Physics 111/101---Lab 1: Measurement of fundamental Quantities

Our understanding of the physical universe ultimately depends on measurements of distance, length and time. Such measurements are always subject to some uncertainty. In this laboratory exercise, you will acquaint yourself with some fundamental measurement techniques. You will also be introduced to some elementary methods for treating the errors associated with these measurements.

Specifically, you will:

1- measure length using the meter stick, the vernier calipers and the micrometer;
2- measure mass using the triple beam balance;
3- measure time using a stopwatch and a microcomputer;
4- evaluate two derived quantities: density and velocity.

You will then analyze the error in your data from two complementary scientific perspectives:

1- systematic experimental error vs. random experimental error;
2- experimental precision vs. experimental accuracy.

Error

All measurements are subject to some errors and, in the sciences, we generally subdivide these into two subclasses: systematic error and random error.

Systematic errors occur when our measurements deviate from the true value by a predictable amount. If the speedometer on your car is not properly adjusted, the instrument might underestimate your speed by a constant percentage, or by a constant amount (e.g. 5 mph). In either case, the speedometer would be said to possess a systematic error, since its readings were always different from the true value: in the example above they are always less.

Possible causes for systematic error include improperly calibrated instruments, consistent personal bias in estimating readings, or other effects of unknown, improperly cintrolled variables (for example an electrical circuit might consist of components which are sensitive to small changes in temperature, and whose readings might therefore vary systematically with temperature).

Random errors arise as a result of unpredictable (and often unavoidable) experimental variations. For example, the vibration of your car might cause your speedometer needle to oscillate around the true value of your speed, sometimes reading a little bit above, and sometimes below, but, on average giving you the correct intermediate value.

One frequent cause of random error is the fluctuation of environmental parameters which affect instrumentation such as random fluctuations in temperature, barometric pressure, line voltage or lighting. Other causes can include equipment vibrations and unbiased errors in estimating readings. Note that random and systematic erors can often arise from the same kind of causes; the distinction lies not so much in the physical nature of the cause as it lies in the how it varies and how this variation is related to our measurement.

Precision and Accuracy

Errors lead to results which are not completely correct. In the sciences, we use two terms, precision and accuracy, to express our judgment of the correctness of our results.

The accuracy of an experiment is an evaluation of how closely a result reflects the true, objective value of the quantity being measured. The precision of an experiment is an evaluation of the reproducibility of a result. Generally, experimental **inaccuracy is associated with systematic error**, and experimental **imprecision is associated with random error.**

In measuring the boiling point of water, it is conceivable that you would be using a thermometer which gives a reading at the boiling point of 101 ˚C because it was manufactured incorrectly. Your readings, using this thermometer, would be said to be inaccurate. Likewise, if you failed to correct for atmospheric pressure when you measured the boiling point, you might introduce another kind of inaccuracy. Note how both these errors are systematic in nature.

On the other hand, suppose you made several readings of the boiling temperature, as follows:

100.4 ˚C
101.1 ˚C
99.7 ˚C
100.0 ˚C
98.3 ˚C
99.5 ˚C
99.5 ˚C
101.1 ˚C
98.9 ˚C
100.5 ˚C

The average of these readings is 99.9 degrees. This is close to the accepted value for the boiling point, and the results appear to be randomly scattered about this central value. These results appear to be quite accurate, but there is some unexplained imprecision, perhaps because of problems in estimating the last digit in the temperature, or perhaps because of superheated regions in the water, or perhaps due to some other unexplained reason. This imprecision manifests itself in the random deviations of the individual measurements from the mean.

When we write down the error associated with an experiment, it is usually the random error that we report. Unfortunately, we are usually unaware of systematic errors, because, if we knew about them, we would correct them. This is why it is important to note all observations during an experiment. It may be that these observations will later provide a clue about systematic experimental deviations.

The examination of error may seem unimportant when we already know the true value of a quantity. However, the point of understanding experimental error is so that we may use this understanding when we are measuring quantities whose value we do not already know. In most experimental situations, a scientist first tests his or her equipment and technique by measuring known quantities, in order to characterize their precision and accuracy. They are then aware of the uncertainty of their experimental results from measurements of unknown quantities. Almost all data published in the scientific literature is accompanied by an estimation of experimental error.

Arithmetic Treatment of Random Error

Very often, random errors can be approximated by what is know as a Gaussian Error Function. If many readings are made of a single experimental variable, the most frequent reading occurs at or near some average value (it is hoped that this is also the true value). Values other than the true value are recorded less frequently. This situation is graphically represented by the famous bell curve, shown in Figure 1.

