Experimental Investigations in Introductory Physics

LABORATORY MANUAL
PHYSICS 1010, 1030, 1113, 1133, 1211, AND 1212

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Contents

Part I

INTRODUCTION AND REFERENCE

Chapter 1

Physics—an Experimental Science

The most incomprehensible fact of Nature is
the fact that Nature is comprehensible.

Albert Einstein

Physics is an experimental science based on observations of the world around us. Experiment and theory have both played important roles in the development of our understanding of physics. Sometimes one or the other dominates in a particular advance in physics but often they are so interrelated as to make it difficult to separate the roles. Observations of physical phenomena often result in models or theories or in modifications to existing theories. These theories may be expressed in terms of constants, which must then be experimentally determined, or the theories may suggest possible phenomena for further experimental investigation.

When a theory or model has been extensively tested and found to hold over a wide range of conditions, it may then be considered a 'law' of physics. This may be the case even if it is eventually found that the law does not properly describe observed phenomena under other conditions. Thus, we use the laws of classical mechanics to describe a great many situations even though we know that in other circumstances the laws of quantum mechanics or relativity must be employed for a proper description. Classical mechanics is not so much wrong as it is limited. Likewise, the more general laws of quantum mechanics and relativity someday may be found to be too limited to describe certain observations.

This reliance on observation distinguishes the natural sciences from such areas as metaphysics and astrology. However, the natural sciences also are in contrast to the discipline of mathematics. A mathematical system or theory can be created and it need only be self-consistent. This is, of course, necessary but not sufficient for a physical law. A brief history of the quark theory, which was advanced independently in 1963 by Murray Gell-Mann and George Zweig in an attempt to explain the nature of particles called hadrons, will illustrate the important connection between mathematics and physics. The hadron family consists of particles, like protons and neutrons, whose interaction is dominated by the strong nuclear force and the weak nuclear force. The original quark theory proposed that all hadrons were composed of combinations of three quarks (up, down and strange), which have fractional charges -1/3 and +2/3 times the charge of an electron, and three corresponding antiquarks. The model was successful in predicting many properties of the known hadrons however experimental discrepancies led to the suggestion, in 1967, of the existence of a fourth quark and antiquark (charm). Soon a new hadron, the meson J/ψ, which seemed to be composed of a charm quark and antiquark pair was discovered simultaneously by groups headed by Samuel Ting at Brookhaven National Laboratory and by Burton Richter at Stanford University. Discoveries of even more hadrons led to the proposal of two new quarks named top and bottom. The problem with the quark model was that for many years, and despite numerous experiments, no isolated quarks had been observed and quarks were increasingly regarded as *mathematical entities*.

However, indirect evidence was beginning to accumulate. In 1968, the SLAC-MIT experiment performed by Jerome Friedman, Henry Kendall and Richard Taylor at the Stanford Linear Accelerator Centre revealed an inner structure to protons and neutrons which showed electrical charge was concentrated to components of negligible size. Experimental evidence was also found for the existence of the electrically neutral gluons, which hold the quarks together. Friedman, Kendall and Taylor, a Canadian, were awarded the Nobel Prize in Physics in 1990 for this pioneering work. Today there is firm evidence for the existence of all six quarks. The bottom quark was discovered at Fermilab in 1977 and the very massive top quark in 1995 using a large particle accelerator called the Tevatron. Thus, after many years, the quark model can be accepted as a law of physics.

There are valid reasons for performing experiments for both physics researchers and students: (a) to determine the functional relationship between parameters, (b) to test the validity of a model or theory, (c) to better determine a constant used in a theory or law to describe a relationship. There are examples of each of these types of experiments in this manual. It is hoped these experiments will reinforce concepts discussed in the lectures, introduce related material, provide practise in measurement techniques, data analysis and report writing, and encourage your interest in physics.

Chapter 2

Graphical Representation of Data

. . . that I have succeeded in proposing a new and useful mode of stating accounts has been generally recognized . . . As much information may be obtained in five minutes as would require whole days to imprint on the memory, in a lasting manner, by a table of figures.

William Playfair (1786)

The tool that William Playfair was speaking of in the quote above was the graph. Though Rene Descartes first described the principles on which the modern graph is based in 1637, it was not until the early part of the 20th century that its use became standardized and widespread.

One need only consider a simple table of related values to see the power in the graphical method. Consider the following table.

x	y
-8	-11.13
-6	-8.13
-4	-5.13
-2	-2.13
0	0.88
2	3.88
4	6.88
6	9.88
8	12.88

What is the cause and effect relationship between x and y? This general relationship between two parameters is often what is being looked for through experimentation. Determining it by trying to find the pattern strictly from the numbers in the table can be quite difficult, even when the relationship is simple. The graphical method gives a pictorial view that provides valuable information.

