PHYSICS III: EXPERIMENTS

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Foreword

This book is written with a dual purpose in mind. Firstly, it aims to guide the students in the experiments of the elementary physics courses. Secondly, it incorporates the worksheets that the students use during their 2-hour laboratory session.

There are six books to accompany the six elementary physics courses taught at Bogazici University. After renovating our laboratories, replacing most of the equipment, and finally removing the 110-V electrical distribution in the laboratories, it has become necessary to prepare these books. Each book starts with the basic methods for data taking and analysis. These methods include brief descriptions for some of the instruments used in the experiments and the graphical method for fitting the data to a straight line. In the second part of the book, the specific experiments performed in a specific course are explained in detail. The objective of the experiment, a brief theoretical background, apparatus and the procedure for the experiment are given in this part. The worksheets designed to guide the students during the data taking and analysis follows this material for each experiment. Students are expected to perform their experiment and data analysis during the allotted time and then hand in the completed worksheet to the instructor by tearing it out of the book.

We would like to thank the members of the department that made helpful suggestions and supported this project, especially Arsin Arşık and Işın Akyüz who taught these laboratory classes for years. Our teaching assistants and student assistants were very helpful in applying the procedures and developing the worksheets. Of course, the smooth operation of the laboratories and the continuous well being of the equipment would not be possible without the help of our technicians, Erdal Özdemir and Hüseyin Yamak, who took over the job from Okan Ertuna.

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Part I. BASIC METHODS

Introduction

Physics is an experimental science. Physicists try to understand how nature works by making observations, proposing theoretical models and then testing these models through experiments. For example, when you drop an object from the top of a building, you observe that it starts with zero speed and hits the ground with some speed. From this simple observation you may deduce that the speed or the velocity of the object starts from zero and then increases, suggesting a nonzero acceleration.

Usually when we propose a new model we start with the simplest explanation. Assuming that the acceleration of the falling object is constant, we can derive a relationship between the time it takes to reach the ground and the height of the building. Then measuring these quantities many times we try to see whether the proposed relationship is valid. The next question would be to find an explanation for the cause of this motion, namely the Newton's Law. When Newton proposed his law, he derived it from his observations. Similarly, Kepler's laws are also derived from observations. By combining his laws of motion with Kepler's laws, Newton was able to propose the gravitational law of attraction. As you see, it all starts with measuring lengths, speeds, etc. You should understand your instruments very well and carry out the measurements properly. Measuring things correctly is absolutely essential for the success of your experiment.

Every time a new model or law is proposed, you can make some predictions about the outcome of new and untried experiments. You can test the proposed models by comparing the results of these actual experiments with the predictions. If the results disagree with the predictions, then the proposed model is discarded or modified. However, an agreement between the experimental results and the predictions is not sufficient for the acceptance of the specific model. Models are tested continuously to make sure that they are valid. Galilean relativity is modified and turned into the special relativity when we started measuring speeds in the order of the speed of light. Sometimes the modifications may occur before the tests are done. Of course, all physical laws are based on experimental studies. Experimental results always take precedence over theory. Obviously, experiments have to be done carefully and objectively without any bias. Uncertainties and any contributing systematic effects should be studied carefully.

This book is written for the laboratory part of the Introductory Physics courses taken by freshman and sophomore classes at Bogazici University. The first part of the book gives you basic information about statistics and data analysis. A brief theoretical background and a procedure for each experiment are given in the second part.

Experiments are designed to give students an understanding of experimental physics regardless of their major study areas, and also to complement the theoretical part of the course. They will introduce you to the experimental methods in physics. By doing these experiments, you will also be seeing the application of some of the physics laws you will be learning in the accompanying course.

You will learn how to use some basic instruments and interpret the results, to take and analyze data objectively, and to report their results. You will gain experience in data taking and improve your insight into the physics problems. You will be performing the experiments by following the procedures outlined for each experiment, which will help you gain confidence in experimental work. Even though the experiments are designed to be simple, you may have some errors due to systematical effects and so your results may be different from what you would expect theoretically. You will see that there is a difference between real-life physics and the models you are learning in class.

You are required to use the worksheets to report your results. You should include all your calculations and measurements to show that you have completed the experiment fully and carried out the required analysis yourself.

DATA TAKING AND ANALYSIS

Dimensions and Units

A physical quantity has one type of dimension but it may have many units. The dimension of a quantity defines its characteristic. For example, when we say that a quantity has the dimension of length (L), we immediately know that it is a distance between two points and measured in terms of units like meter, foot, etc. This may sound too obvious to talk about, but dimensional analysis will help you find out if there is a mistake in your derivations. Both sides of an equation must have the same dimension. If this is not the case, you may have made an error and you must go back and recheck your calculations. Another use of a dimensional analysis is to determine the form of the empirical equations. For example, if you are trying to determine the relationship between the distance traveled under constant acceleration and the time involved empirically, then you should write the equation as

$$d = kat^n$$

where k is a dimensionless quantity and a is the acceleration. Then, rewriting this expression in terms of the corresponding dimensions:

$$L = \left(LT^{-2}\right)T^n$$

will give us the exponent n as 2 right away. You will be asked to perform dimensional analysis in most of the experiments to help you familiarize with this important part of the experimental work.

Measurement and Instruments

To be a successful experimenter, one has to work in a highly disciplined way. The equipment used in the experiment should be treated properly, since the quality of the data you will obtain will depend on the condition of the equipment used. Also, the equipment has a certain cost and it may be used in the next experiment. Mistreating the equipment may have negative effects on the result of the experiment, too.

In addition to following the procedure for the experiment correctly and patiently, an experimenter should be aware of the dangers in the experiment and pay attention to the warnings. In some cases, eating and drinking in the laboratory may have harmful effects on you because food might be contaminated by the hazardous materials involved in the experiment, such as radioactive materials. Spilled food and drink may also cause malfunctions in the equipment or systematic effects in the measurements.

Measurement is a process in which one tries to determine the amount of a specific quantity in terms of a pre-calibrated unit amount. This comparison is made with the help of an instrument. In a measurement process only the interval where the real value exists can be determined. Smaller interval means better precision of the instrument. The smallest fraction of the pre-calibrated unit amount determines the precision of the instrument.

You should have a very good knowledge of the instruments you will be using in your measurements to achieve the best possible results from your work. Here we will explain how to use some of the basic instruments you will come across in this course.

Reading analog scales:

You will be using several different types of scales. Examples of these different types of scales are rulers, vernier calipers, micrometers, and instruments with pointers.

The simplest scale is the **meter stick** where you can measure lengths to a millimeter. The precision of a ruler is usually the smallest of its divisions.

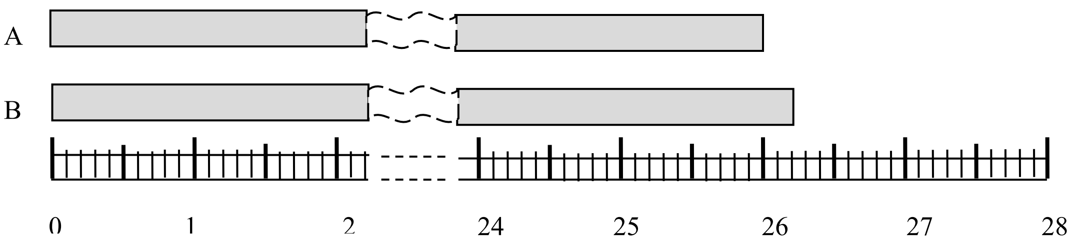


Figure 1. Length measurement by a ruler

In Figure 1, the lengths of object A and B are observed to be around 26 cm. Since we use a ruler with millimeter division the measurement result for the object A should be given as 26.0 cm and B as 26.2 cm. If you report a value more precise than a millimeter when you use a ruler with millimeter division, obviously you are guessing the additional decimal points.

Vernier Calipers (Figure 2) are instruments designed to extend the precision of a simple ruler by one decimal point. When you place an object between the jaws, you may obtain an accurate value by combining readings from the main ruler and the scale on the frame attached to the movable jaw. First, you record the value from the main ruler where the zero line on the frame points to. Then, you look for the lines on the frame and the main ruler that looks like the same line continuing in both scales. The number corresponding to this line on the frame gives you the next digit in the measurement. In Figure 2, the measurement is read as 1.23 cm. The precision of a vernier calipers is the smallest of its divisions, 0.1 mm in this case.

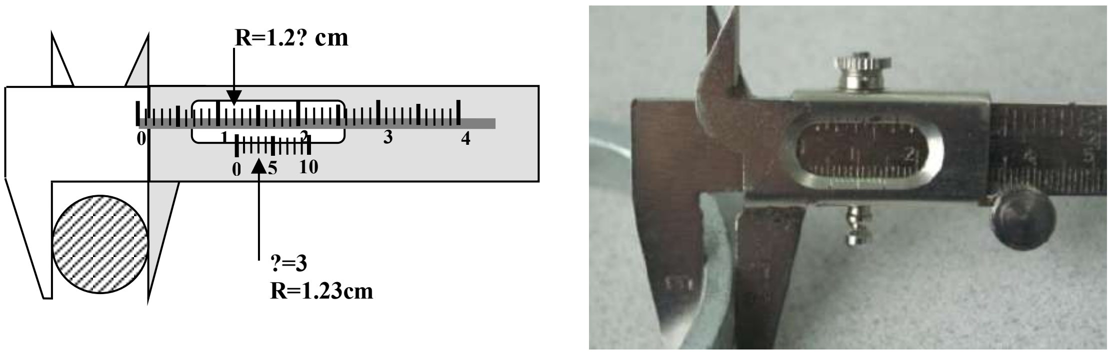


Figure 2. Vernier Calipers.

Micrometer (Figure 3) is similar to the vernier calipers, but it provides an even higher precision. Instead of a movable frame with the next decimal division, the micrometer has a cylindrical scale usually divided into a hundred divisions and moves along the main ruler like a screw by turning the handle. Again the coarse value is obtained from the main ruler and the more precise part of the measurement comes from the scale around the rim of the cylindrical part. Because of its higher precision, it is used mostly to measure the thickness of wires and similar things. In Figure 3, the measurement is read as 1.187 cm. The precision of a micrometer is the smallest of its divisions, 0.01 mm in this case.

Here is an example for the measurement of the radius of a disk where a ruler, a vernier calipers, and a micrometer are used, respectively:

Measurement	Precision	Instrument
$R = (23 \pm 1)mm$	1 mm	Ruler
$R = (23.1 \pm 0.1)mm$	0.1 mm	Vernier calipers
$R = (23.14 \pm 0.01)mm$	0.01 mm	Micrometer

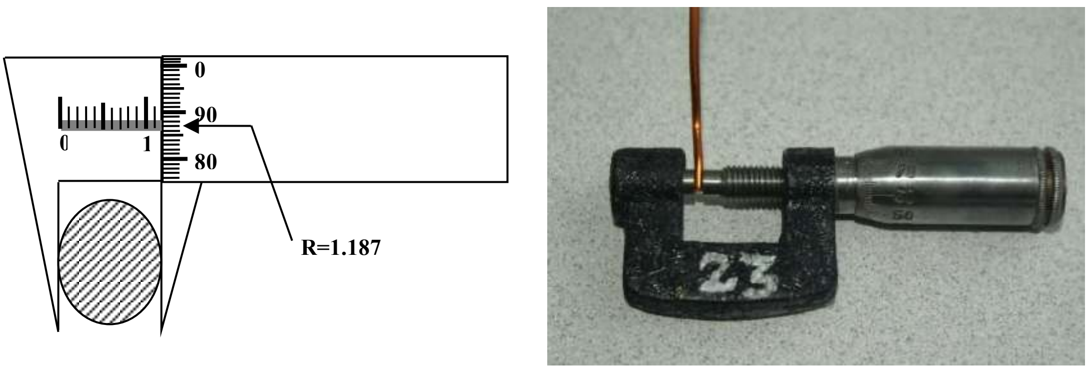


Figure 3. Micrometer.

Spherometer (Figure 4) is an instrument to determine very small thicknesses and the radius of curvature of a surface. First you should place the spherometer on a level surface to get a calibration reading (CR). You turn the knob at the top until all four legs touch the surface. When the middle leg also touches the surface, the knob will first seem to be free and then tight. The reading at this position will be the calibration reading (CR). Then you should place the spherometer on the curved surface and turn the knob until all four legs again touch the surface. The reading at this position will be the measurement reading (MR). You will read the value from the vertical scale first and then the value on the dial will give you the fraction of a millimeter. Then you can calculate the radius of curvature of the surface as:

$$R = \frac{D}{2} + \frac{A^2}{6D}$$

where D = |CR-MR| and A is the distance between the outside legs.

Figure 4. Spherometer.