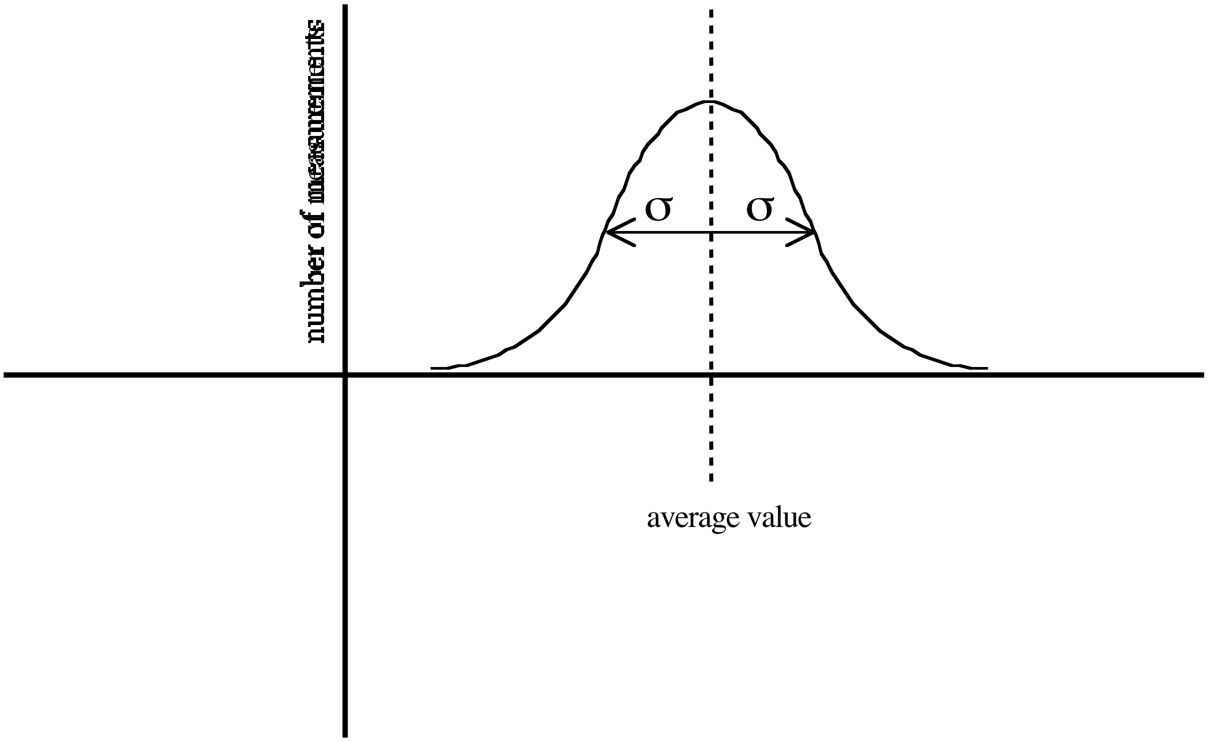


Figure 1: Gaussian Error Distribution

The Greek letter σ (pronounced sigma) stands for a quantity known as the standard deviation. There is a 68% probability that a measurement will be within one standard deviation of the average value, provided that our errors are completely random. It is common practice to assume, in the absence of information to the contrary, that errors are random. If this is assumption is made the error in an experiment is generally reported as “plus or minus” one standard deviation.

The standard deviation for the temperature data above is 0.9 ˚C, and hence we would report our result for the boiling point of water as:

$$99.9 \pm 0.9\ ^\circ\mathrm{C}$$

Thus, the larger the value of σ, the greater the reported error.

It is reasonable to ask at this point “How do you calculate σ ?” There are two ways: the hard way and the easy way. The hard way is to use the following formula:

[1]

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

[1]

In equation [1], N represents the number of measurements, and x is the variable being measured. The bar over x means that it is the average value, and the subscript, i, means to do the calculation for each value of x.

The easy way is to use your calculator or a microcomputer. Almost every good scientific calculator has a straightforward and convenient method for calculating the standard deviation. The program "Logger Pro" enables you to rapidly calculate the standard deviation for data that you enter into it.

Since every measurement is inherently imprecise, we cannot report our data with arbitrary precision. If you measure your kitchen floor with a meter stick, will you find out that it is 7 meters long, 7.1 meters long, 7.089 meters long, or 7.0891254633 meters long? Of course the answer is "It depends." It depends on your assessment of the error which inheres in your measurement. You would report a value of 7 meters if your measurement was casual not very careful. On the other hand, it is unlikely that you could find apparatus accurate and precise enough to justify the last number quoted above.

