure of the first and second digits (3 and 7) but have to estimate the third (3). The recorded result contains a single estimated digit. This result has 3 significant figures. In the second measurement we are sure of only the first digit (3), and must estimate the second (7). This result contains a single estimated digit, like the first, but has 2 significant figures.

When experimental measurements are used in calculations (e.g., addition, multiplication, etc.) the result of the operation should be written so that it contains all of the digits that we are sure of and *one* estimated digit. The obvious difficulty is determining exactly how many digits we are sure of. How, exactly, does one go about determining this? Unfortunately, there is no blanket rule that covers every case that you are likely to encounter. The "rules of thumb" given in the following examples, however, may be used as general guidelines:

Addition and Subtraction: Let's use the numbers obtained in the measurement above. These are added below. The estimated digits in each number are highlighted.

3.7**3**
+3.**7**
7.**43**

Notice that if there is an estimated digit in a column of any of the numbers being added (as in the tenths column above), the same column in the sum also contains an estimated digit. Think about it, if there is uncertainty in any one of a series of digits that are being summed, then the sum of these digits must also be subject to the same uncertainty.

The answer obtained in this example contains 2 estimated digits. As before, we wish to express this value in terms of all the digits that we are sure of and 1 estimated digit. In this case, we are sure of only the first digit. After rounding, the sum in this example becomes 7.4, and the number of significant figures in the answer is 2.

In general, the result of an addition or subtraction should not be carried beyond the first column that contains an estimated digit.

Multiplication and Division: To illustrate the rules for these operations, consider the following example:

3.7**3**
x 3.**7**
2611
1119
13801

The first number in this operation (3.73) contains 3 significant figures; the second (3.7) contains 2 significant figures. After rounding, the result of this operation is 14. This answer contains 2 significant figures, the same number of significant figures as are contained in the second multiplier. Notice that this is not the same as 14.0, which contains 3 significant figures, and implies that we are sure of the digit in the units place, which we are not.

Another example:

$$\begin{array}{r} 20.55 \\ \times\ 5.55 \\ \hline 10275 \\ 10275 \\ 10275 \\ \hline 114.0525 \end{array}$$

After rounding, the result of this operation is 114. This answer contains 3 significant figures, the same number of significant figures as are contained in the second multiplier (i.e., the multiplier with the fewest number of significant figures).

In general, the result of multiplication or division should not be carried beyond the first column that contains an estimated digit.

Notice that this is the same rule that applies to addition/subtraction.

Rounding Answers: As seen in the previous examples, it is usually necessary to round off answers in order to preserve the correct number of significant figures. We will adopt the following convention for rounding:

The last digit retained is rounded up if the first digit dropped is equal to 5 or greater.

Part 2. Calculation of Errors, Mean Values, Standard Deviation

Every scientific experiment is subject to a certain amount of experimental error. Researchers in the real world devote a significant portion of their time to data handling and error analysis. You will have to learn the techniques of error analysis to perform the experiments in this lab.

There are two types of errors that you will be concerned with in this lab: random errors and systematic errors. Random errors are unavoidable errors that are always present when one measures to the limit of available accuracy. In one of the first experiments that we will be doing in this lab you will use a stopwatch to time the interval between the first and second bounce of a golf ball. A typical digital stopwatch measures intervals of time to a hundredth of a second. As you collect your data, you will notice that the times you record for the interval between the first and second bounce vary a small amount from trial to trial. This is largely due to your inability to start and stop the watch at precisely the right times. Over a large number of trials the times recorded are equally likely to be too high as too low (i.e., random). Hence, the use of the term random errors.

Systematic errors are errors that cause measurements to be skewed, that is, consistently off in one direction. Systematic errors are often caused by improperly calibrated instruments. If the stopwatch that you use to measure the interval between the first and second bounce of the golf ball is running slow, for example, your measurements of the time interval will be consistently too short.

A type of error commonly encountered by students in physics laboratories is known as a blunder. A blunder can be the result of careless execution of an experiment, incorrect recording of data, a mistake in experimental calculations, a mistake in data interpretation, or all of the above. **A blunder is not an experimental error**. If you measure the interval between the second and third bounce of the golf ball instead of the first and second, you have committed a blunder, not an experimental error

Percentage Error: If an accepted value is available for the quantity being measured, an estimate of the accuracy of the measured data may be obtained by calculating a percentage error, i.e., the percent difference between the measured and accepted values:

$$\%Error = \left(\frac{Measured\ value - Accepted\ value}{Accepted\ value} \right) \times 100\%$$

Notice that the result of this calculation will be either positive or negative depending upon whether the measured value was greater or less than the accepted value.