Instruments with pointers usually have a scale along the path that the pointer moves. Mostly the scales are curved since the pointers move in a circular arc. To avoid the systematic errors introduced by the viewing angle, one should always read the value from the scale where the pointer is projected perpendicularly. You should not read the value by looking at the pointer and the scale sideways or at different angles. You should always look at the scale and the pointer perpendicularly. Usually in most instruments there is a mirror attached to the scale to make sure the readings are done similarly every time when you take a measurement (Figure 5). When you bring the scale and its image on the mirror on top of each other, you will be looking at the pointer and the scale perpendicularly. Then you can record the value that the pointer shows on the scale. Whenever you measure something by such an instrument, you should follow the same procedure.

Figure 5. A voltmeter with a mirror scale.

Data Logger

In some experiments we will be using sensors to measure some quantities like position, angle, angular velocity, temperature, etc. The output of these sensors will be converted into numbers with the help of a data acquisition instrument called DATA LOGGER (Figure 6).

Data Logger is a versatile instrument that takes data using changeable sensors. When you plug a sensor to its receptacle at the top, it recognizes the type of the sensor. When you turn the data logger on with a sensor attached, it will start displaying the default mode for that sensor. Data taking with the data logger is very simple. You can start data taking by pressing the Start/Stop button (7). You may change the display mode by pressing the button on the right with three rectangles (6). To change the default measurement mode, you should press the plus or minus buttons (3 or 4). If there is more than one type of quantity because of the specific sensor you are using, you may select the type by pressing the button with a check mark (5) to turn on the editing mode and then selecting the desired type by using the plus and minus buttons (3 or 4). You will exit from the editing mode by pressing the button with the check mark (5) again. You may edit any of the default settings by using the editing and plus-minus buttons. For a more detailed operation of the instrument you should consult your instructor.

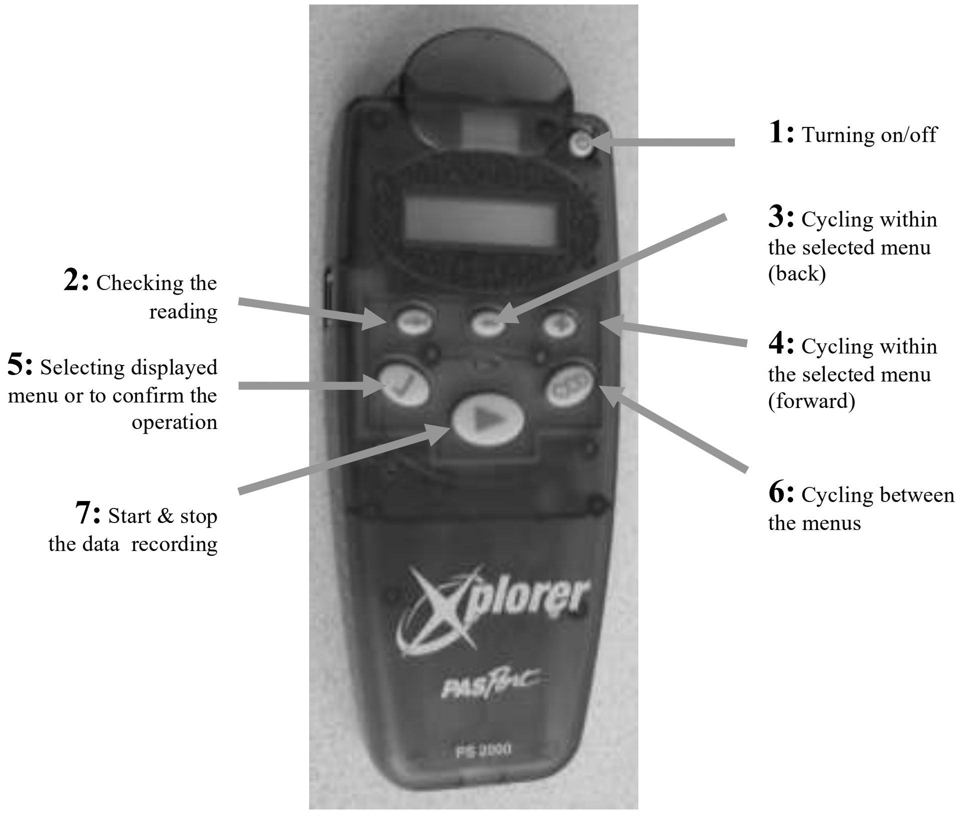


Figure 6. Data Logger.

Basics of Statistics and Data Analysis

Here, you will have an introduction to statistical methods, such as distributions and averages.

All the measurements are done for the purpose of obtaining the value for a specific quantity. However, the value by itself is not enough. Determining the value is half the experiment. The other half is determining the uncertainty. Sometimes, the whole purpose of an experiment may be to determine the uncertainty in the results.
Error and uncertainty are synonymous in experimental physics even though they are two different concepts. Error is the deviation from the true value. Uncertainty, on the other hand, defines an interval where the true value is. Since we do not know the true value, when we say error we actually mean uncertainty. Sometimes the accepted value for a quantity after many experiments is assumed to be the true value.

Sample and parent population

When you carry out an experiment, usually you take data in a finite number of trials. This is our sample population. Imagine that you have infinite amount of time, money, and effort available for the experiment. You repeat the measurement infinite times and obtain a data set that has all possible outcomes of the experiment. This special sample population is called parent population since all possible sample populations can be derived from this infinite set. In principle, experiments are carried out to obtain a very good representation of the parent population, since the parameters that we are trying to measure are those that belong to the parent population. However, since we can only get an approximation for the parent population, values determined from the sample populations are the best estimates.

Mean and Standard deviation

Measuring a quantity usually involves statistical fluctuations around some value. Multiple measurements included in a sample population may have different values. Usually, taking an average cancels the statistical fluctuations to first degree. Hence, the average value or the mean value of a quantity in a sample population is a good estimate for that quantity.

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

Even though the average value obtained from the sample population is the best estimate, it is still an estimate for the true value. We should have another parameter that tells us how close we are to the true value. The variance of the sample:

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

gives an idea about how scattered the data are around the mean value. Variance is in fact a measure of the average deviation from the mean value. Since there might be negative and positive deviations, squares of the deviations are averaged to avoid a null result. Because the variance is the average of the squares, square root of variance is a better quantity that shows the scatter around the mean value. The square root of the variance is called standard deviation:

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

However, the standard deviation calculated this way is just the standard deviation of the sample population. What we need is the standard deviation of the parent population. The best estimate for the standard deviation of the parent population can be shown to be:

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

As the number of measurements, N, becomes large or as the sample population approaches parent population, standard deviation of the sample is almost equal to the standard deviation of the parent population.

Distributions

The probability of obtaining a specific value can be determined by dividing the number of measurements with that value to the total number of measurements in a sample population. Obviously, the probabilities obtained from the parent population are the best estimates. Total probability should be equal to 1 and probabilities should be larger as one gets closer to the mean value. The set of probability values associated with a population is called the probability distribution for that measurement. Probability distributions can be experimental distributions obtained from a measurement or mathematical functions. In physics, the most frequently used mathematical distributions are Binomial, Poisson, Gaussian, and Lorentzian. Gaussian and Poisson distributions are in fact special cases of Binomial distribution. However, in most cases, Gaussian distribution is a good approximation. In fact, all distributions approach Gaussian distribution at the limit (Central Limit Theorem).

Errors

The result of an experiment done for the first time almost always turns out to be wrong because you are not familiar with the setup and may have systematic effects. However, as you continue to take data, you will gain experience in the experiment and learn how to reduce the systematical effects. In addition to that, increasing number of measurements will result in a better estimate for the mean value of the parent population.

Errors in measurements: Statistical and Systematical errors

As mentioned above, error is the deviation between the measured value and the true value. Since we do not know the true value, we cannot determine the error in this sense. On the other hand, uncertainty in our measurement can tell us how close we are to the true value. Assuming that the probability distribution for our measurement is a Gaussian distribution, 68% of all possible measurements can be found within one standard deviation of the mean value. Since most physical distributions can be approximated by a Gaussian, defining the standard deviation as our uncertainty for that measurement will be a reasonable estimate. In some cases, two-standard deviation or two-sigma interval is taken as the uncertainty. However, for our purposes using the standard deviation as the uncertainty would be more than enough. Also, from now on, whenever we use error, we will actually mean uncertainty.

Errors or uncertainties can be classified into two major groups; statistical and systematical.

Statistical Errors

Statistical errors or random errors are caused by statistical fluctuations in the measurements. Even though some unknown phenomenon might be causing these fluctuations, they are mostly random in nature. If the size of the sample population is large enough, then there is equal number of measurements on each side of the mean at about similar distances. Therefore, averaging over such a large number of measurements will smooth the data and cancel the effect of these fluctuations. In fact, as the number of measurements increases, the effect of the random fluctuations on the average will diminish. Taking as much data as possible improves statistical uncertainty.

Systematical Errors

On the other hand, systematical errors are not caused by random fluctuations. One could not reduce systematical errors by taking more data. Systematical errors are caused by various reasons, such as, the miscalibration of the instruments, the incorrect application of the procedure, additional unknown physical effects, or anything that affects the quantity we are measuring. Systematic errors caused by the problems in the measuring instruments are also called instrumental errors. Systematical errors are reduced or avoided by finding and removing the cause.

Example 1: You are trying to measure the length of a pipe. The meter stick you are going to use for this purpose is constructed in such a way that it is missing a millimeter from the beginning. Since both ends of the meter stick are covered by a piece of metal, you do not see that your meter stick is 1 mm short at the beginning. Every time you use this meter stick, your measurement is actually 1 mm longer than it should be. This will be the case if you repeat the measurement a few times or a few million times. This is a systematical error and, since it is caused by a problem in the instrument used, it is considered an instrumental error. Once you know the cause, that is, the shortness of your meter stick, you can either repeat your measurement with a proper meter stick or add 1 mm to every single measurement you have done with that particular meter stick.

Example 2: You might be measuring electrical current with an ammeter that shows a nonzero value even when it is not connected to the circuit. In a moving coil instrument this is possible if the zero adjustment of the pointer is not done well and the pointer always shows a specific value when there is no current. The error caused by this is also an instrumental error.

Example 3: At CERN, the European Research Center for Nuclear and Particle Physics, there is a 28 km long circular tunnel underground. This tunnel was dug about 100 m below the surface. It was very important to point the direction of the digging underground with very high precision. If there were an error, instead of getting a complete circle, one would get a tunnel that is not coming back to the starting point exactly. One of the inputs for the topographical measurements was the direction towards the center of the earth. This could be determined in principle with a plumb bob (or a piece of metal hung on a string) pointing downwards under the influence of gravity. However, when there is a mountain range on one side and a flat terrain on the other side (like the location of the CERN accelerator ring), the direction given by the plumb bob will be slightly off towards the mountainous side. This is a systematic effect in the measurement and since its existence is known, the result can be corrected for this effect.

Once the existence and the cause of a systematic effect are known, it is possible to either change the procedure to avoid it or correct it. However, we may not always be fortunate enough to know if there is a systematic effect in our measurements. Sometimes, there might be unknown factors that affect our experiment. The repetition of the measurement under different conditions, at different locations, and with totally different procedures is the only way to remove the unknown systematic effects. In fact, this is one of the fundamentals of the scientific method.

We should also mention the accuracy and precision of a measurement. The meaning of the word "accuracy" is closeness to the true value. As for "precision," it means a measurement with higher resolution (more significant figures or digits). An instrument may be accurate but not precise or vice versa. For example, a meter stick with millimeter divisions may show the correct value. On the other hand, a meter stick with 0.1 mm division may not show the correct value if it is missing a one-millimeter piece from the beginning of the scale. However, if an instrument is precise, it is usually an expensive and well designed instrument and we expect it to be accurate.

Reporting Errors: Significant figures and error values

As mentioned above, determining the error in an experiment requires almost the same amount of work as determining the value. Sometimes, almost all the effort goes into determining the uncertainty in a measurement.

Using significant figures is a crude but an effective way of reporting the errors. A simple definition for significant figures is the number of digits that one can get from a measuring instrument (but not a calculator!). For example, a digital voltmeter with a four-digit display can only provide voltage values with four digits. All these four digits are significant unless otherwise noted. On the other hand, reporting a six digit value when using an analog voltmeter whose smallest division corresponds to a four-digit reading would be wrong. One could try to estimate the reading to the fraction of the smallest division, but then this estimate would have a large uncertainty.

Significant figures are defined as following:

- Leftmost nonzero digit is the most significant figure.

  Examples: 0.0000**6**520 m
  1234 m
  41.02 m
  126.1 m
  4120 m
  12000 m

- Rightmost nonzero digit is the least significant figure if there is no decimal point.

  Examples: 123**4** m
  41**2**0 m
  1**2**000 m

- If there is a decimal point, rightmost digit is the least significant figure even if it is zero.