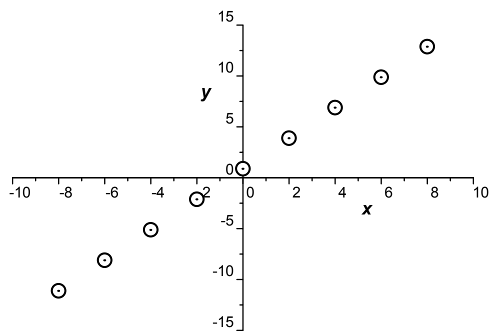


Figure 2.1: Plotted Data

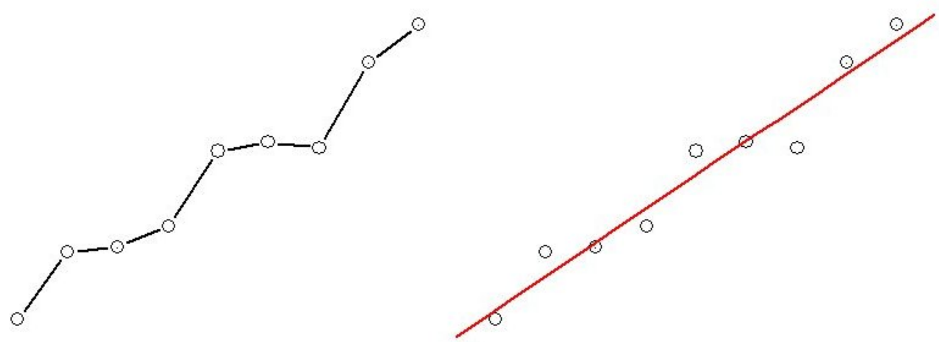
Graphing the data shows a linear relationship in this case. This visual representation of the data makes analysis much easier.

The aim in an experimental study is to vary one condition at a time while holding all others constant and observe the effect on the quantity that is suspected to depend on the first. The existing relationship is most easily interpreted from the graph if the first quantity, the independent variable, is plotted on the abscissa scale (the horizontal or x-axis) and the dependent variable is plotted on the ordinate scale (the vertical or y-axis). For example, say you were interested in finding out how the period of a simple pendulum varies with the pendulum's length. The instruction in the lab manual would ask that you plot T vs. L. The period (T) would go on the vertical axis and the length (L) on the horizontal one.

The choice of an appropriate scale is also an important factor when plotting a graph. The scale for either axis should be chosen such that the entire range of values may be fit onto the graph. Major divisions should be picked in a way that they are easily subdivided. Divisions on the vertical and horizontal axes need not be the same.

2.1 Plotting and Drawing the Curve

Use a sharp pencil and make small dots to locate the points. The coordinates of the points are not generally written on the graph paper. Carefully encircle each of the data points with a 2 to 3 mm circle. It will not always be possible to make all of the points fit on a smooth curve. In cases such as this, a smooth curve should be drawn through the series of points to follow the general trend as shown in figure 2.2(b).



(a) Incorrect Fit for Trend

(b) Correct Fit for Trend

Figure 2.2: Fitting Curves to Data

Sometimes a data point appears to have no relationship to the rest of the data. You should take care not to give the point to much weight when considering the best fit. The graph points out that this point may be inconsistent with the other measurements. It is usually useful, whenever possible to re-evaluate or re-determine the apparent inconsistency.

2.2 Analysis and Interpretation

A principal advantage of the graphical method is the ease with which information can be obtained. The shape of the graph tells us immediately how the dependent variable changes with a change in the independent variable. Of the multitude of possibilities for graphs, the straight line is by far the easiest to analyze.

2.2.1 The Straight Line: A Linear Relationship

The equation of a straight line is $y = mx + b$. These equations have a dependent variable called y and an independent variable called x. The letters x and y, often used in mathematics to represent variables, are rarely used for this purpose in physics. Variables in physics are often denoted by the first letter in the name of the quantity being considered. An example is v for velocity. Many cases also exist where the quantities have been given special symbols, such as letters from the ancient Greek alphabet, like Φ and θ that are used to denote angles. The slope of the line, m, gives the rate at which the dependent variable changes with respect to the independent variable. The last piece of the puzzle represented by this equation is the y-intercept, b. This is usually related to an initial condition.

Consider an example of an apparatus that measures the speed, at different times, of a ball dropped from rest. The ball in this case is under the influence of a constant acceleration, the acceleration due to gravity, g. The equation describing the change in the ball's speed with time is

$$v = gt + v_0$$

The initial condition is the ball's speed at the instant prior to it being dropped. Since the ball is dropped from rest, its initial speed is zero. Thus, $v_0 = 0$. A data set from such an experiment is given below.

t(s)	*v(m/s)*
0.000	0.000
0.500	4.998
1.000	9.604
1.500	14.480
2.000	19.603
2.500	25.235
3.000	29.429
3.500	33.957
4.000	39.396
4.500	43.439
5.000	50.225

Figure 2.3 shows the plotted data and a best-fit line. Points A and B are chosen such that they are on the line and their coordinates are used to determine the slope, g.