The number of digits we use in reporting data, then, reflects our confidence in our experimental technique. The precise rules for significant figures are given in your classroom text. For our purposes, it is important to remember two rules:

1) Only use the number of digits warranted by your experimental precision;
2) In calculations, round your answer off to the number of significant figures of the least precisely known quantity.

Percent Error

We frequently speak of the per cent error in an experiment. The per cent error is usually the ratio of one standard deviation to the mean value, expressed as a percentage. Suppose for example, that the following result was reported for a measurement of the boiling point of ethanol:

$$79.9 \pm 1.7\ ^{\circ}\mathrm{C}$$

The percentage error is:

$$\frac{1.7\ ^{\circ}\mathrm{C}}{79.0\ ^{\circ}\mathrm{C}} = 2.2\% \qquad [2]$$

and it would be equally proper to report the result as:

$$79.9 \pm 2.2\%$$

Least Squares Fit

Very often there is a linear relation between data. For example, if we plot x vs. t for an object moving at a constant velocity, we should obtain a line, as shown in figure 2.

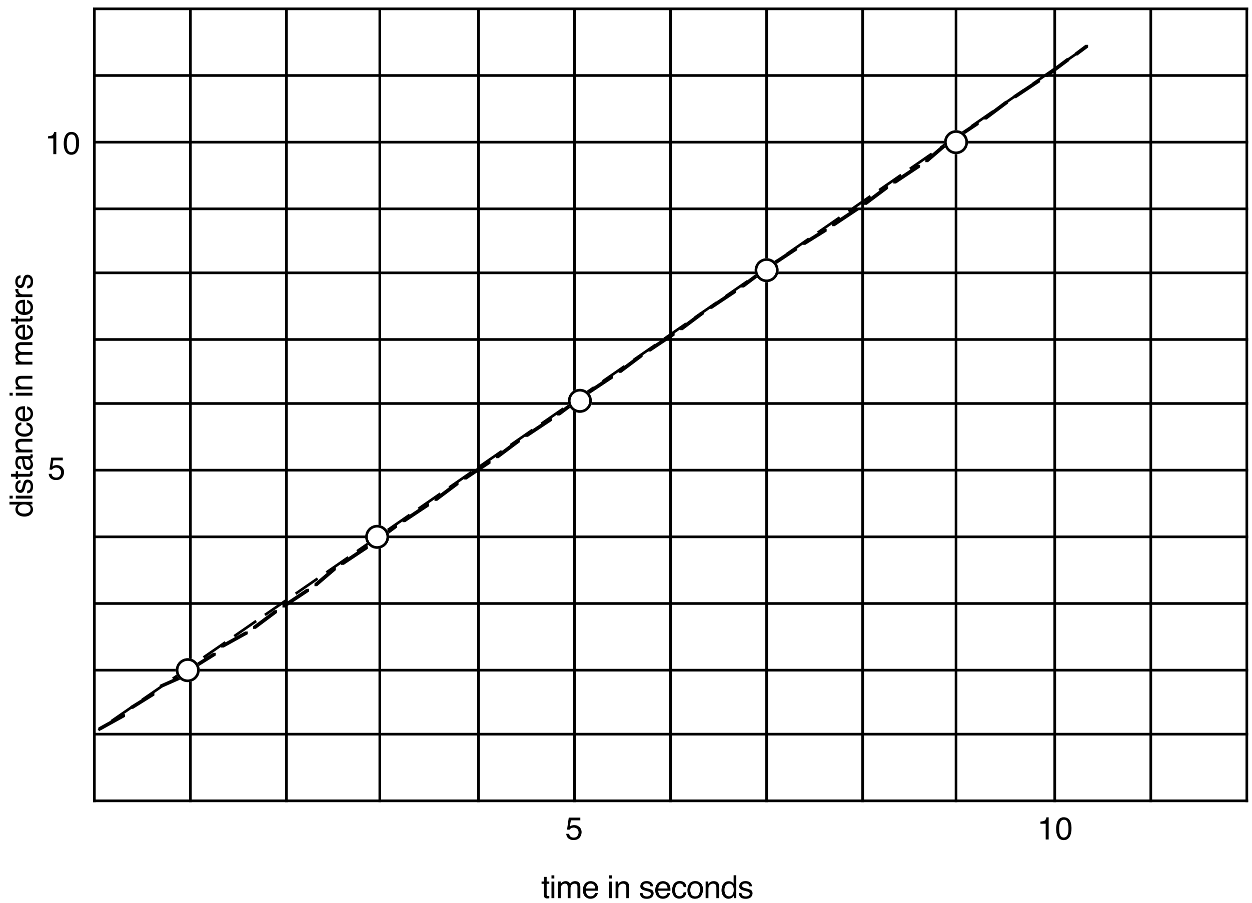


Figure 2: Fitting Data to a Line

The slope of the line we obtain in this case would be 1 meter per second, the velocity of our object.