  Examples: 0.0000652**0** m
  41.0**2** m
  126.**1** m

Then, the number of significant figures is the number of digits between the most and the least significant figures including them.

Examples:	0.0000**6**52**0** m	4 significant figures
	123**4** m	4 sf
	41.0**2** m	4 sf
	126.**1** m	4 sf
	41**2**0 m	3 sf
	12000 m	2 sf
	1.200**0** x 10^4 m	5 sf

Significant figures of the results of simple operations usually depend on the significant figures of the numbers entering into the arithmetic operations. Multiplication or division of two numbers with different numbers of significant figures should result in a value with a number of significant figures similar to the one with the smallest number of significant figure. For example, if you multiply a three-significant-figure number with a two-significant-figure number, the result should be a two-significant-figure number. On the other hand, when adding or subtracting two numbers, the outcome should have the same number of significant figures as the smallest of the numbers entering into the calculation. If the numbers have decimal points, then the result should have the number of significant figures equal to the smallest number of digits after the decimal point. For example, if three values, two with two significant figures and one with four significant figures after the decimal point, are added or subtracted, the result should have two significant figures after the decimal point.

Example: Two different rulers are used to measure the length of a table. First, a ruler with 1-m length is used. The smallest division in this ruler is one millimeter. Hence, the result from this ruler would be 1.000 m. However, the table is slightly longer than one meter. A second ruler is placed after the first one. The second ruler can measure with a precision of one tenth of a millimeter. Let's assume that it gives a reading of 0.2498 m. To find the total length of the table we should add these two values. The result of the addition will be 1.2498, but it will not have the correct number of significant figures since one has three and the other has four significant figures after the decimal point. The result should have three significant figures after the decimal point. We can get the correct value by rounding off the number to three significant figures after the decimal point and report it as 1.250 m.

More Examples for Addition and Subtraction:

$$\begin{array}{rl} & 4.122 \\ & 3.\mathbf{74} \\ + & \underline{0.011} \\ & 7.873 = 7.\mathbf{87} \end{array}$$

(2 digits after the decimal point)

Examples for Multiplication and Division:

4.782 x **3.05** = 14.5851 = **14.6** (3 significant figures)

<u>3.728</u> / 1.6781 = 2.22156 = **<u>2.222</u>** (4 significant figures)

Rounding off

Sometimes you may have more numbers than the correct number of significant figures. This might happen when you divide two numbers and your calculator may give you as many digits as it has in its display. Then you should reduce the number of digits to the correct number of significant figures by rounding it off. One common mistake is by starting from the rightmost digit and repeatedly rounding off until you reach the correct number of significant figures. However, all the extra digits above and beyond the number of correct significant figures have no significance. Usually you should keep one extra digit in your calculations and then round this extra digit at the end. You should just discard the extra digits other than the one next to the least significant figure. The reasoning behind the rounding off process is to bring the value to the correct number of significant figures without adding or subtracting an amount in a statistical sense. To achieve this you should follow the procedure outlined below:

- If the number on the right is less than 5, discard it.
- If it is more than 5, increase the number on its left by one.
- If the number is exactly five, then you should look at the number on its left.
  - If the number on its left is even then again discard it.
  - If the number on the left of 5 is odd, then you should increase it by one.

This special treatment in the case of 5 is because there are four possibilities below and above five and adding five to any of them will introduce a bias towards that side. Hence, grouping the number on the left into even and odd numbers makes sure that this ninth case is divided into exactly two subsets; five even and five odd numbers. We count zero in this case since it is in the significant part. We do not count zero on the right because it is not significant.

Example: Rounding off 2.4456789 to three significant figures by starting from all the way to the right, namely starting from the number 9, and repeatedly rounding off until three significant figures are left would result in 2.45 but this would be wrong. The correct way of doing this is first dropping all the non-significant figures except one and then rounding it off, that is, after truncation 2.445 is rounded off to 2.44.

More Examples: Round off the given numbers to 4 significant figures:

43.3**7**468	=	43.37	=	43.**4**
43.3**4**468	=	43.34	=	43.**3**
43.*3***5**468	=	43.35	=	43.**4**
43.*4***5**568	=	43.45	=	43.**4**

If we determine the standard deviation for a specific value, then we can use that as the uncertainty since it gives us a better estimate. In this case, we should still pay attention to the number of significant figures since reporting extra digits is meaningless. For example if you have the average and the standard deviation as 2.567 and 0.1, respectively, then it would be appropriate to report your result as 2.6±0.1.

Weighted Averages

Sometimes we may measure the same quantity in different sessions. As a result we will have different sets of values and uncertainties. By combining all these sets we may achieve a better result with a smaller uncertainty. To calculate the overall average and standard deviation, we can assign weight to each value with the corresponding variance and then calculate the weighted average.

$$\mu = \frac{\sum_{i=1}^{m} \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^{m} \frac{1}{\sigma_i^2}}$$

Similarly we can also calculate the overall standard deviation.

$$\sigma_{\mu} = \sqrt{\frac{1}{\sum_{i=1}^{m} \frac{1}{\sigma_i^2}}}$$

Error Propagation

If you are measuring a single quantity in an experiment, you can determine the final value by calculating the average and the standard deviation. However, this may not be the case in some experiments. You may be measuring more than one quantity and combining all these quantities to get another quantity. For example, you may be measuring x and y and by combining these to obtain a third quantity z:

$$z = ax + by \qquad \text{or} \qquad z = f(x, y)$$

You could calculate z for every single measurement and find its average and standard deviation. However, a better and more efficient way of doing it is to use the average values of x and y to calculate the average value of z. In order to determine the variance of z, we have to use the square of the differential of z:

$$(dz)^2 = \left(\sum (\frac{\partial f}{\partial x})dx + (\frac{\partial f}{\partial y})dy \right)^2$$

Variance would be simply the sum of the squares of both sides over the whole sample set divided by the number of data points N (or N-1 for the parent population). Then, the general expression for determining the variance of the calculated quantity as a function of the measured quantities would be:

$$\sigma_z^2 = \sum_{i=1}^{k} \left(\frac{\partial f}{\partial x_j} \right)^2 \sigma_j^2 \qquad \text{for } k \text{ number of measured quantities.}$$

Applying this expression to specific cases would give us the corresponding error propagation rule. Some special cases are listed below:

$$\sigma_z^2 = a^2\sigma_x^2 + b^2\sigma_y^2 \qquad \text{for} \qquad z = ax \pm by$$

$$\frac{\sigma_z^2}{z^2} = \frac{\sigma_x^2}{x^2} + \frac{\sigma_y^2}{y^2} \qquad \text{for} \qquad z = axy \text{ or } \frac{ax}{y} \text{ or } \frac{ay}{x}$$

$$\frac{\sigma_z^2}{z^2} = b^2 \frac{\sigma_x^2}{x^2} \qquad \text{for} \qquad z = ax^b$$

$$\frac{\sigma_z^2}{z^2} = (b \ln a)^2 \sigma_x^2 \qquad \text{for} \qquad z = a^{bx}$$

$$\frac{\sigma_z^2}{z^2} = b^2 \sigma_x^2 \qquad \text{for} \qquad z = ae^{bx}$$

$$\sigma_z^2 = a^2 \frac{\sigma_x^2}{x^2} \qquad \text{for} \qquad z = a \ln(bx)$$

Multivariable measurements: Fitting procedures

When you are measuring a single quantity or several quantities and then calculating the final quantity using the measured values, all the measurements involve unrelated quantities. There are no relationships between them other than the calculated and measured quantities. However, in some cases you may have to set one or more quantities and measure another quantity determined by the independent variables. This is the case when you have a function relating some quantities to each other. For example, the simplest function would be the linear relationship:

$$y = ax + b$$

where a is called the slope and b the y-intercept. Since we are setting the value of the independent variable x, we assume its uncertainty to be negligible compared to the dependent variable y. Of course, we should be able to determine the uncertainty in y. From such an experiment, usually we have to determine the parameters that define the function; a and b. This can be done by fitting the data to a straight line.

The least squares (or maximum likelihood, or chi-square minimization) method would provide us with the best possible estimates. However, this method involves lengthy calculations and we will not be using it in this course.

We will be using a graphical method that will give us the parameters that we are looking for. It is not as precise as the least squares method and does not give us the uncertainties in the parameters, but it provides answers in a short time that is available to you.

Graphical method is only good for linear cases. However, there are some exceptions to this either by transforming the functions to make them linear or plotting the data on a semi-log or log-log or polar graph paper (Figure 7).$1/r$, $1/r^2$, $y = ax^5$, $y = ae^{-bx}$, are some examples for nonlinear functions that can be transformed to linear expressions. $1/r^n$ type expressions can be linearized by substituting $1/r^n$ with a simple *x*: $y = A + B/r^n \rightarrow y = A + Bx$ where $x = 1/r^n$. Power functions can be linearized by taking the logarithm of the function: $y = ax^n$ becomes $\log y = \log a + n \log x$ and then through $y' = \log y$, $a' = \log a$, and $x' = \log x$ transformation it becomes $y' = a' + nx'$. Exponential functions can be transformed similar to the power functions by taking the natural logarithm: $y = ae^{-bx}$ becomes $\ln y = \ln a - bx$ and through $y' = \ln y$ and $a' = \ln a$ transformation it becomes $y' = a' - bx$.

Before attempting to obtain the parameters that we are looking for, we have to plot the data on a graph paper. As long as we have linearly dependent quantities or transformed quantities as explained above, we can use regular graph paper.

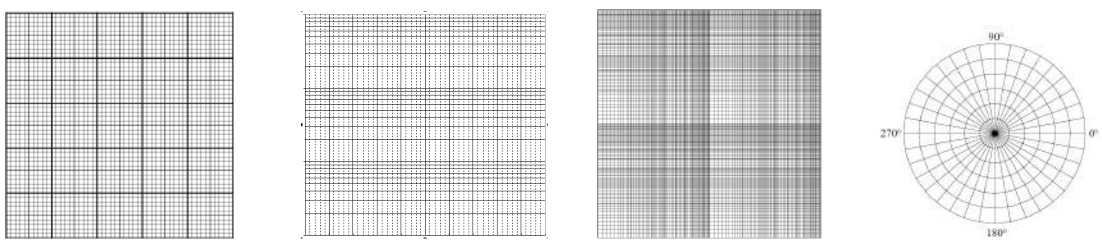


Figure 7: Different types of graph papers: linear, semi-log, log-log, and polar.

You should use as much area of the graph paper as possible when you plot your data. Your graph should not be squeezed to a corner with lots of empty space. To do this, first you should determine the minimum and maximum values for each variable, *x* and *y*, then choose a proper scale value. For example, if you have values ranging from 3 to 110 and your graph paper is 23 centimeters long, then you should choose a scale factor of 1 cm to 5 units of your variable and label your axis from 0 to 115 and marking each big square (usually linear graph papers prepared in cm and millimeter divisions) at increasing multiples of 5. You should choose the other axis in a similar way. When you select a scale factor you should select a factor that is easy to divide by, like 1, 2, 4, 5, 10, etc. Usually scale factors like 3, 4.5, 7.9 etc., are bad choices. Both axis may have different scale factors and may start from a nonzero value. You should clearly label each axis and write down the scale factors. Then you should mark the position corresponding to each data pair with a cross or similar symbols. Usually you should also include the uncertainties as vertical bars above and below the data point whose lengths are determined according to the scale factor. Once you finish marking all your data pairs, then you should try to pass a straight line through all the data points. Usually, this may not be possible since the data points may not fall into a straight line. However, since you know that the relationship is linear there should be a straight line that passes through the data points even though not all of them fall on a line. You should make sure that the straight line passes *through* the data points in a balanced way. An equal number of data points should be below and above the straight line. Then, by picking two points on the line as far apart from each other as possible, you should draw parallel lines to the axes, forming a triangle (Figure 8). The slope is the slope of the straight line. You can calculate the slope as:

$$Slope = \frac{\Delta y}{\Delta x}$$

and read the y-intercept from the graph by finding the point where the straight line crosses the y-axis. You can estimate the uncertainties of the slope and intercept by finding different straight lines that still pass through all the data points in an acceptable manner. The minimum and maximum values obtained from these different trials would give us an idea about the uncertainties. However, obtaining the parameters will be sufficient in this course.