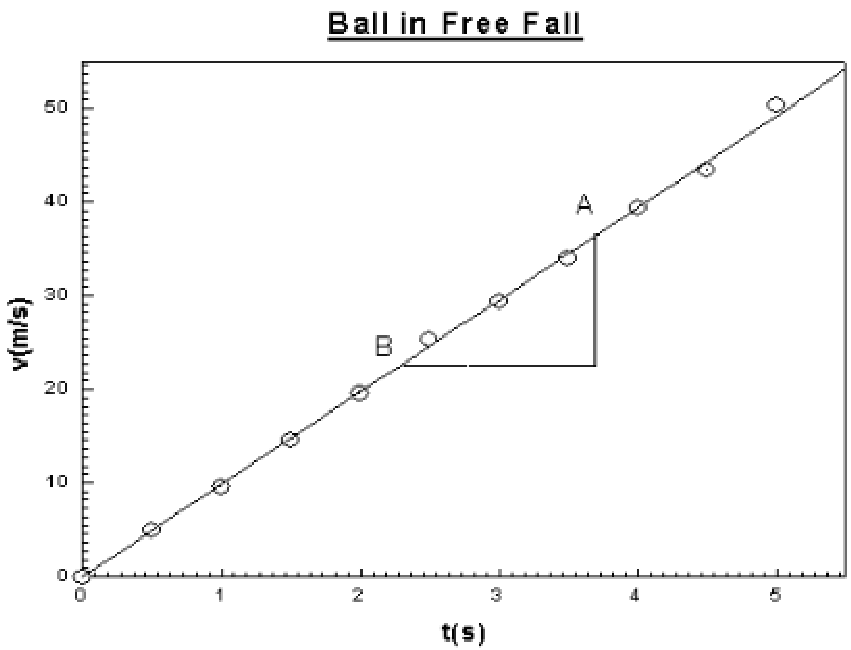


Figure 2.3: $v = gt$

2.2.2 Nonlinear Relationships

A great many of the natural phenomena that are explored in physics are described by relationships that are not linear. The displacement, velocity and acceleration of an ideal harmonic oscillator, for example, are sinusoidal. Other nonlinear relationships that are quite common are power law and exponential relationships. We have powerful mathematical tools at our disposal to deal with the analysis of these last two types of relationships.

An example of a power law relationship comes from the study of fluids. Suppose that we are interested in how force is transmitted through a fluid between two connected cylinders. Say the apparatus consists of a fixed diameter cylinder connected to one that has a variable diameter. We vary the diameter of the one cylinder while measuring the force it produces when a fixed force is applied to the other. A typical dataset is plotted in Figure 2.4.

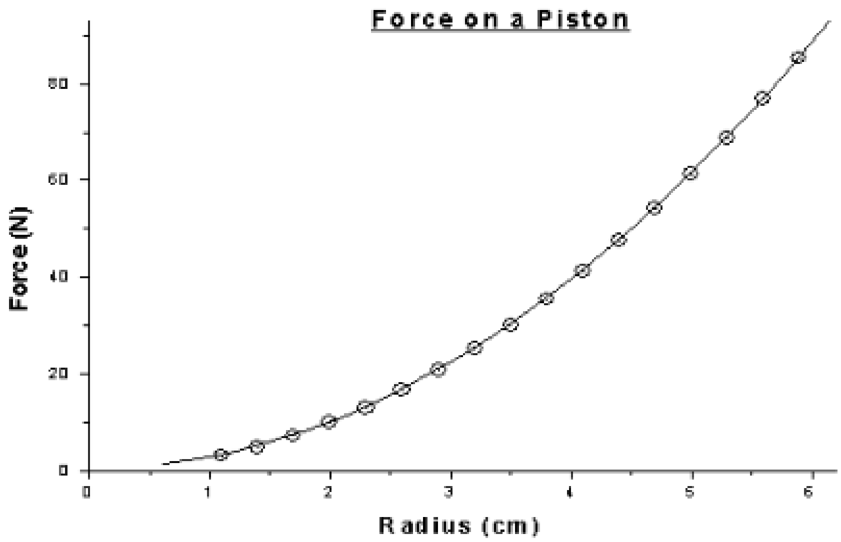


Figure 2.4: Force Transmitted Through a Fluid

Our final example is the exponential relationship that tells us how the pressure of an ideal gas changes with height. This is often used as a model to estimate the changes in atmospheric pressure with changes in altitude. Consider a weather balloon fitted with an altimeter, a barometer and a radio to relay the data to the surface. The plot of such an experiment could look like the graph shown in Figure 2.5.

The previous examples were created using known relationships but experiments often explore undetermined relationships. Suppose that we do not know what the relationships are. Determining them from the data as collected could be somewhat difficult. What tools do we have at hand to simplify the job?