The measured value used in the percent error calculation may actually be (and most often is) the *mean* of a number of measurements. A mean or *average* value of a set of numbers is obtained by adding up all of the numbers in the set and dividing by the number of items added together. If, for instance one wishes to find the mean or average value of a set of 3 numbers one merely adds the three numbers together and divides the sum by 3.

Whenever a large number of measurements of a quantity are taken, their individual values will always vary, at least by a small amount, due to random errors. One is usually justified in assuming that the average or mean value of the measurements is a more accurate estimate of their value than any of the individual measurements.

Another quantity related to the mean value of a set of measurements is the *standard deviation* of the set. The standard deviation of a data set is a measure of how much, on average, each measurement deviates from the mean of all measurements. Your calculators will compute the standard deviation for any set of measurements.

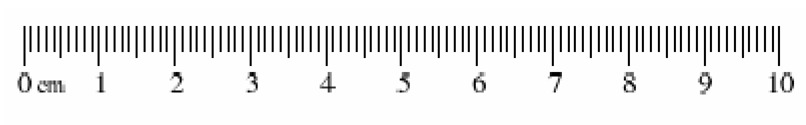
It can be shown that approximately 68% of all the measurements will lie within one standard deviation of the mean of a set of data, 95% within two standard deviations and 99% within three standard deviations. It is customary to record the mean and standard deviation of a set of numbers in the form: mean ±standard deviation.

A relatively large standard deviation generally means that at least some of the measurements in a set of data may be unreliable. If two sets of measurements for the same thing have overlapping standard deviations it indicates that in a statistical sense the measurements are identical.

Part 3. Experimental Measurements

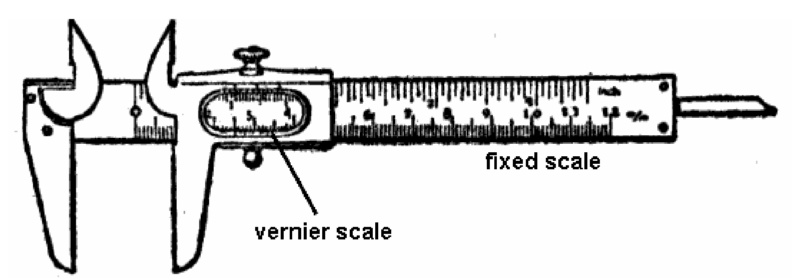
In the course of this lab you will be required to make measurements using a variety of devices. In all cases we'll use the metric system of measurement which is almost universally used in science. We'll take the opportunity here to introduce you to metric rulers, scales, and vernier calipers.

Metric rulers: Meter sticks and metric rulers are fairly easy to read. They deal with meters, centimeters, and millimeters only. Take a look at the following metric scale.



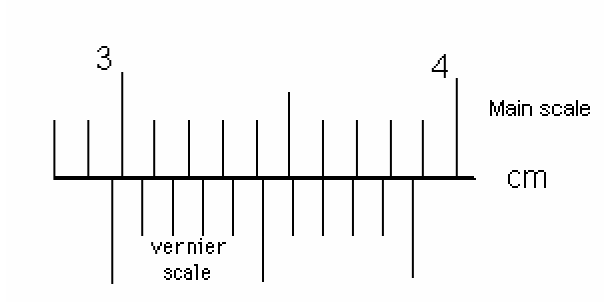
The larger lines with numbers are centimeters, and the smallest lines are millimeters. There are 100 cm in a meter and 10 mm in a cm. Since millimeters are 1/10th of a centimeter, if you measure 7 marks after a centimeter, it is 1.7 centimeters long.

Vernier Calipers: Vernier calipers are also used to measure lengths. Because of the second Vernier scale, you may obtain an extra digit of accuracy compared to a metric ruler.

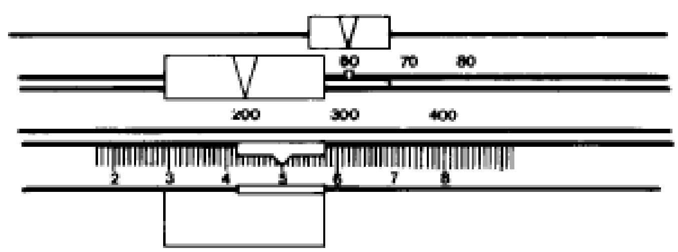


Courtesy of Regents Exam Prep Center

To read the vernier calipers, start with the left end of the sliding or *vernier* scale. The left most line points to a measurement on the fixed or main scale. If it points between two numbers, use the lower value. Now, to get the extra digit of accuracy, find the line on the sliding scale that aligns the best with a line on the fixed scale. For example, in the image to the right, the left most line points between 2.9 cm and 3.0 cm. The seventh line on the vernier scale lines up the best with the line on the main scale. Using the lower value from step one, 2.9 cm, and the 7 for the seventh line, we indicated a measurement of 2.97 cm.