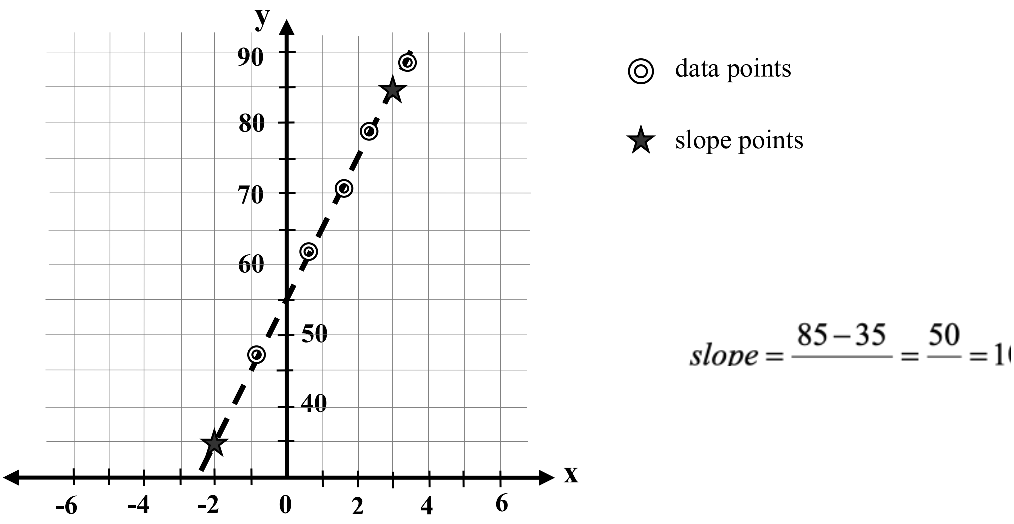


Figure 8: Determining the slope and y-intercept.

Special graph papers, like semi-log and log-log graph papers, are used when you have relationships that can be transformed into linear relationships by taking the base-10 logarithm of both sides. Semi-log graph papers are used if one side of the expression contains powers of ten or single exponential function resulting in a linear variable when you take the base-10 logarithm of both sides.

Logarithmic graph papers are used when you prefer to use the measured values directly without taking the logarithms and still obtaining a linear graph. Each logarithmic axis is divided in such a way that when you use the divisions marked on the paper it will have the same effect as if you first took the logarithm and then plotted on a regular graph paper. Logarithmic graph papers are divided linearly into decades and in each decade is divided logarithmically. There is no zero value in a logarithmic axis. You should plot your data by choosing appropriate scale factors for each axis and then mark the data points directly without taking the logarithms. You should again draw a straight line that will pass through all the data points in a balanced way. The slope of the line would give us the exponent in the relationship. For example, a relationship like $y = ax^n$ would be linearized as $\log y = \log a + n \log x$. If you plot this on a regular graph paper, the slope will be given by $n = (\log y_2 - \log y_1)/(\log x_2 - \log x_1)$ where you will read the logarithms directly from the graph. On the other hand, when you plot your data on a log-log paper, you will be using the measured values directly. When you picked the two points from the straight line that fits the data points best, the slope should be calculated by $n = (\log y_2 - \log y_1)/(\log x_2 - \log x_1)$ where you will calculate the logarithms using the values read from the graph. y-intercept would be directly the value where the straight line crosses the vertical axis at $x = 1$.

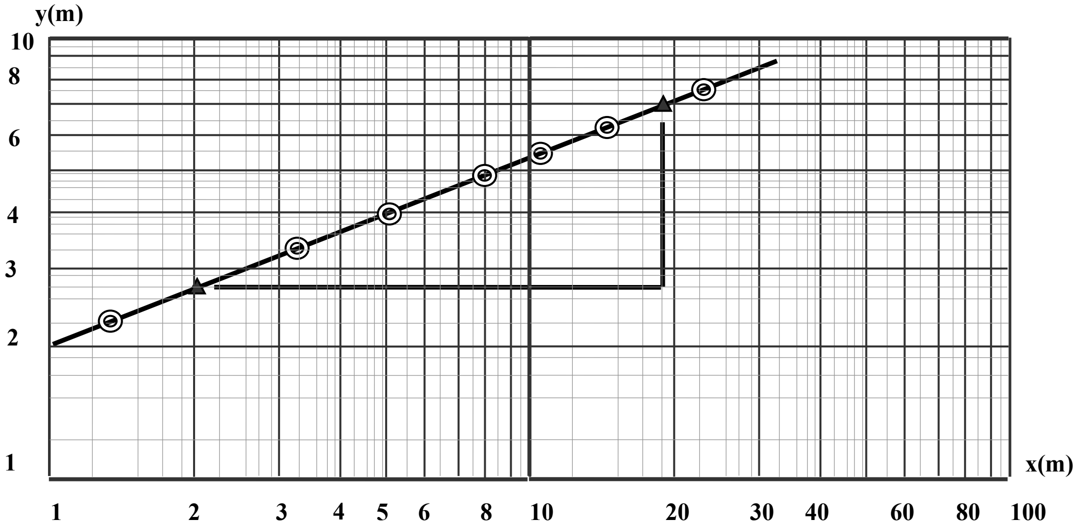


Figure 9: Determining the slope and y-intercept.

slope point 1: (2.0 ; 2.6) and slope point 2 : (18.0 ; 7.0)

$$\text{slope} = \frac{\log(7.0) - \log(2.6)}{\log(18.0) - \log(2.0)} = \frac{0.4301}{0.9542} = 0.4507 \qquad \text{and} \qquad y\text{-intercept} = 2.0.$$

Reports

Obviously, doing an experiment and getting some results are not enough. The results of the experiment should be published so that others working on the same problem will know your results and use them in their calculations or compare with their results. The reports should have all the details so that another experimenter could repeat your measurements and get the same results. However, in an introductory teaching lab there is no need for such extensive reports since the experiments you will be doing are well established and time is limited. You have to include enough details to convince your lab instructor that you have performed the experiment appropriately and analyzed it correctly. The results of your analysis, including the uncertainties in the measurements, should be clearly expressed. The comparisons with the accepted values may also be included if possible.

Part II: EXPERIMENTS

1. *MEASUREMENT OF RESISTANCE - OHM'S LAW*

OBJECTIVE **:** To determine the resistance of a conductor making use of Ohm's Law.

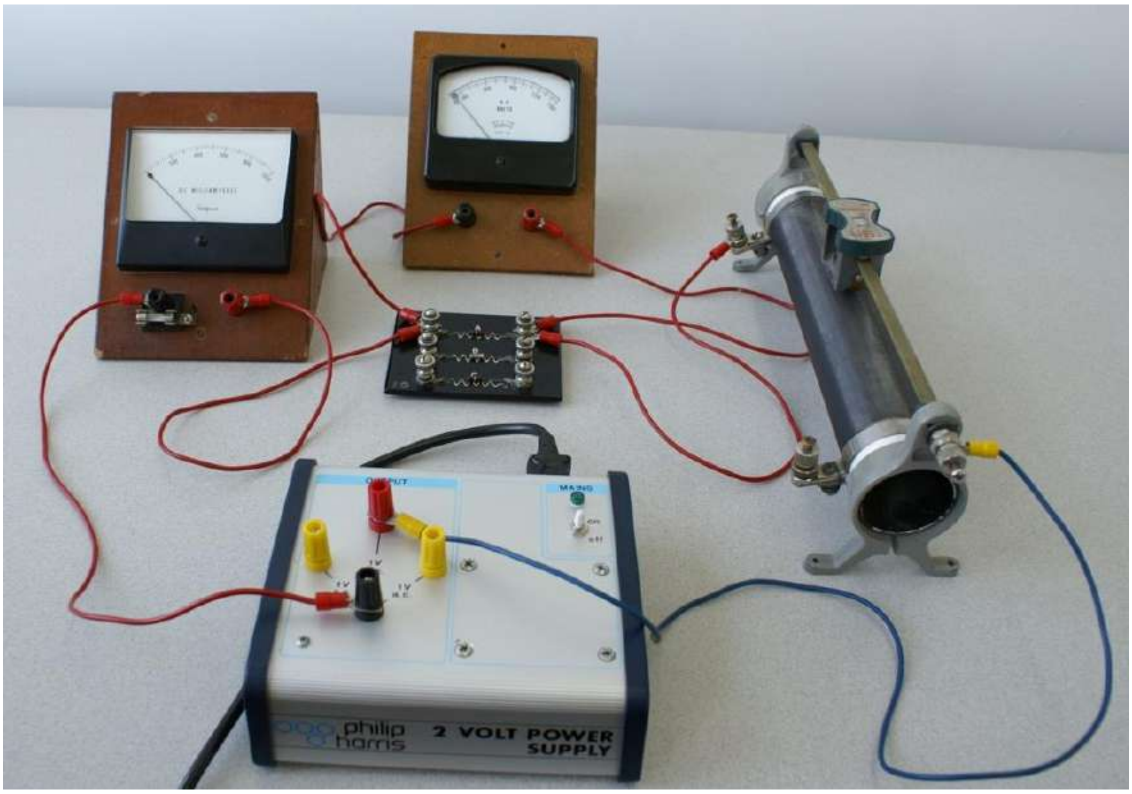
THEORY **:** Most conductors show ohmic character when current passes through them. There is a linear relationship between the potential difference across such a conductor and the current passing through it:

$$\Delta V = R\,I$$

where the proportionality constant R is the resistance. This is Ohm's Law.

APPARATUS **:** Ammeter (0.5 A), voltmeter (3 V), rheostat, 2-V power supply, resistance board, knife switch.

PROCEDURE **:** Construct the circuit with the 2-V DC-power supply. Vary the applied voltage with the help of the rheostat and record ten readings for the current and the corresponding voltage across the conductor. Calculate the corresponding resistance for each voltage-current pair and compute the average and the standard deviation of the resistance.



MEASUREMENT OF RESISTANCE - OHM'S LAW

Name & Surname : **Experiment #:**

Section : **Date :**

QUIZ:

DATA:

Draw the circuit:

Unknown Resistance Number = ...

# of measurements, ***N***	***Voltage across the Resistance V ( )***	***Current in the Circuit I ( )***
	# of Significant Figures :	***# of Significant Figures :***
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

CALCULATIONS:

# of measurements, N	R_i ( ) # of Significant Figures :	$R_{average}$ - R_i ( )	$(R_{average} - R_i)^2$ ( )
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
$\sum_{i=1}^{N}(R_i) =$ Average of R =		$\sum_{i=1}^{N}(R_{average} - R_i)^2 =$	

Description	Symbol		Calculation (show each step)	Result
Mean Resistance	R_{average}	=	. . . .	
			. . . .	
Standard Deviation of the Resistance Value	σ_R	=	. . . .	
			. . . .	

RESULT:

$\boldsymbol{R = R_{\text{average}} \pm \sigma_R =}$ . . . .

Show the Dimensional Analysis of $\boldsymbol{R}$ clearly:

2. *AMMETERS AND VOLTMETERS*

OBJECTIVE **:** To convert a galvanometer into an ammeter and a voltmeter of a given range.

THEORY **:** Ammeters are instruments for measuring the current passing through them. Ideally they should have zero internal resistance so that the voltage across them will be zero without changing the circuit characteristics that they are connected. However, the real ammeters have some resistance even though it is very small.

Voltmeters are instruments to measure the potential difference between the two points they are connected in a specific circuit. Ideal voltmeters should have infinite internal resistance so that they do not draw current from the circuit that they are connected. But the real voltmeters have some finite internal resistance.

To build a voltmeter we could use a sensitive galvanometer with a very high internal resistance to start with. Since we will be connecting the voltmeter in parallel to any circuit section with a voltage difference up to a maximum value, we should connect a series resistance to the galvanometer. If the full scale deflection (FSD) is desired to be V, then equating the voltage across the voltmeter to V would give us:

$$I_G R_G + I_G R_{series} = V$$

where I_G and R_G are the galvanometer current and internal resistance, respectively. We can determine the series resistance from this expression.