The Exponential Function and Logarithms

In its most general form the exponential function $g(x)$ is given by

$$g(x) = a^x \tag{2.1}$$

where $a \neq 1$ and x is any real number. Now for $x > 0$, $a > 0$, and $a \neq 1$ the logarithmic function is given by

$$f(x) = \log_a(x) \tag{2.2}$$

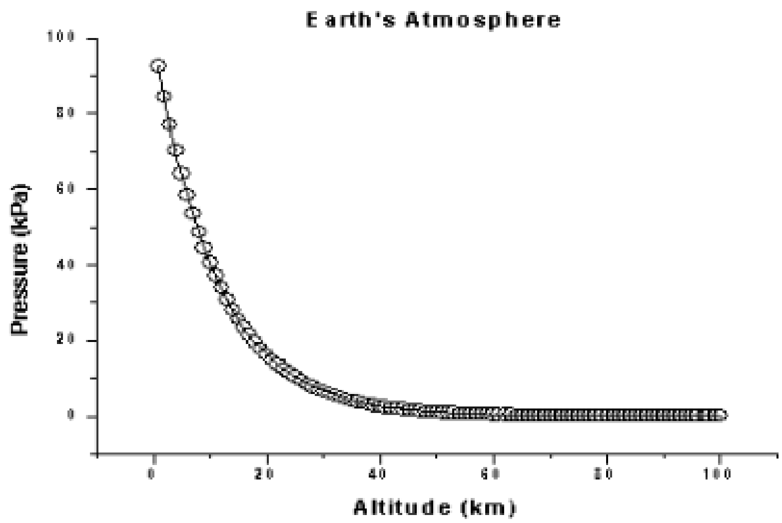


Figure 2.5: Atmospheric Pressure

The logarithm is the inverse of the exponential function. This means that we can recover the exponent x as follows

$$x = a^{\log_a(x)} \tag{2.3}$$

The most commonly used logarithm are the *common logarithm*, which has a base of 10, and the *natural logarithm*, which is of base *e*.

Since logarithms are exponents they follow the simple rules of exponents: Say $u = a^n$ and $v = a^m$

RULE 1:

$$\log_a(uv) = \log_a(u) + \log_a(v) \tag{2.4}$$

which follows from $a^n a^m = a^{(n+m)}$

RULE 2:

$$\log_a\left(\frac{u}{v}\right) = \log_a(u) - \log_a(v) \tag{2.5}$$

which follows from $a^n \div a^m = a^{(n-m)}$

RULE 3:

$$\log_a(u^x) = x\log_a(u) \tag{2.6}$$

which follows from $(a^n)^x = a^{nx}$

The common logarithm is a powerful ally when it comes to the analysis of nonlinear data, so much so that special graphing paper has been designed that makes the calculation of the logarithms themselves unnecessary. The user need only plot the data points directly on the paper. The layout of the paper calculates the logarithm. The graphing paper is available in both log-log and semilog styles. The log—log version takes the logarithm of both sides of the functional relationship whereas the semilog version takes the log of only one side.

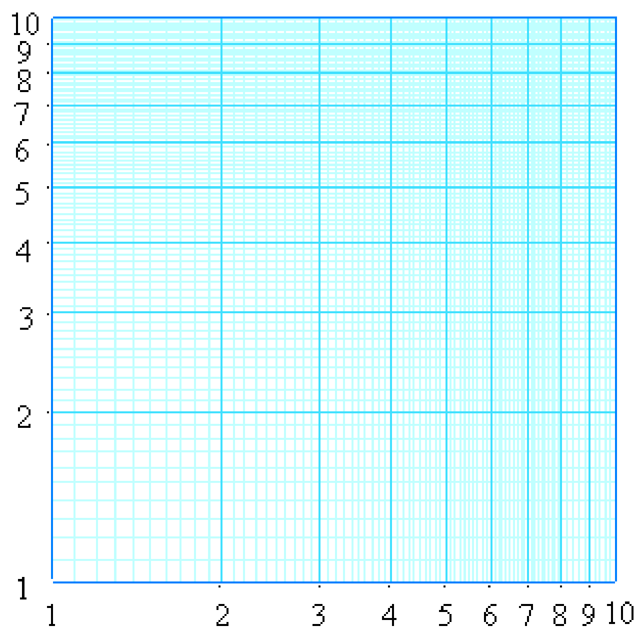


Figure 2.6: Single Cycle log-log Paper

The number of cycles is the number of powers of 10 that can be displayed on the graph. The division indices shown on the axes are multiplied by the power of 10 chosen for each separate axis. As an example, say your data ranges from 12 to 87. This range will fit into a cycle based on 10^1. Multi-cycle graph paper will be required when the data ranges over many powers of 10.