There is something suspicious about this graph: all the points lie on the line: in realistic situations, there is always some random deviation due to random error. Sometimes the deviation is too small too see, but often it is all too evident. A displacement versus time graph showing typical random deviation is shown in Figure 3.

None of the points lies directly on the line. Rather they are spaced roughly evenly on either side of it. We could find the velocity of the object in this second experiment, once again, simply by calculating the slope of the line.

A more important question is: how do we figure out how to draw the line. There are two ways to do this.

The first requires simply that we do a little guesswork. We draw a line which appears to our eye to lie with the points evenly spaced on either side of it. This method is not exact but gives us a fast, first-order estimate of the relationship between the two quantities.

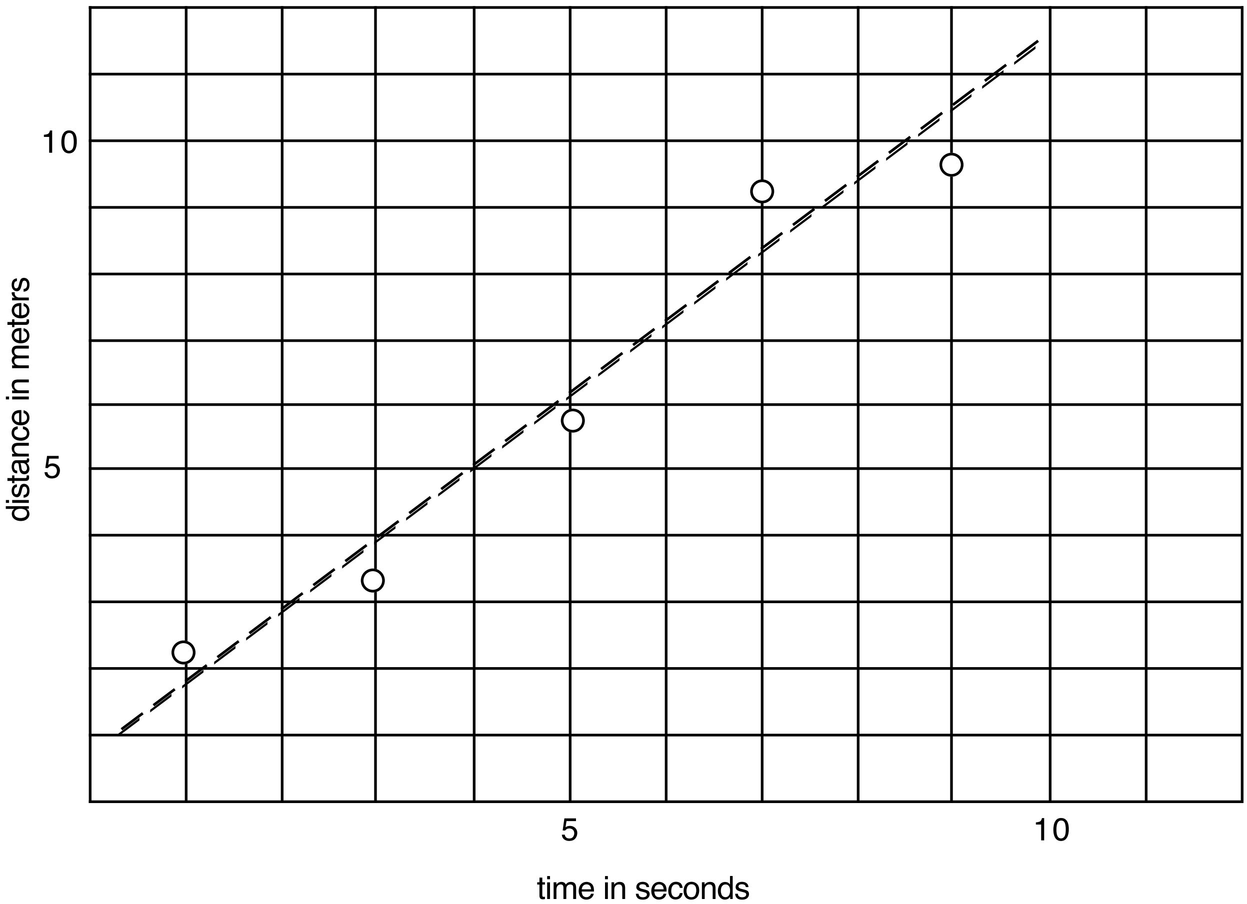


Figure 3: Experimentally obtained data shown a linear dependence of distance traveled on time