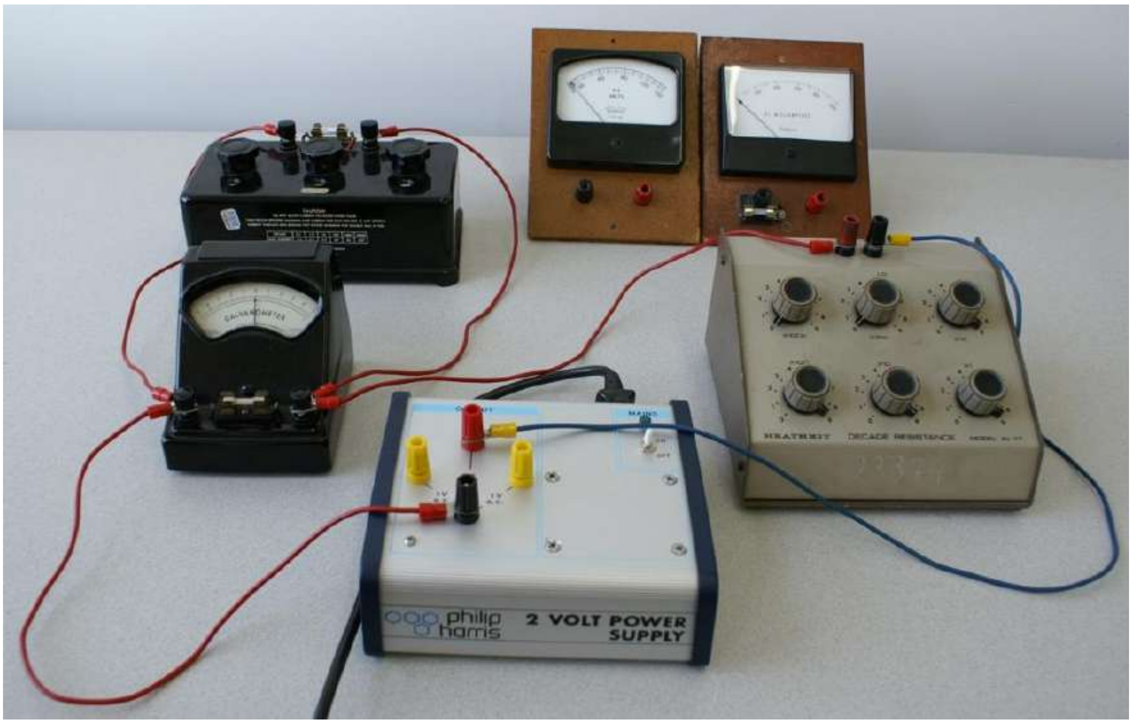
We can also use the same galvanometer to construct an ammeter. This time we should connect a parallel resistance to the galvanometer to shunt the excess current from the galvanometer. In this case the voltage difference across the galvanometer and the shunt resistance will be the same:

$$I_G R_G = (I - I_G) R_{paralel}$$

where I is the current at which the galvanometer shows full scale deflection. We can determine the parallel resistance from this expression for our ammeter.

APPARATUS **:** Galvanometer, various wires and resistance boxes, switch, voltmeter, ammeter, and a 2-V power supply.

PROCEDURE **:** Procedure is included in the worksheet part.


philip harris
2 VOLT POWER SUPPLY
HEATHKIT DECADE RESISTANCE

AMMETERS AND VOLTMETERS

Name & Surname : **Experiment #:**

Section : **Date :**

QUIZ:

PROCEDURE, DATA and CALCULATIONS:

PART – 1: DETERMINATION OF THE CONSTANTS OF A GALVANOMETER

Draw the circuits:

Set the resistance to 9999Ω and reduce it till you observe **F**ull **S**cale **D**eflection on the Galvanometer scale. Read R_1.

Set the paralel resistance to 999Ω and reduce it till you observe **H**alf **S**cale **D**eflection on the Galvanometer scale. Read R_2.

Description / Symbol		**Formula / Value & Unit**
Resistance to set for **FSD**	R_1 =	. . . .
Applied Potential	V_{app} =	. . . .
Resistance to set for **HSD**	R_2 =	. . . .
Internal resistance of the Galvanometer	R_G =	. . . .
Max. Galvanometer Current	I_G =	. . . .
		. . . .

PART – 2: CONSTRUCTION OF AN AMMETER

Circuit for ammeter:

Description / Symbol	Value & Unit
Range for the Constructed Ammeter *(given)* I_R =	. . . .
Resistance per unit length of the Copper Wire ρ_{cw} =	. . . .

Description / Symbol	Calculation (show each step)	Result
Shunt Resistance R_S =	. . . .	. . . .
	. . . .	
Length of the Copper Wire L =	. . . .	. . . .
	. . . .	

Circuit in which the constructed ammeter is used:

Description / Symbol	**Value / Calculation**	**Result**
Value read from the Galvanometer G_x =	. . . .	
Value read from the Constructed Ammeter I_{EV} =	. . . .	. . . .
	. . . .	
Value read from a Real Ammeter I_{TV} =	. . . .	. . . .
	. . . .	

% Error for *I*:

PART – 3: CONSTRUCTION OF A VOLTMETER

Circuit of voltmeter:

Description / Symbol	Calculation (show each step)	Result
Range for the Constructed Voltmeter V_R	$=$ given $=$	. . . .
Series Resistance R_{Ser}	$=$	. . . .
	. . . .	
	. . . .	

Circuit in which the constructed voltmeter is used:

Description	Symbol	Value / Calculation	Result
Value read from the Galvanometer	$Gx =$	. . . .	. . . .
Value read from the Constructed Voltmeter	V_{EV} =	. . . .	. . . .
Value read from a Real Voltmeter	V_{TV} =	. . . .	. . . .

% Error for *V*:

QUESTIONS : *(answer 1 or 2 for Ammeter experiment and 3 or 4 for Voltmeter experiment)*

1) A certain DC voltmeter has an internal resistance of 1000 Ohms per volt. What current in milliamperes is required for full scale deflection?

2) What would be the values displayed by two ammeters be if they are connected in series in a circuit? Would the answer be different if their internal resistances were different?

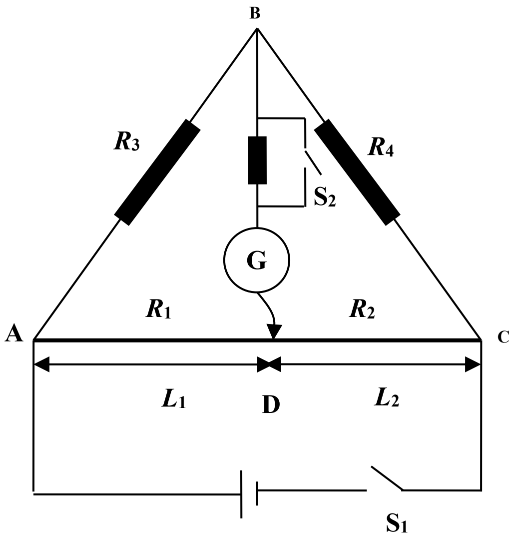
3) When you connect two voltmeters with different internal resistances in series to a battery, what would they display? What happens if they are connected in parallel to the battery?

4) An ammeter and a voltmeter will be used to measure the current and the voltage across an electric lamp, respectively. If the voltmeter is connected as an ammeter and the ammeter as a voltmeter, what will happen?

3. *WHEATSTONE BRIDGE*

OBJECTIVE: To determine the resistance of various conductors and their series and parallel combinations using a slide-wire Wheatstone Bridge.

THEORY :



In Wheatstone bridge there are two pairs of resistors connected in parallel. A galvanometer is connected between the points where individual resistors are connected together in each pair. To protect the galvanometer against excessive currents, a large resistance is connected in series with the galvanometer with the option to short it out using a switch. A low voltage power supply is connected across the points where each pair is connected in parallel to each other. In slide-wire Wheatstone Bridge case one pair of resistors is simply a wire and the galvanometer is connected to a point on the wire with the help of a sliding connection. The resistance ratio on this part of the circuit is simply the ratio of the lengths of the wire sections on each side of the sliding connection.

Assuming that the resistances in the wire part of the circuit are R_1 and R_2 and the other part are R_3 and R_4, let us further assume that the current passing through the wire part is I_1 and the other part is I_2. Then, adjusting the position of the sliding contact on the wire, the current through the galvanometer is brought to zero. This means that the potential differences across the resistances opposing each other in each pair will be equal:

$$I_1 R_1 = I_2 R_3$$

$$I_1 R_2 = I_2 R_4$$

Dividing the first expression by the second one, we get

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} = \frac{L_1}{L_2}$$

since the resistance of a wire is proportional to its length, cross section and its material. Both parts being part of the same wire, the ratio of the resistances is equal to the ratio of their lengths. Using such a bridge and a known resistance, we can determine the value of an unknown resistance as:

$$R_x = R_1 \, (100 - L_1) / L_1$$

for a 100 cm wire in the bridge.

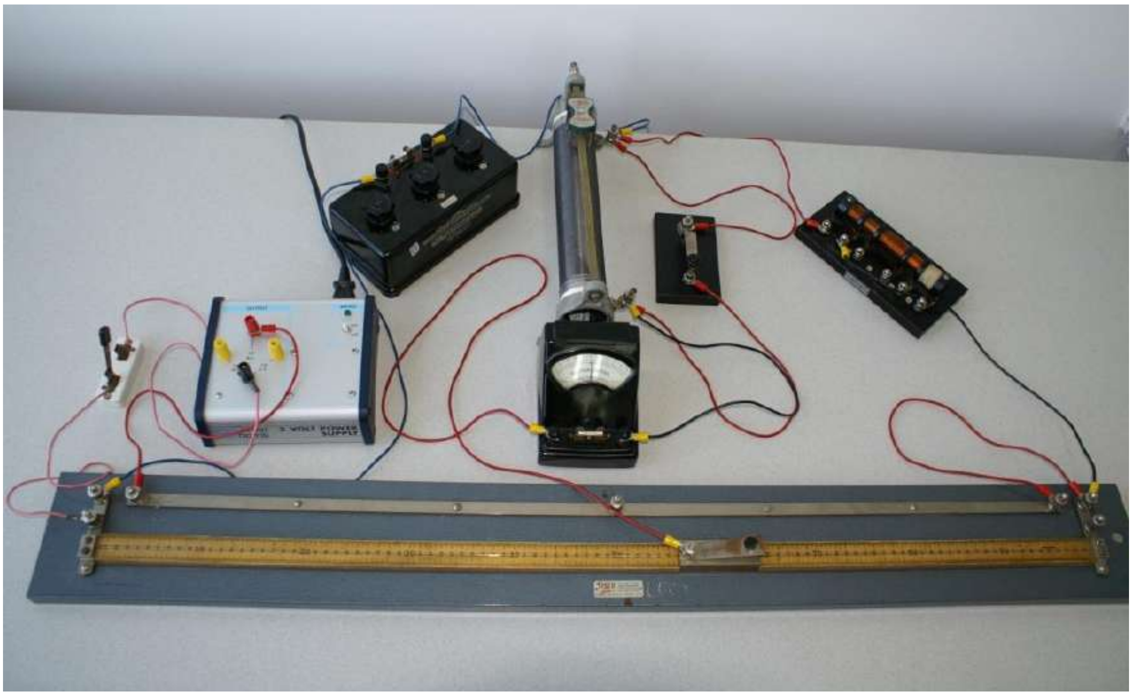
APPARATUS **:** Slide-wire Wheatstone Bridge, galvanometer, resistance box, large resistance (rheostat), unknown resistance set, 2 switches, 2-V power supply.

PROCEDURE **:**

- Connect the circuit. Set the resistance box to an appropriate value and move the contact key on the slide wire until bridge is balanced. For the final precise adjustments close the switch and observe zero deflection on the galvanometer. Calculate the value of the unknown resistances.

- Combine any two non-adjacent conductors **in series** and place them into the bridge. Determine the value of the combined resistance.

- Combine the same conductors **in parallel** and place them into the bridge. Determine the value of the combined resistance.



WHEATSTONE BRIDGE

Name & Surname : **Experiment #:**

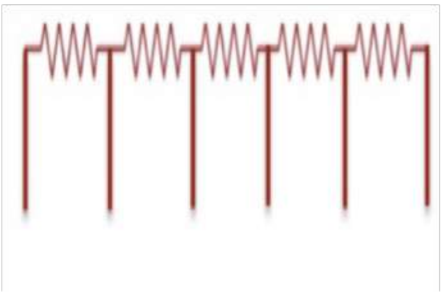
Section : **Date :**

QUIZ:

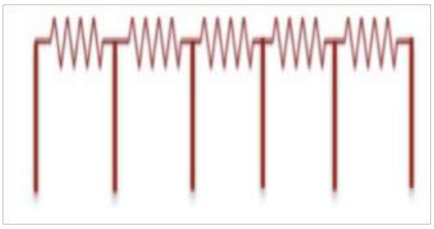
DATA:

Draw The Circuit:

Show Series Connection:



Show Parallel Connection:



Name of the Resistance	R_1 ( ) (Resistance Box)	L_1 ( )	L_2 ( )
		# of Significant Figures =	*# of Significant Figures =*
R_A			
R_B			
R_C			
R_D			
R_E			
R_{series} (and)			
$R_{Parallel}$ (and)			

CALCULATIONS and RESULTS:

Symbol	Calculations (show each step)	Result
R_A =	. . . .	
R_B =	. . . .	
R_C =	. . . .	
R_D =	. . . .	
R_E =	. . . .	

Symbol	Calculations (show each step)	Result
R_s =	. . . .	. . . .
$R_{//}$ =	. . . .	. . . .
R_s = *(Theoretical calculation)*	. . . .	. . . .
$R_{//}$= *(Theoretical calculation)*	. . . .	. . . .
% Error for R_s :	. . . .	. . . .
% Error for $R_{//}$:	. . . .	. . . .

Dimension for *R*: . . . .

QUESTIONS :

1) Explain what happens when the galvanometer and the power supply are exchanged in a balanced Wheatstone bridge.

2) Determine the uncertainty ΔR in the value of the unknown resistance if the uncertainty in determining the balance point on the slide-wire is ΔL.