Let's analyze the "Force on a Piston" data using this powerful graphing technique. The radius data ranges from 0 to 6 and the force data from 0 to 100. This means that a single cycle is required on the horizontal axis and two cycles are needed for the vertical one. The data is plotted directly on the graph paper. It is important to remember that no logarithms need to be calculated, the paper does that. The resulting graph is a straight line. This implies that the equation is of the form $F \propto r^n$. The slope of the line gives the power n to which the independent variable, in this case the radius, is raised. The calculation of the slope however requires that the logarithms of the abscissa and ordinate be calculated at two points. Otherwise, the slope calculation follows the standard prescription

$$m = \frac{y_2 - y_1}{x_2 - x_1} \text{ where } (x_i, y_i) \equiv (\log(r_i), \log(F_i)) \qquad (2.7)$$

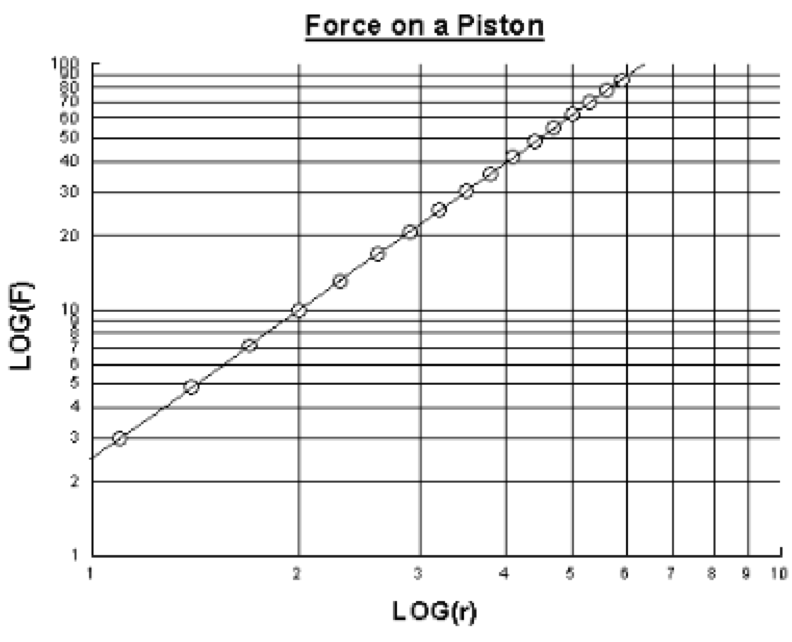


Figure 2.7: Logarithm Plot of the Force Transmitted Through a Fluid

The slope calculation for figure 2.7 gives $m = 2$ which determines that the functional relationship between the Force and the cross-sectional Radius is

$$F \propto r^2$$

Chapter 3

Uncertainty of Measurements

. . . if two persons start to count the vibrations, the one the large, the other the small, they will discover that after counting tens and even hundreds they will not differ by a single vibration, not even by a fraction of one.

Galileo

A measurement may be done quite accurately and using the best experimental technique, but no measurement of a physical quantity is exact. An experimenter needs to know not only the magnitude of a measurement, but also with what accuracy the measurement was performed. Suppose the length of an object is measured to be 5.34 cm, but the accuracy is such that the uncertainty of the measurement is 0.02 cm. This means that the actual length of the object according to this measurement is between 5.32 cm and 5.36 cm. This measurement and its uncertainty can be written as 5.34 ± 0.02 cm. Here the uncertainty has been expressed in absolute terms. Another way to express this uncertainty is to write it as a percentage of the measured quantity, i.e. 5.34 ± 4%. It is necessary to know how to make reasonable estimates of the uncertainties involved in any physical measurements, and how to handle the propagation of these uncertainties when measured quantities are manipulated mathematically. The uncertainty should be stated by no more than two digits and measured value should not include digits outside the limits of this uncertainty, i.e. 5.34 ± 0.02 rather than 5.342 ± 0.02.

It is necessary to understand the difference between two terms used in the discussion of measurement:

a. **accuracy** refers to uncertainty involved in the magnitude of the measurement in comparison with the accepted international standard, whereas

b. **precision** or reliability refers to the reproducible sensitivity of a measurement.

To better understand the distinction between the two, consider the following examples involving a copper rod. If the density of the rod is experimentally determined to be 8.8 ± 0.2 g/cm^3 then the result is accurate in comparison to the accepted density for copper, 8.9 g/cm^3, and *fairly* precise with an uncertainty of less than 2.5%. If we wish to know the length of the rod, then it is the accuracy of the measurement that is important. In a measurement of the change in length of the rod due to thermal expansion, the precision is more important.

There are many causes for inaccuracy or errors in measurements. These are sometimes divided into two types. **Systematic errors** are the result of unwanted effects that show up as consistent or reproducible errors. Systematic errors may be present due to poor experimental technique or apparatus. For example, a voltmeter may be incorrectly calibrated and hence give consistently high readings. **Random errors or scatter** are present in all measurements. These are the results of non-reproducible effects and tend to be random in their sign and magnitude. They can result from such things as temperature variations or estimations of scale division fractions.