The second method involves using a technique known as “least squares fitting” (linear regression is another synonymous term). This is a mathematical technique which minimizes the total distance between the points and the proposed line.

While it is possible to perform a least squares fit by hand, it is extremely tedious to do so. However many scientific calculators contain least squares routines, and there are numerous computer programs which also give these results. Such programs report three quantities:

1) the slope
2) the y-intercept
3) the correlation coefficient or R-squared coefficient.

The last quantity, the correlation coefficient, tells us how good a fit the line is. The nearer it is to 1 or to -1, the better the fit; the nearer to zero, the worse the fit. We generally expect to see correlation coefficients higher than 0.90 for a good linear fit to our data.

Many programs also report the error in the slope and the intercept.

Equipment

The equipment for the introductory lab consists of the following items:

Air Source
Air Track
Foam Poster Board
Glider (red, 300 gram)
Knife
Marble
Meter Stick
Micrometer
Stop Watch
Triple Beam Balance
Vernier Calipers

Two pieces of equipment which you may find unfamiliar are the vernier calipers and the micrometer.

The vernier calipers are useful for precise measurements of length and can be used to measure inside diameters, outside diameters and depth. Your instructor will demonstrate each type of measurement.

The sliding scale of the vernier calipers is shown in figure 4 and is read by adding the results from the major division, the minor division, and the aligned hash mark on the sliding scale.

Your instructor will also demonstrate the operation of the micrometer, which is typically used to measure small outside diameters or thicknesses. A sketch of a micrometer being used to measure a marble is shown in figure 5, along with the names of the principal functioning parts of the micrometer.

Our micrometers have 1.0 mm scale divisions above the reading line and 0.5 mm scale divisions below it. When taking a reading with a micrometer, tighten the thimble until the sample to be measured, at its widest point, can just barely slip from the anvil at spindle. Never tighten thimble so as to force the micrometer closed either on itself, or around a sample.

There are 50 divisions on the thimble, and the thimble moves out along the sleeve by 0.5 mm in each rotation. Therefore, each division represents 0.01 mm (0.001 cm). Two complete rotations are therefore necessary to move the thimble a distance of 1 mm.

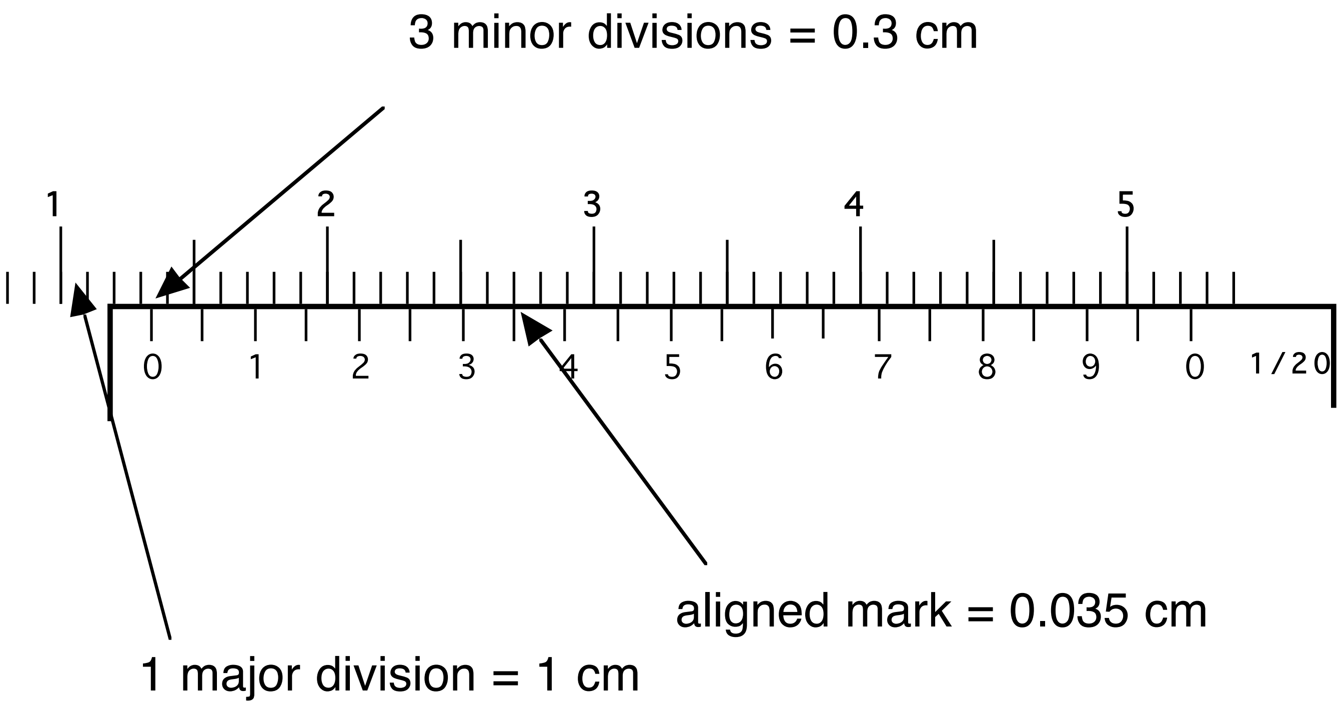
When taking a reading, be careful to note whether the thimble is in its first or second rotation--you can do this by examining whether the last visible scale division is above the reading line (first rotation) or below the reading line (second rotation).