3) Calculate the current in each resistance and the parts of the wire assuming that the power supply provides 2 V

4. *FORCE BETWEEN CHARGED PLATES*

OBJECTIVE : To measure the force between two parallel plates as the voltage across them is varied, and to analyze the dependence of this force on the constants of the system, and to determine the permittivity constant.

THEORY : The force between two charged plates can be shown as:

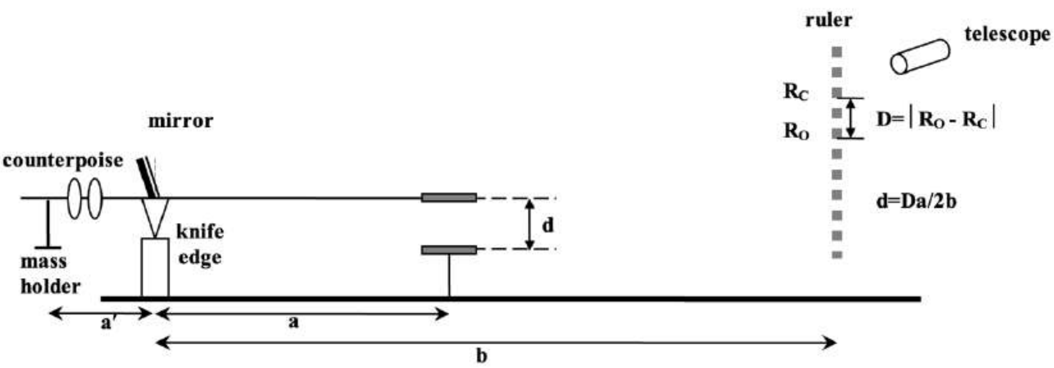
$$F = \frac{\varepsilon_o A}{2d^2} V^2$$

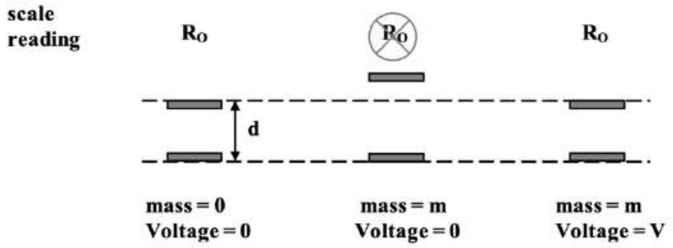
where ***A*** is the area of the plates, ***d*** is the separation between the plates and ***V*** is the voltage across them.

APPARATUS : Specially constructed apparatus, telescope with a ruler attached, high voltage power supply.

PROCEDURE :

$$2.6mm \le d \le 3.4mm$$





$$F_e = kV^2$$

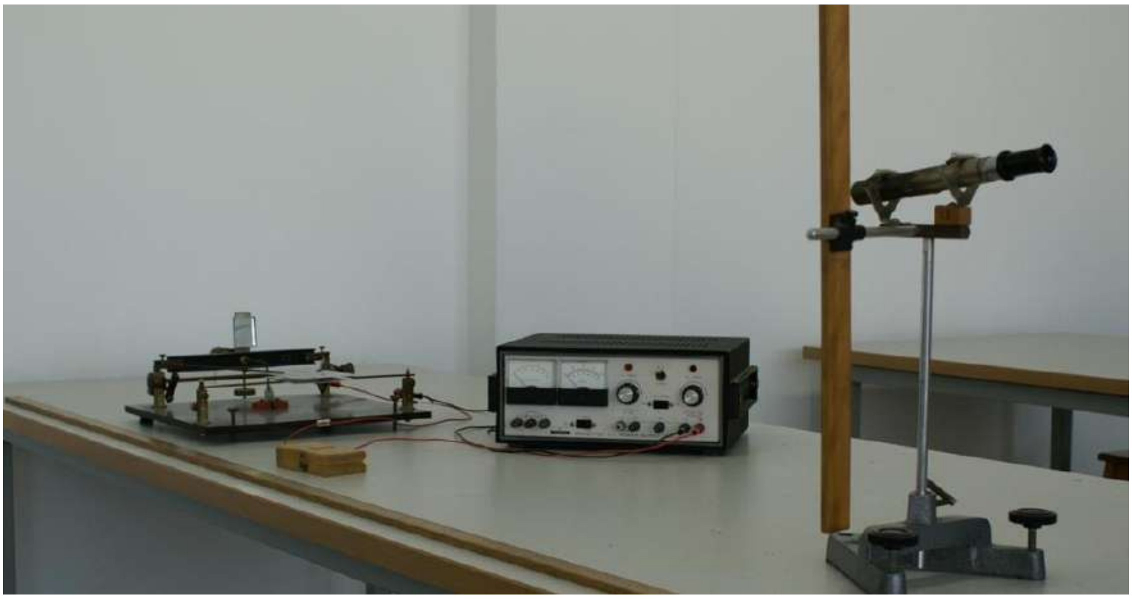
$$k = \frac{\varepsilon_o A}{2d^2}$$

Adjust the counterpoise so that the separation between the plates is about 3 mm. Record the scale reading at equilibrium. Then the upper plate is depressed until it is in contact with the lower plate, and a new scale reading is recorded. The separation *d* is calculated using the expression

$$d = Da/2b$$

where D is the difference in the readings on the ruler attached to the telescope, b is the distance between the knife edge and the telescope, and a is the distance between the knife edge and the plate center.

Add weights to the mass holder and increase the voltage until the original value of the plate separation d is recovered. Record the corresponding values of V and m. Compute the value of F_e for each value of m. Plot F_e versus V^2 and find ε_o from the slope.



FORCE BETWEEN CHARGED PLATES

Name & Surname : **Experiment #:**
Section : **Date :**

QUIZ:

DATA:

Description	**Symbol**		**Value & Unit**
	$(\varepsilon_o)_{TV}$	=	$8.85\ 10^{-12}$ N/V^2
Length of the lever arm	a	=	. . . .
Lever arm for the weight	a'	=	. . . .
Distance from the mirror scale to the ruler	b	=	. . . .
Length of the plate	L	=	. . . .
Area of the plate	A	=	. . . .
Reading when the plates are open	R_O	=	. . . .
Reading when the plates are closed	R_C	=	. . . .

Description	Symbol		Calculation (show each step)	Result
Difference in readings	D	=	. . . .	. . . .
Separation between the plates	d	=	. . . .	. . . .
			. . . .	

Limits for *d*: 2.6 mm. $\leq d \leq$ 3.4 mm.

Mass **m ( )**	**$F_e = mga'/a = kV^2$ ( )**	**Potential** **V ( )**	**Square of Potential** **V^2 ( )**

CALCULATIONS and RESULTS:

Draw a graph between F_e and V^2:

A) **From the graph, choose two SLOPE POINTS other than data points,**

SP_1 : (;)

SP_2 : (;)

B) Calculate,

Description	**Calculation (show each step)**	**Result**
SLOPE =	. . . .	. . . .
	. . . .	
$(\mathcal{E}_0)_{EV}$ =	. . . .	. . . .
	. . . .	

% Error for $\mathcal{E}_0$:

Show the Dimensional Analysis for $\mathcal{E}_0$:

QUESTIONS :

4) Using geometrical and optical properties, show that $d=Da/2b$.

5) What are the dimensions of the slope when you plot F versus V^2?

5. *THE CATHODE RAY OSCILLOSCOPE*

OBJECTIVE **:** To learn how to operate a cathode ray oscilloscope and how to use it in studying alternating current (AC) circuits.

THEORY **:** Cathode Ray Tube Oscilloscope displays all types of waveforms with an electron beam hitting the fluorescent screen. Electron beam is deflected according to the voltage applied to its vertical and horizontal inputs through amplifying circuits. Usually the voltage applied to its horizontal input is a periodic signal generated internally so that the screen displays a dynamic picture of the waveform applied to the vertical input. The rate of this internal sweeping frequency is set by the time-base dial or the horizontal sweep rate. Usually the horizontal sweep is calibrated to set specific time interval per centimeter on the screen. Similarly the vertical scale is set by the voltage knobs as specific voltage values per centimeter.

Selecting appropriate vertical gain values, you can measure the voltage as a function of time. Voltage measurements made with an oscilloscope are usually peak-to-peak values as opposed to the root-mean-square values displayed by AC-voltmeters:

$$V_{rms} = \frac{V_{pp}}{\sqrt{2}}$$

Period or time intervals are also determined by measuring the horizontal length and multiplying this length by the horizontal sweep rate. Frequency of a periodic signal is also determined by inverting the period. Make sure that the calibration dials are turned all the way to the right (or in the direction of the arrow next to the dial) to ensure that the V/DIV and TIME/DIV settings are correct.

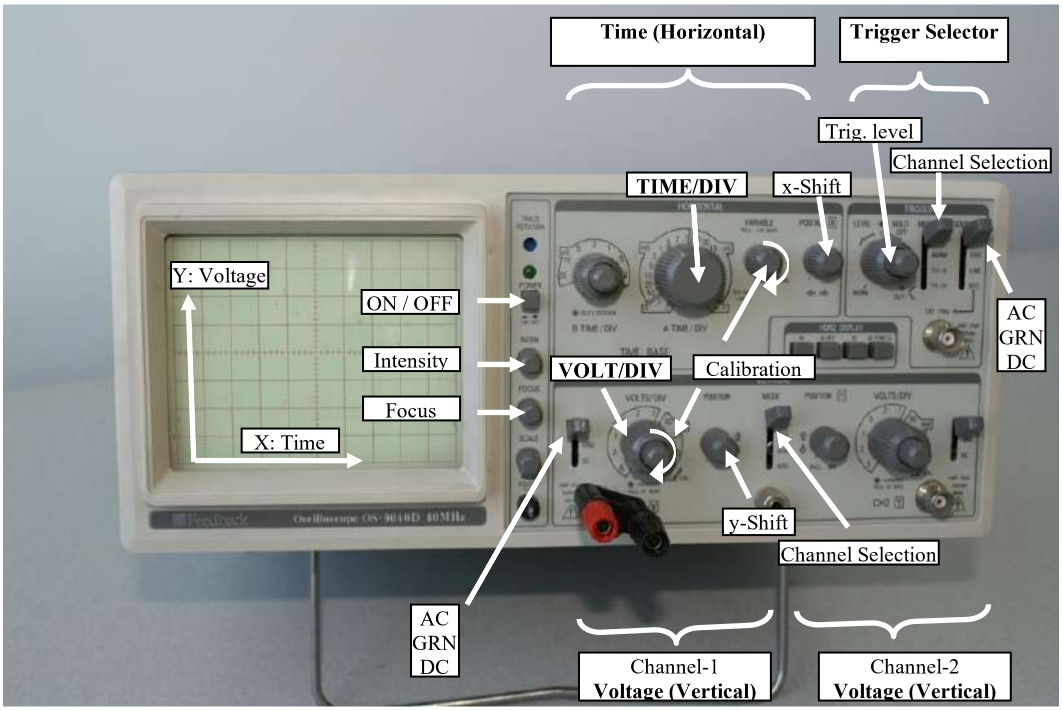
Displayed image on the screen can be moved up and down and left to right with corresponding dials. Starting position of the waveform display can be chosen by the adjustment of the trigger knob either automatically (*auto*) or manually (*normal*). There are also dials to adjust the intensity, focus, astigmatism, and panel lighting. Input type of the signal is selected through the three-position switch next to the vertical gain dial. AC means that the AC component of the signal is displayed. DC means the signal is displayed with its DC offset. GND means the input is grounded. This is selected if you want to make adjustments to the oscilloscope without the interference of the input signal. There are two identical sets of most of these dials in a two-channel oscilloscope that you will be using. You should refer to the oscilloscope manual for more specific dials.

APPARATUS **:** Two-channel oscilloscope and an oscillator.

PROCEDURE :

- Examine the front panel of the oscilloscope to become familiar with the various dials and controls.

- Set the oscillator to produce a sine wave. To measure the frequency of the oscillator, set the TIME/DIV sweep dial to a number of values. For each sweep dial value, measure the length of the wave on the screen and calculate the period. Then, determine the corresponding frequency. Compare the calculated frequency with the oscillator frequency.



THE CATHODE RAY OSCILLOSCOPE

Name & Surname : **Experiment #:**

Section : **Date :**

QUIZ:

DATA AND CALCULATIONS:

Show the formulation for the following:

Length of one wave (λ) = ...

Period (T) = ...

Frequency (f) = ...

V_{pp} (Volt) = ...

V_{max} = ...