3.1 Propagation of Errors

3.1.1 Addition and Subtraction

If two measurements of length are 6.4 ± 0.1 cm and 12.3 ± 0.2 cm, then when the two objects are placed end to end, the total length must be between (6.4-0.1)+(12.3-0.2) = 18.4 cm and (6.4+0.1)+(12.3+0.2) = 19.0 cm. This is the same as adding the magnitudes and adding the uncertainties to obtain 18.7 ± 0.3 cm. A similar *thought experiment* for subtraction will show that the errors also add. **Thus for both addition and subtraction, the absolute uncertainties add**. This can be expressed mathematically with Δx and Δy representing the uncertainty in measurements of x and y respectively:

$$\begin{aligned} z \pm \Delta z &= (x \pm \Delta x) \pm (y \pm \Delta y) \\ &= (x \pm y) \pm (\Delta x + \Delta y) \end{aligned}$$

Thus the uncertainty in *z* is

$$\Delta z = \Delta x + \Delta y \tag{3.1}$$

3.1.2 Multiplication and Division

Consider the uncertainty in a quantity z that is the product of two measured quantities x and y, each having their own uncertainty. That is

$$\begin{aligned} z \pm \Delta z &= (x \pm \Delta x)(y \pm \Delta y) \\ &= xy \pm (x\Delta y + y\Delta x + \Delta x\Delta y) \end{aligned} \tag{3.2}$$

The term $\Delta x\Delta y$ within the brackets in equation (3.2) is of second order in the error terms and can be neglected ($\Delta x\Delta y << x\Delta y + y\Delta x$). Thus, we write that

$$z \pm \Delta z = xy \pm (x\Delta y + y\Delta x) \tag{3.3}$$

Clearly the uncertainty in z is

$$\Delta z = x\Delta y + y\Delta z \tag{3.4}$$

Dividing equation (3.4) by $z = xy$ yields

$$\frac{\Delta z}{|z|} = \frac{\Delta x}{|x|} + \frac{\Delta y}{|y|} \tag{3.5}$$

A similar result holds for division. **Hence, for multiplication and division, the percentage errors add**.

As an example, consider the division

$$x = \frac{64.3 \pm 0.5}{1.20 \pm 0.05}$$

In order to perform this division the uncertainties must be converted to either *relative form* or *percentage form*:

$$x = \frac{64.3 \pm \frac{0.5}{64.3}}{1.2 \pm \frac{0.05}{1.20}} = \frac{64.3 \pm 0.8\%}{1.2 \pm 4.2\%}$$

Now the division can be performed and the uncertainties added to yield

$$\begin{aligned} x &= 53.6 \pm 5\% \\ &= 53.6 \pm 2.7 \end{aligned}$$

Note that results are always written with the uncertainties in absolute form with the uncertainty stated in no more than two digits and the experimental value rounded appropriately.

It also follows that if either x or y is a constant then the percentage error is unchanged and the absolute uncertainty is simply divided or multiplied by the constant just as is the magnitude of the measurement. Thus, for the expression $z = kx$, where k is a constant, we have

$$z \pm \Delta z = k(x \pm \Delta x) \tag{3.6}$$

and

$$\Delta z = |k| \Delta x \tag{3.7}$$

For example

$$\begin{aligned} 3(64.3 \pm 0.5) &= 3(64.3) \pm 3(0.5) \\ &= 129.9 \pm 1.5 \end{aligned}$$

or, equivalently

$$\begin{aligned} 3(64.3 \pm 0.5) &= (3 \pm 0)(64.3 \pm 0.5) \\ &= (3 \pm 0\%)(64.3 \pm 0.8\%) \\ &= 192.9 \pm 0.8\% \\ &= 192.9 \pm (\frac{0.8}{100} * 192.9) \\ &= 192.9 \pm 1.5 \end{aligned}$$

3.1.3 Powers & Roots

Integral powers are a special case of multiplication, so we would expect to simply multiply the uncertainty by the power. It can be shown that the expected integral result holds for in general for real valued exponents. Thus if a quantity having uncertainty is raised to some power, say,

$$z \pm \Delta z = (x \pm \Delta x)^y \text{ where } y \in \mathbf{R} \tag{3.8}$$

then the percentage uncertainty is given by

$$\frac{\Delta z}{|z|} = y\frac{\Delta x}{|x|} \tag{3.9}$$

For powers and roots of a measurement, the uncertainty of the result is the product of the exponent and the percentage uncertainty of this measurement.