To better follow this explanation, consult the drawing and accompanying explanation in figure 6. Note that the 11 mm mark is visible (above the reading line) but that there is a an additional 5 mm scale marker visible (below the reading line). This means that the thimble is in its “second rotation”--in this case this means that the final reading will be 11 mm + 0.5 mm (complete first rotation) + 0.33 mm (because the 33rd division lines up with the reading line).

Safety

Please observe all safety precautions. Do not misuse or eat the marble.

Note: The location of the "0" mark on the sliding scale tells you how many major divisions and minor divisions you should count



Total = 1 + 0.3 + 0.035 = 1.335 cm

Figure 4: Reading the Vernier Calipers

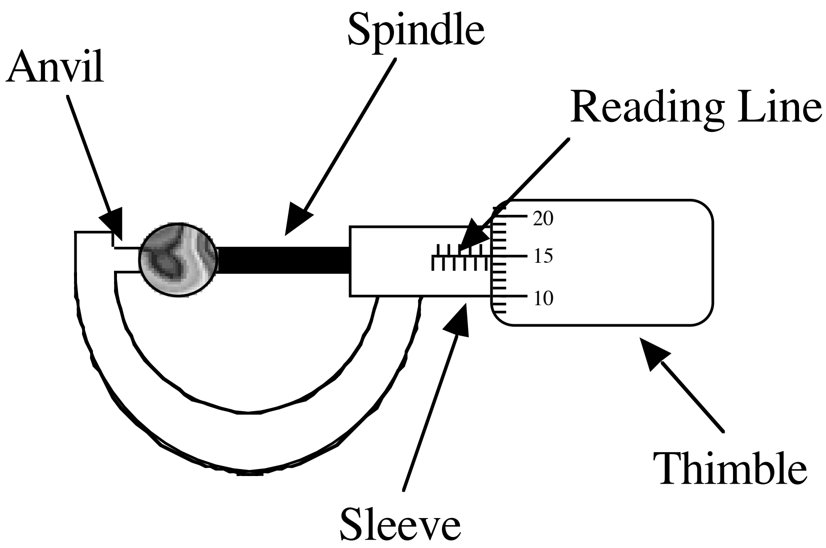
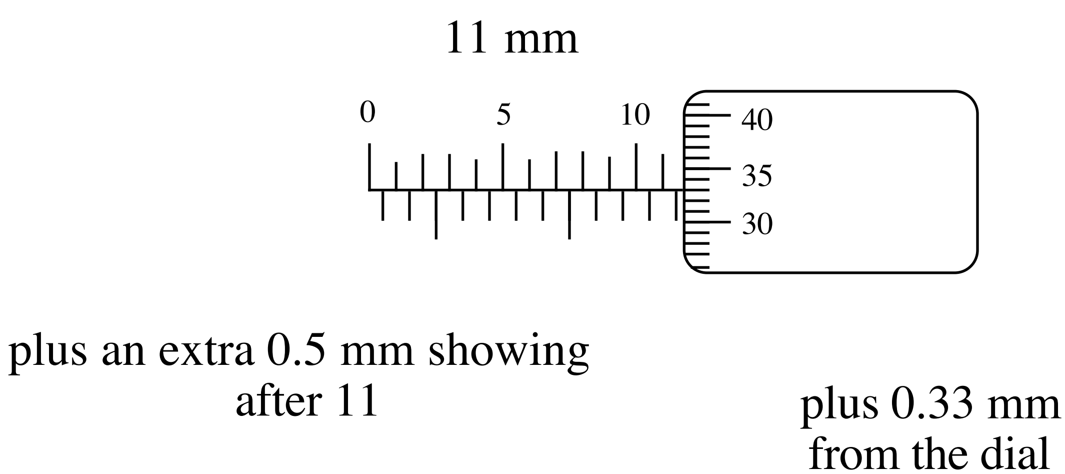