V_{rms} = ...

f_{TV}	**500 Hz.** (will be different on Online Lab)

	TIME MESAUREMENTS	
1st Reading	[TIME / DIV]$_1$	
	L_1	
	# of waves$_1$ in L_1	
	Length of the wave, λ_1	
	Period, T_1	
	Frequency, $f_{EV\text{-}1}$	

2nd Reading	[TIME / DIV]$_2$	
	L_2	
	# of waves$_2$ in L_2	
	Length of the wave, λ_2	
	Period, T_2	
	Frequency, $f_{EV\text{-}2}$	
	$f_{EV} = (f_{EV\text{-}1} + f_{EV\text{-}2})/2$	

% Error for f:

VOLTAGE MEASUREMENT	
[VOLT / DIV]	
V_{pp} (div)	
V_{pp} (Volt)	
$V_{max} = V_{pp} / 2$	
$V_{rms} = V_{max} / \sqrt{2}$	

f_{TV}	**10,000 Hz.** (will be different on Online Lab)

	TIME MESAUREMENTS	
1st Reading	[TIME / DIV]$_1$	
	L_1	
	# of waves$_1$ in L_1	
	Length of the wave, λ_1	
	Period, T_1	
	Frequency, f_{EV-1}	

2nd Reading	[TIME / DIV]$_2$	
	L_2	
	# of waves$_2$ in L_2	
	Length of the wave, λ_2	
	Period, T_2	
	Frequency, f_{EV-2}	
	$f_{EV} = (f_{EV-1} + f_{EV-2})/2$	

% Error for f:

VOLTAGE MEASUREMENT	
[VOLT / DIV]	
V_{pp} (div)	
V_{pp} (Volt)	
$V_{max} = V_{pp} / 2$	
$V_{rms} = V_{max} / \sqrt{2}$	

f_{TV}	**20,000 Hz**. (will be different on Online Lab)

TIME MESAUREMENTS	
[TIME / DIV]	
L	
# of waves in L	
Length of the wave, λ	
Period, T	
Frequency, f_{EV}	

% Error for f:

UNKNOWN FREQUENCY:

$V_{\text{measured}} = V_{TV}$	

TIME MESAUREMENTS	
[TIME / DIV]	
L	
# of waves in L	
Length of the wave, λ	
Period, T	
Frequency, f_{EV}	

VOLTAGE MEASUREMENT	
[VOLT / DIV]	
V_{pp} (div)	
V_{pp} (Volt)	
$V_{max} = V_{pp} / 2$	
$V_{rms} = V_{max} / \sqrt{2}$	

% Error for V_{rms} :

6. CHARACTERISTICS OF A CAPACITOR

OBJECTIVE : To observe and measure the effects caused by the growth and decay of currents in a capacitor.

THEORY : When you connect a capacitor and a resistor in series and apply a specific waveform, the behavior of the circuit can be understood by applying the Kirchoff's laws:

$$R\frac{dq}{dt} + \frac{q}{C} = V_{app}\,.$$

Solution of this first order differential equation depends on the applied waveform. If the applied voltage is constant, then the solution for the charge or the voltage on the capacitor is a function that increases exponentially until it reaches the maximum value. On the other hand if we apply a square wave signal, choosing a period much longer than the half-life of the RC circuit or the RC time constant,

$$t_{1/2} = (\ln 2)RC\,,$$

provides us with a waveform repeatedly displaying the discharge of the capacitor when the square wave goes to the low level or "turns off."

On the other hand, if we go to the other extreme and choose a square wave signal with a period much shorter than the RC time constant, then the voltage across the capacitor is basically the integral of the applied potential. The circuit equation above can be approximated as:

$$R\frac{dq}{dt} \approx V_{app} \Rightarrow \frac{dq}{dt} = \frac{V_{app}}{R}$$

since the voltage on the capacitor is negligible compared to the voltage across the resistance. Even though we neglect the voltage across the capacitor when determining the current passing through the RC circuit, we can still get a nonzero voltage across it.

$$V_c = \frac{q}{C} = \frac{1}{RC}\int V_{app}\,dt$$

with the approximation that $V_c \ll V_{app}$.

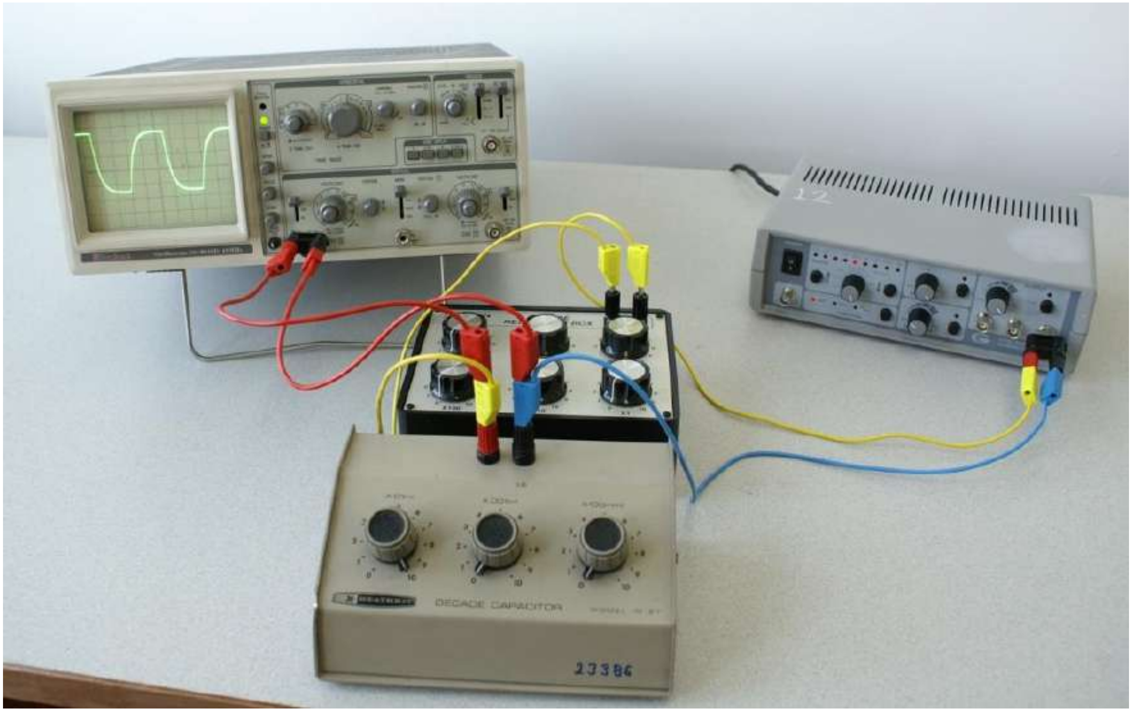
APPARATUS : Oscilloscope, oscillator, resistance and capacitor boxes.

PROCEDURE :

Part 1: Use 3000 Ω (will be different on Online Lab) for R and 0.1 μF for C. Calculate the true value of half-life of the RC circuit and determine the square wave frequency to set.

Construct your circuit and turn on your oscilloscope. Adjust the controls for optimum focus, stability and trigger action. From observed pattern on the oscilloscope screen, measure $t_{1/2}$. Calculate R.

<u>Part 2:</u> Use the same circuit, but set much higher frequency on the Square Wave Generator. Draw one period of the applied square wave voltage and using the same scale draw the corresponding pattern for the voltage across the capacitor below that. Show that the capacitor voltage is proportional to the integral of the applied square wave voltage



CHARACTERISTICS OF A CAPACITOR

Experiment # :
Date :

QUIZ:

DATA and CALCULATIONS:

PART - 1: DISCHARGING CHARACTERISTICS

Draw the Circuit:

Description	**Symbol**		**Value & Unit**	**# of Significant Figures**
Resistance set on the Resistance Box	R	=	....	....
Internal Resistance of the SWG	R_{SWG}	=	....	....
Total Resistance *(True Value)*	R_T	=	....	....
Capacitance	C	=	....	....
[VOLT/DIV]		=	....	....
[TIME/DIV]		=	....	....

Description	Symbol		Calculation (show each step)	Result
True Value of the Half-Life	$t_{1/2}$	=	....	....
Period	T	=	$20\ t_{1/2}$ =...................	....
Frequency of the SWG	f_{SWG}	=	....	....
Half-Life in cm	$t_{1/2\mathrm{EV}}$	=	....	....
Half-Life in sec	$t_{1/2\mathrm{EV}}$	=	....	....
Total Resistance of the circuit	R_{EV}	=	....	....

% Error for *R*:

PART - 2: AN INTEGRATING CIRCUIT

Description	Symbol		Value & Unit	# of Significant Figures
Frequency of the SWG	f_{SWG}	=	. . . .	. . . .
Total Resistance	R_T	=	. . . .	. . . .
Capacitance	C	=	. . . .	. . . .
[TIME/DIV]		=	. . . .	. . . .
for Saw-Tooth Pattern [VOLT/DIV]		=	. . . .	. . . .
for Applied Voltage [VOLT/DIV]		=	. . . .	. . . .

Draw the Capacitor Voltage Waveform:

Draw the applied Square Waveform:

From the Graphs for the chosen t_1 and t_2, read the following data:

Symbol & Formula		**Calculation (show each step)**	**Result**
$V_c = V_{c2} - V_{c1}$	=	. . . .	. . . .
		. . . .	
$\int_{t_1}^{t_2} V_{app}\,dt$	=	. . . .	. . . .
		. . . .	
$(\frac{1}{R_T C})_{TV}$	=	. . . .	. . . .
		. . . .	
$(\frac{1}{R_T C})_{EV} = \frac{V_{c2} - V_{c1}}{\int_{t_1}^{t_2} V_{app}\,dt}$	=	. . . .	. . . .
		. . . .	
% Error for (1/*RC*)	**=**	. . . .	. . . .

7. *FORCE BETWEEN CURRENT CARRYING WIRES*

OBJECTIVE : To measure the force between parallel, current carrying conductors and to analyze the dependence of this force on the constants of the system.

THEORY : Force between the current carrying wires is given as:

$$F = \frac{\mu_o}{2\pi}\frac{L}{d}I_1 I_2$$

and if the same current is passing through the wires as:

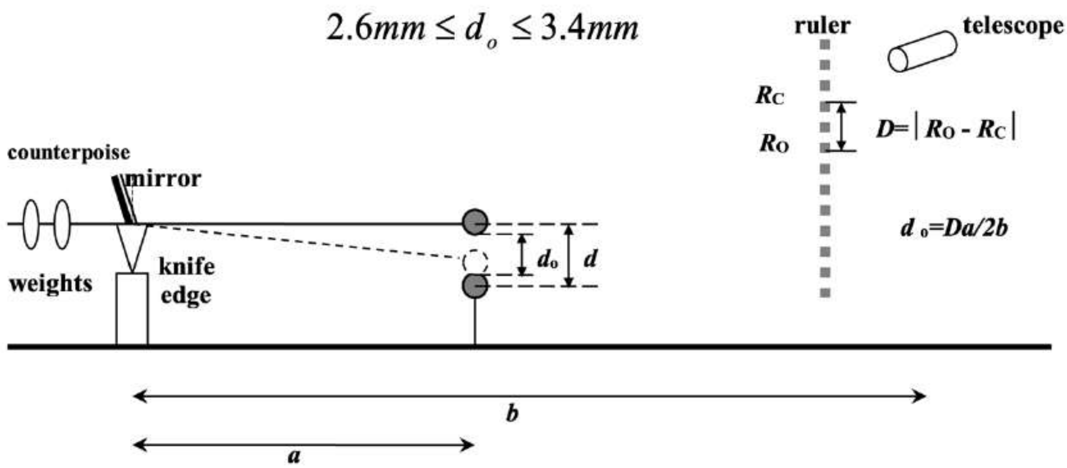
$$F = \frac{\mu_o}{2\pi}\frac{L}{d}I^2$$

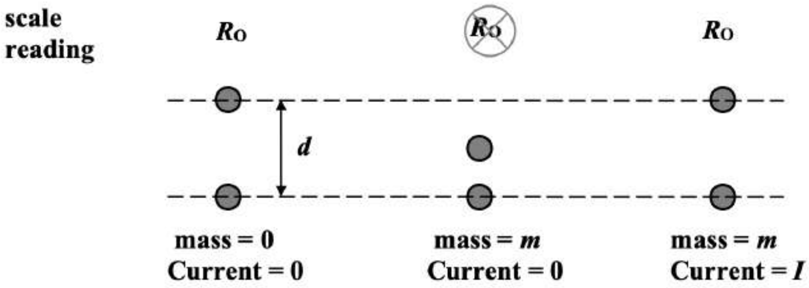
where L is the length of the wires and d is the separation between the parallel wires. By measuring the force between current carrying parallel wires as a function of the current passing through them, we can determine the permeability of air. When the force values are plotted as a function of the squares of the corresponding current values, the straight line that fits the data best will have a slope that includes the permeability constant. From the slope of the straight line we can calculate the permeability constant as:

$$\mu_o = \frac{2\pi(slope)d}{L}$$

APPARATUS : Parallel-wires apparatus, telescope with a ruler, meter stick, 9-A AC-ammeter, AC power supply with a transformer.