Balance scales: Balance scales are used to determine the mass of an object. To use, place the object on the center of the platform. Starting with the largest capacity beam, move the 500 g poise to the right to the first notch which causes the pointer to drop, then, move it back one notch, causing the pointer to rise. Repeat procedure with the 100 g poise. Slide the 10 g poise to the position which brings the pointer to rest at zero. The mass of the object is the sum of the values of all poise positions.



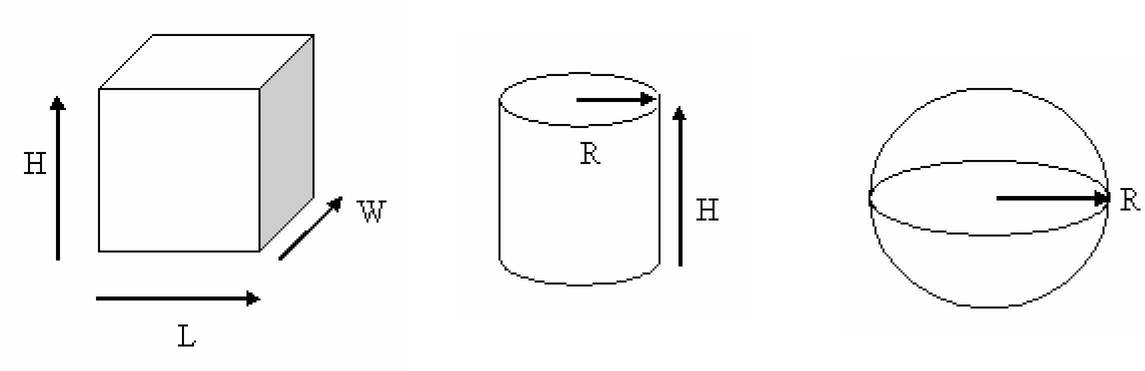
Courtesy of Ohaus

Experimental

In this procedure you will determine the density (ρ) for objects of different sizes, shapes and masses. The density of an object is defined as its mass divided by its volume.

$$\rho = \frac{m}{V}$$

The volume of an object depends upon its geometry.



Volume of a rectangle = $L \times W \times H$

Volume of a cylinder = $\pi R^2 H$

Volume of a sphere $\frac{4}{3}\pi R^3$

Beginning with the rectangles in compartment AB1 of the PASCO density set. measure the mass of each. Using a metric ruler, determine the values for length, width, and height for each. Record your answers in the table below. Calculate the volume and density and record them with the correct number of significant figures in the table below.

Object	**Mass**	**Length**	**Width**	**Height**	**Volume**	**Density**

What is the average value for the density of the metal rectangles (__________)? What is the standard deviation (__________)? If the accepted value for the density is 2.677 g/cm^3, what is your percent error ?

$$\left(\frac{\_\_\_\_\_\_\_\_\_\_ - 2.677\, g/cm^3}{2.677\, g/cm^3} \right) \times 100\% = \_\_\_\_\_\_\_\_\_\_$$

Next, use the cylinders in compartments B3-B6 of the PASCO set. Again, measure the mass and record the value in the table below. Using vernier calipers measure the diameter and height of the cylinders and record the values. Calculate the volume and density and record the values with the correct number of significant figures.

Object	Mass	Height	Diameter	Radius	Volume	Density

What is the average value for the density of the cylinders (__________)? What is the standard deviation (__________)? If the accepted value for the density is 1.400 g/cm^3, what is your percent error?

$$\left(\frac{\_\_\_\_\_\_\_\_\_\_ - 1.400\, g/cm^3}{1.400\, g/cm^3} \right) \times 100\% = \_\_\_\_\_\_\_\_\_\_$$

Last, using the spheres in compartments C3-C6 of the PASCO set, repeat the process.

Object	Mass	Diameter	Radius	Volume	Density

What is the average value for the density of the spheres? What is the standard deviation (__________)? If the accepted value for the density is 1.184 g/cm^3, what is your percent error?

$$\left(\frac{\_\_\_\_\_\_\_\_\_\_ - 1.184\, g/cm^3}{1.184\, g/cm^3}\right) \times 100\% = \_\_\_\_\_\_\_\_\_\_$$

Questions for Thought

1. Do your values match accepted values? Why or why not?

2. Of all the objects measured, which one was the densest? Which one was the least dense?

3. Which measurement limited your accuracy the most?