Figure 5: The Micrometer



11 + 0.5 + 0.33 = 11.83 mm or 1.183 cm

Figure 6: Making a measurement with the micrometer

Experimental

A) Basic Measurements

1) Use the meter stick to make poster board cutouts of length 2.5, 5.0, 10 and 15.0 cm. Each should be 7.5 cm tall. Each group should make 1 set of these and KEEP THEM because they will be used in subsequent experiments. Measure the board carefully on both sides and use the exacto knives supplied to cut it.

2) Using the Vernier Calipers to measure the diameters of 25 glass marbles, and the balance to measure their masses, make 25 separate calculations of the density of glass and calculate the standard deviation using the Data Logger program. Please observe all rules for safe handling of the glass marble

3) Count the number of the various colors of M&M's from 5 small bags of M&M's. Find the percentage of each color in each bag. What is the mean value of this number and what is its standard deviation? In a large bag of M&M's , we have found that the numbers are as follows:

red	green	brown	orange	yellow	blue
76	94	88	178	74	187

4) Use the micrometer to measure the thickness of a 10 cm long piece of iron or aluminum wire once.

5) Weigh the piece of wire once (either aluminum or iron will be supplied)

B) Speed

Your instructor will demonstrate the technique to use for the air track. Be sure to level the air track prior to using it. If you are using a mechanics track with wheeled tracks, the same sort of precautions apply, i.e., taking reasonable care against scratching the track, and general damage to the track, cars and accessories.

> *Please remember that the air track is an expensive instrument whose performance depends on precise tolerances both in the track itself and the gliders. This means that any activity that might cause a scratch on the surface of the track or on the inside surface of the glider must be avoided. Please be especially attentive to the following precautions:*
>
> *1) Do not push the glider along the track when it is not supported by a cushion of air.*
>
> *2) Do not push or drag the glider along the track in any way which cause the inner surface of the glider to rub against the surface of the air track*
>
> *3) Do not drop or press down on the glider or lean on the glider in any way.*

1) Using an air track and a stopwatch measure the time it takes a car to travel 1 meter along the track, or 1 meter along the mecahnics track. The value of the speed is not important.

2) Using an air track and a computer, find the average and standard deviation of 10 measurements of the speed of an air track glider using the following procedure. Use the **EX1Stopwatch2007.cmbl** file supplied on your computer. The glider will again travel 1 meter, but, using a computer, you will make 10 measurements of the glider's speed during its 1 meter journey. Plan ahead by mentally selecting a "starting point", which allows the glider 1 meter of travel.

Now perform the experiment as follows. Press the START button in the Logger Pro software. Set the glider in motion ahead of your "starting point". When it passes the starting point, block and unblock the photogate as demonstrated to you by your instructor. Continue to press the space bar each time the glider moves an additional 0.1 meters.

You may prefer to use teamwork to perform this experiment. For example, partner #1 could press start, and say, "Ready". Partner #2 would then push the glider and say "now" when the glider passed the starting point and each time it passed a 10 cm mark (note--the markings on the track are in mm!); partner #1 would press the space bar at each "now". Of course this might add error...or would it?

If you have done the experiment correctly, you should collect 10 data points, each with similar (*but not identical*) values for delta t, and similar values for "instantaneous" velocity. You may discover that the first or last point point is the most error prone...for good reason. Use the method described in the software supplement (page 8) to eliminate this point and then use the computer to find the standard deviation.

3) Now analyze the data you got in section 2 above, using the linear regression feature of Data Logger. Your instructor will demonstrate these techniques, and they are discussed in detail in the computer supplement., and find the velocity by using the <u>least squares fit option</u> given in the graph that the program plots.