Consider the following example

$$\begin{aligned} x &= (5.4 \pm 0.2)^{\frac{1}{2}} \\ &= (5.4 \pm 4\%)^{\frac{1}{2}} \\ &= (5.4)^{\frac{1}{2}} \pm \frac{1}{2}(4\%) \\ &= 2.32 \pm 2\% \\ &= 2.32 \pm 0.05 \end{aligned}$$

3.1.4 Logarithms

You may occasionally need to consider the uncertainty of the logarithm of a measurement. We shall only state the result here. If

$$z \pm \Delta z = \log(x \pm \Delta x),$$

then

$$\Delta z = \max(\left|\log(x+\Delta x) - \log(x)\right|, \left|\log(x-\Delta x) - \log(x))\right| \tag{3.10}$$

Summary

Table I.3.1: Summary of Error Analysis Rules

Operation	Error Term
$z = x \pm y$	$\Delta z = \Delta x + \Delta y$
$z = xy$ or $z = \frac{x}{y}$	$\frac{\Delta z}{z} = \frac{\Delta x}{x} + \frac{\Delta y}{y}$
$z = kx$ where k is a constant	$\Delta z = \lvert k \rvert \Delta x$
$z = x^y$	$\frac{\Delta z}{z} = y\frac{\Delta x}{x}$
$z = \log(x)$	$\Delta z = \max\begin{cases} \lvert\log(x+\Delta x) - \log(x)\rvert \\ \lvert\log(x-\Delta x) - \log(x)\rvert \end{cases}$

3.1.5 Graphing and Uncertainties

When experimental data is plotted on a graph, the uncertainties can be indicated by error bars. Sample data points are plotted in figure 3.1 with error bars for the y-parameter drawn to scale. We shall assume here that the uncertainty in the x-parameter is too small to appear on this graph although it is common to plot data with uncertainty in both the x and y-coordinates. What is the uncertainty in determining the slope of the line through the data points? The solid line indicates a visual best fit to the data. The dashed lines indicate the maximum and minimum slopes, which are consistent with the data, each passing through or near as many error bars as possible. From the graph, it is evident that the experimentally determined slope lies between the maximum and minimum values. The slope can be expressed as

$$m \pm \Delta m = m_{best} \pm \max(\lvert m_{best} - m_{\min}\rvert, \lvert m_{best} - m_{\max}\rvert) \tag{3.11}$$

which reflects the range of possible slope values.

As an example of this technique, refer to figure 3.1 where m_{best}=2.5, $m_{\max}$=2.9, and $m_{\min}$=2.0. The experimentally determined slope is then 2.5 ± 0.5. The y-intercept and its uncertainty can be determined in the same fashion, where, in figure 3.1, $b_{best} = 6.0$, $b_{\max} = 8.0$, and $b_{\min} = 3.5$. Our method determines the intercept to be 6.0 ± 2.5. Combining these results gives us the equation for the data graphed in figure 3.1: $y = (2.5 \pm 0.5)x + (6.0 \pm 2.5)$. It is important to note that if measurements are made over a greater range of x and y parameters, then, though the uncertainty in each measurement may be the same, the uncertainty in the slope and intercept will be reduced.

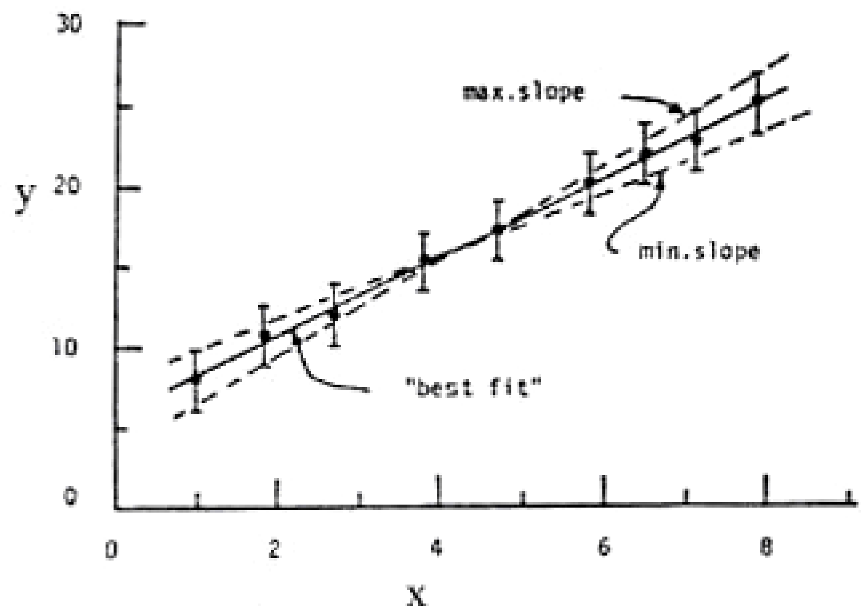


Figure 3.1: Data plotted with error bars. The solid line is a *best fit*, and the dashed lines represent the minimum and maximum slopes indicated by the data. The slope lines have been extrapolated to obtain the y-intercept.

3.1.6 Distribution of Measurements

It is constructive to look a little more closely into the meaning of the term random error. It is assumed that each measurement, x, is just one of a set of a very large number, N, of possible measurements and it is also assumed that this theoretical set of measurements would be distributed symmetrically about the mean value, $\bar{x}$, so that if the number of measurements that yield a value x, n_x, is plotted against the measurement, x, a graph of the form shown in figure 3.2 would be obtained. This theoretical distribution is known as a

Gaussian or normal distribution. The assumption that any particular set of measurements will be Gaussian is not always justified, but because of its great mathematical simplicity, this assumption is usually made.