PROCEDURE:



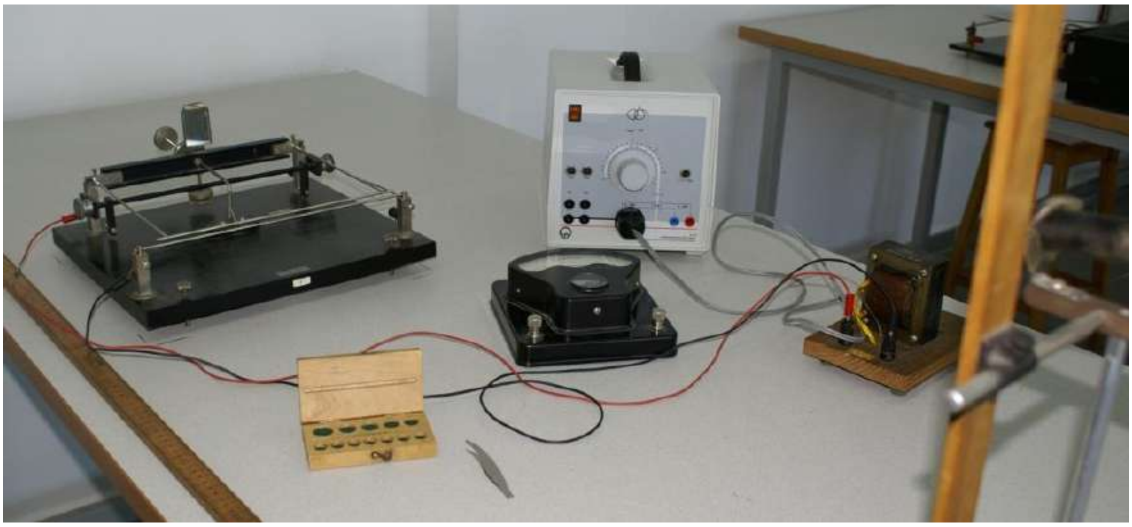


$$F_m = kI^2$$

$$k = \frac{\mu_o}{2\pi}\frac{L}{d}$$

Adjust the counterpoise so that the separation between bars, d_o, is about 3 mm. Record the scale reading at equilibrium (R_o). Then the upper bar is depressed until it is in contact with the lower bar, and a new scale reading is noted (R_c). The separation d_o is calculated.

To make measurements, add a certain mass to the weight pan, increase the current until the scale reading indicates the initial reading, R_o. Read the ammeter. Plot F_m versus I^2 and determine μ_o.



FORCE BETWEEN CURRENT CARRYING WIRES

Name & Surname : **Experiment #:**

Section : **Date :**

QUIZ:

DATA:

Description	**Symbol**		**Value & Unit**
	μ_{oTV}	=	$4\pi \times 10^{-7}$ N /A^2
Length of the lever arm	a	=	....
Distance from the scale with the mirror to the ruler	b	=	....
Diameter of the wire	$2r$	=	....
Length of the wire	L	=	....
Reading when the wires are open	R_O	=	....
Reading when the wires are closed	R_C	=	....

Description	Symbol	Calculation (show each step)	Result
Difference in readings	D =	. . . .	. . . .
Separation between the wires	d_o =	. . . .	. . . .
Separation between the wire centers	d =	. . . .	. . . .

Mass ***m*** **( )**	**Current** ***I*** **( )**	$F_m = m.g = k I^2$ **( )**	**Square of the Current** I^2 **( )**

Plot F_m versus I^2:

A) From the graph, choose two SLOPE POINTS other than data points,

SP_1 : (;)

SP_2 : (;)

B) Calculate,

Description		**Calculation (show each step)**	**Result**
SLOPE	**=**	....	....
		....	
$(\mu_o)_{EV}$	=	....	....
		....	
% Error for μ_o	**=**	....	....
		....	

Show the Dimensional Analysis for μ_o:

QUESTIONS :

1) What are the relative current directions in the wires in this experiment? How would you change the procedure or modify the setup if the relative directions were different?

APPENDICES

A. Physical Constants:

Planck's constant	h	6.626×10^{-34} J or 4.136×10^{-21}Mev
	$\hbar$	1.05×10^{-34}J.sec or 6.58×10^{-22} Mev.sec
Universal Gas Constant	R	8.314 J/^{o}K mole
Avagadro's Number	N_A	6.022×10^{23}
Boltzman Constant	k	1.381×10^{-23} J/^{o}K or 8.617×10^{-5} ev/^{o}K
Electron charge	e	1.602×10^{-19} C
Speed of light in vacuum	c	2.998×10^{8} m/sec
Stefan-Boltzman Constant	σ	5.67×10^{-8} W/m^{2}.^{o}K^{4}
Gravitational Constant	G	6.672×10^{-11} N.m^{2}/kg^{2}
Gravitational acceleration	g	9.81 m/sec^{2}
Permeability of Vacuum	μ_o	1.257×10^{-6} H/m or
Permitivity of Vacuum	ε_o	8.854×10^{-12} C^{2}/J.m
Rydberg Constant	R_∞	1.097×10^{7} m^{-1}
Fine structure constant	$\alpha = e^2/(2\varepsilon_o hc)$	7.297×10^{-3}
First Bohr radius	α_o	5.29×10^{-11} m
Charge to mass ratio of the electron	e/m	1.759×10^{11} C/kg
Bohr Magneton	μ_B	9.27×10^{-24} A.m^{2}
Atomic mass unit (amu)	u	1.66×10^{-27} kg or 931.5 Mev
Electron rest mass	m_e	9.11×10^{-31} kg or 511 kev
Proton rest mass	M_p	1.672×10^{-27} kg or 938.2 Mev
Neutron rest mass	M_n	1.675×10^{-27} kg or 939.6 Mev
Compton wavelength of electron	λ_C	$2.43 \times 10_{-12}$ m
$\hbar c$		197 Mev. Fermi
Standard volume of ideal gas		2.24×10^{-2} m^{3}/mole
1 eV		1.602×10^{-19} J
1 amu		931.14 Mev
1 g		5.610×10^{26} Mev
1 electron mass		0.51098 Mev
Ice point	T_o	273.16 ^{o}K

B. Conversion Tables:

LENGTH

	cm	meter	km	$\mathring{A}$	inch	foot	mile
cm	1	10^{-2}	10^{-5}	10^{8}	0.3937	$3.281x10^{-2}$	$6.214x10^{-6}$
meter	100	1	10^{-3}	10^{10}	39.37	3.281	$6.214x10^{-4}$
km	10^{5}	1000	1	10^{13}	$3.937x10^{4}$	3281	0.6214
$\mathring{A}$	10^{8}	10^{10}	10^{13}	1	$3.937x10^{-9}$	$3.281x10^{-10}$	$4.214x10^{-14}$
inch	28.540	0.0254	$2.540x10^{-5}$	$2.540x10^{8}$	1	0.0833	$1.578x10^{-5}$
foot	30.48	0.3048	$3.048x10^{-4}$	$3.048x10^{9}$	12	1	$1.894x10^{-4}$
mile	$1.609x10^{5}$	1609	1.609	$1.609x10^{13}$	$6.336x10^{4}$	5280	1

AREA

	m^2	cm^2	ft^2	$in.^2$	circ mile
m^2	1	10^{4}	10.76	1550	$1.974x10^{9}$
cm^2	10^{-4}	1	$1.076x10^{-3}$	0.1550	$1.974x10^{5}$
ft^2	$9.290x10^{-2}$	929.0	1	144	$1.833x10^{8}$
$in.^2$	$6.452x10^{-4}$	6.452	$6.944x10^{-3}$	1	$1.273x10^{6}$
circular mill	$5.067x10^{-10}$	$5.065x10^{-6}$	$5.454x10^{-9}$	$7.854x10^{-7}$	1

VOLUME

	m^3	cm^3	liter	ft^3	$in.^3$
m^3	1	10^{6}	1000	35.31	$6.102x10^{4}$
cm^3	10^{-6}	1	$1.000x10^{-3}$	$3.531x10^{-5}$	$6.102x10^{-2}$
liter	$1.000x10^{-3}$	1000	1	$3.531x10^{-2}$	61.02
ft^3	$2.832x10^{-2}$	$2.832x10^{4}$	28.32	1	1728
$in.^3$	$1.639x10^{-5}$	16.39	$1.639x10^{-2}$	$5.787x10^{-4}$	1

MASS

	kg	gram	ounce	pound	amu	m slug	ton
kg	1	10^{3}	35.27	2.205	$6.024x10^{26}$	$1.021x10^{-1}$	10^{-3}
gram	10^{-3}	1	$3.527x10^{-2}$	$2.205x10^{-3}$	$6.024x10^{23}$	$1.021x10^{-4}$	10^{-6}
ounce	$2.835x10^{-2}$	28.35	1	$6.250x10^{-2}$	$1.708x10^{25}$	$2.895x10^{-3}$	$2.835x10^{-5}$
pound	$4.536x10^{-1}$	$4.536x10^{2}$	16	1	$2.372x10^{25}$	$4.630x10^{-2}$	$4.536x10^{-4}$
amu	$1.66x10^{-27}$	$1.66x10^{-24}$	$5.854x10^{-26}$	$3.66x10^{-27}$	1	$1.695x10^{-28}$	$1.660x10^{-30}$
m slug	9.806	$9.806x10^{3}$	$3.454x10^{2}$	21.62	$5.9x10^{27}$	1	$9.806x10^{-3}$
ton	10^{3}	10^{6}	$3.527x10^{4}$	$2.205x10^{-3}$	$6.024x10^{29}$	$1.021x10^{2}$	1

TIME

	second	minute	hour	year
second	1	1.667×10^{-2}	2.778×10^{-4}	3.165×10^{-8}
minute	60	1	1.667×10^{-2}	1.901×10^{-6}
hour	3600	60	1	1.140×10^{-4}
year	3.156×10^{7}	5.259×10^{5}	8.765×10^{3}	1

FORCE

	Nt	Dyne	Kg F
Nt	1	10^5	0.1020
Dyne	10^{-5}	1	1.020×10^{-6}
Kg F	9.807	9.807×10^5	1

PRESSURE

	pa	mm Hg	mbar	kgf/m^2	dyne/cm^2	atmosphere
Pascal	1	7.501×10^{-3}	10^{-2}	0.1020	10	9.869×10^{-6}
torr	1.333×10^2	1	1.333	13.6	1.333×10^3	1.316×10^{-3}
mbar	10^2	0.7501	1	10.20	10^3	9.869×10^{-4}
dyne/cm^2	0.1	7.501×10^{-4}	10^{-3}	10.20×10^{-3}	1	9.869×10^{-7}
kgf/m^2	9.807	9.807×10^{-2}	9.807×10^{-2}	1	98.07	9.679×10^{-5}
atm	1.013×10^5	7.601×10^2	1.013×10^{-3}	1.033×10^4	1.013×10^6	1

ENERGY

	Joule	kilowatt-hour	Btu	erg	Calorie	electron volt
Joule	1	2.778×10^{-7}	9.480×10^{-4}	10^7	0.2389	6.242×10^{18}
kilowatt-hour	3.6×10^6	1	3.412×10^3	3.6×10^{13}	8.6×10^5	2.247×10^{25}
Btu	1.055×10^3	2.930×10^{-4}	1	1.055×10^{10}	2.468×10^2	6.585×10^{21}
erg	10^{-7}	2.778×10^{-14}	9.480×10^{-11}	1	2.389×10^{-8}	6.242×10^{11}
calorie	4.187	1.163×10^{-6}	4.053×10^{-3}	4.187×10^7	1	2.613×10^{19}
electron volt	1.602×10^{-19}	4.450×10^{-26}	1.519×10^{-22}	1.602×10^{-12}	3.827×10^{-20}	1

POWER

	watt	erg/sec	calorie/sec	kgfm/sec	Btu/sec	HP
watt	1	10^7	0.2388	0.1020	3.413	1.360×10^{-3}
erg/sec	10^{-7}	1	2.388×10^{-8}	1.020×10^{-8}	3.413×10^{-7}	1.360×10^{-10}
calorie/sec	4.187	4.187×10^7	1	0.4268	14.29	5.694×10^{-3}
kgfm/sec	9.807	9.807×10^7	2.343	1	33.47	133.3
Btu/sec	0.2931	2.931×10^6	6.999×10^{-2}	2.987×10^{-2}	1	3.982×10^{-4}
HP	735.5	7.355×10^9	175.7	75	2.511×10^3	1

MAGNETIC FIELD

	gauss	TESLA	milligauss
gauss	1	10^{-4}	1000
TESLA	10^4	1	10^7
milligauss	0.001	10^{-7}	1

REFERENCES