NOTE: You could in principle get the data from the stopwatch and the computer simultaneously, with one partner watching the computer, and one the stopwatch. This would be the optimum protocol enabling you to compare the three methods directly.

If you are uncertain about using the computer software, please refer to the ***computer supplement*** *for this experiment. You will also find additonal details and pointers about taking your data and analyzing it.*

Data

ALL DATA MUST BE ENTERED INTO YOUR BOUND LAB NOTEBOOK. THE NOTEBOOK CANNOT BE A RING NOTEBOOK OR A SPIRAL NOTEBOOK. PAGES MUST NEVER BE RIPPED OUT OF YOUR NOTEBOOK.

It is frequently helpful to *tabulate* your data. This means that you prepare a table in your notebook leaving space for data that you will enter, as well as calculated quantities that you will derive from the data that you have entered. An illustration of how you might construct such a data table is shown in figure 6.

In addition to your 25 data points for the mass and diameter of a marble, you should have a single measurement for the length, diameter, and mass of the length of iron (or aluminum) wire. *You should also note down the precise dimensions of your poster board cutouts. This will affect your results throughout the semester. These cutouts must be brought to lab every week during the first semester.*

You will have three sets of data from the air track measurements

first--the data taken using the stop watch

second--the data from the v vs. t plot (Mean, stddev etc)

third--the data from the linear regression analysis of the x vs t plot.

Since the computer programs tabulate the data for you automatically, you may find it preferable in future labs to have the computer generate a printed copy of your data that you can hand in with your report. For today's lab, you *must* hand in the computer print outs demonstrating that you have used the computer software to calculate standard deviations and to ascertain the slope.

	Mass	diameter	radius	Volume	Density
Reading #1					
#2					
#3					
#4					
#5					
#6					
#7					
#8					
#9					
#10					
#11					
#12					
#13	Measured using balance	Measured using calipers	Calculated from diameter	Calculated using the radius	Calculated using the mass and the volume
#14					
#15					
#16					
#17					
#18					
#19					
#20					
#21					
#22					
#23					
#24					
#25					
Average					
Std Deviation					
% Error					

Calculations

Figure 7: Possible data table for density of glass--This is meant as an example. Do not enter your data on this sheet. Enter it in your lab notebook.

Find the density of glass and the density of iron. In the case of the glass report the standard deviations as your error. Take care to carry through the proper number of significant figures. Use the graphical analysis program to find averages and standard deviations. Find the per cent error for your measurements of the diameter and mass of the marble, as well as your calculated values for volume and density.

Compare your range of values for the probaility of finding a given value with some of the varied “official values”. Try, for example:

http://global.mms.com/cai/mms/
http://joshmadison.com/article/mms-color-distribution-analysis/

Find the average speed of the car for the measurement with the stopwatches.

As noted above, use the two computer based methods to evaluate the velocity data obtained by the computer. Print out the graphs from your computer run, showing both the standard statistics and the regression results.

Things to Discuss

This section provides questions to stimulate your thinking. There may be issues you wish to raise in your discussion section in addition to those outlined here. In addition, you will probably not want to address ***every*** *issue raised here. In any case, your discussion should be a self-contained, coherent, logical essay, and not be a series of responses to or restatements of the talking points raised below.*

Characterize your errors: what were the sources of error? Were the errors likely to be systematic or random? Was your experimental technique precise? Was it accurate? If the answers to these questions seem ambiguous, what additional information do you need to make you more certain of your position?

If you don't have a value for the standard deviation, can you still estimate your error?

Why does the slope of the line in the second computer experiment give you the speed? Of the three methods for finding the speed, does any seem to stand out as more reliable?

In evaluating the density, you measured the mass, and then measured the diameter, and finally calculated the density. If you had taken 25 mass measurements and taken the average and then taken 25 volume determinations and taken the average, and then calculated an average density as the ratio of the average mass to the average volume, would your answer be different? Would the error in the experiment be different?

Is the value of the per cent error in the density less than, greater than, or roughly the same as the per cent error for the volume? For the mass?

Report:

Introduction: Write a brief introduction stating the objectives of the experiment, and a concise summary of the methods that will be used.

Experimental: Describe the experimental apparatus and precisely what variables will be measured and how they will be measured.

Results: Summarize the results of the experiment. Show sample calculations. If you are attaching computer generated tables or graphs, briefly explain them here.

Discussion: Explain the significance of your results and their connection with more general physical principles. Where it is possible, compare your numbers with accepted values. Explain any sources of error.