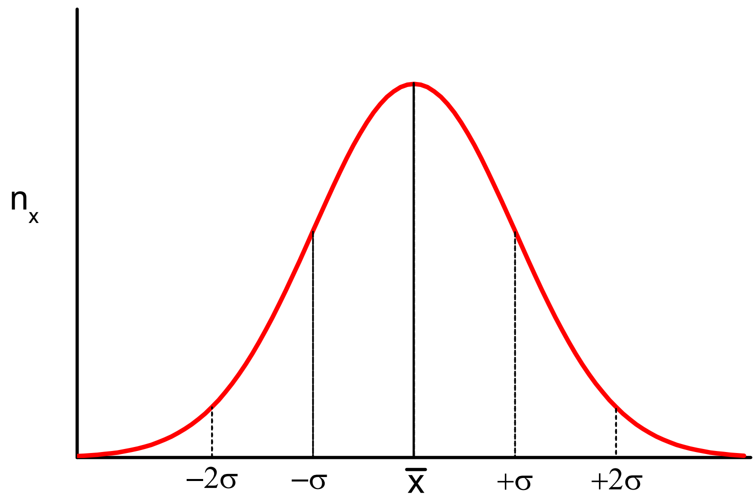


Figure 3.2: Gaussian Distribution

The width of this distribution is clearly related to the error of each measurement, and the mean value, $\bar{x}$, is the one with the highest frequency. It is usual to define a quantity, σ, known as the standard deviation:

$$\sigma = \sqrt{\left(\frac{1}{N}\right)\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3.12}$$

which is a measure of the spread of the distribution. In fact, it can be shown that 68% of the measurements will fall within the range $x \pm \sigma$ and that 95% will be in the range $x \pm 2\sigma$. The meaning of this for the first year laboratory is that if we make a single measurement of some quantity x, it has a 68% chance of being within $\pm\sigma$ of the true value x in a very large set of measurements. We will be using the standard deviation σ as the error estimate.

Chapter 4

Laboratory Notebook and Report

You have formed a theory, then? At least I have a grip of the essential facts of the case. I shall enumerate them to you, for nothing clears up a case so much as stating it to another person . . .

Arthur Conan Doyle

A laboratory notebook is simply a record of an experiment as it is performed. A university physicist investigating the electrical properties of a semiconductor, a government chemist monitoring pollution, an engineer doing testing or development work for a corporation will all keep some form of notebook. Later each of these people will usually write a report utilizing the information contained in their notebooks. The report may take the form of an article in a scientific journal, a report to a government agency or a submission to a corporate executive. In this course, you will also be required to keep careful notes about your laboratory work and submit a brief report at the end of each experiment.

Your lab notebook should contain enough information about the experiment so that later you, or someone else, can understand what has been done without referring to the lab manual. Data, notes about experimental techniques, equations, calculations, sources of error, graphs, conclusions, etc. should all be entered. Accuracy is the other primary requirement in a notebook; it does little good to record an observation if it is not correctly noted. Literary style is of no real concern; a phrase, a few sentences or a diagram will often provide a proper explanation. Clarity and organization are of great value in a lab notebook.

Although there are many ways of recording an experiment, the following sections are often included in a student lab report. The use of subtitles will help organize your laboratory work. Detailed instructions regarding lab reports will be provided by your course professor, the First-Year Lab coordinator and the laboratory teaching assistant supervising your lab section.

Students should prepare for each lab class by carefully reading both the experiment and the suggested pre-lab readings, by designing data tables suitable for the experiment and by carrying out required advance calculations. Many of the questions found at the end of the experiments can be answered prior to the lab class. The laboratory experiments are, in most cases, synchronized with the lecture material so you will find your class notes a useful reference.

Your lab notebooks will be graded and a mark will be assigned to your lab report. The mark will reflect your experimental technique, results and the quality of your report. Lab reports will be marked in reasonable detail with emphasis on the data, analysis and results, and conclusion sections. Lab notebooks are usually returned at the beginning of the next lab period.

Prior to each experiment, your laboratory instructor will briefly discuss the theory, use of the equipment, any cautions to be observed and review any special data analysis techniques required. Please feel free to ask questions during this discussion or if you encounter difficulties either in performing your experiments or writing your reports.

4.1 Lab Report Format

PURPOSE

The purpose of your experiment consists of one or two sentences describing what is being tested, investigated or measured. State the purpose in complete sentences, avoiding the use of the first person (I). **DO NOT COPY THE PURPOSE DIRECTLY FROM YOUR LAB MANUAL**.

APPARATUS

List the apparatus used in the experiment, as it is being performed.

Often a carefully labelled sketch or circuit diagram is the best way of describing the apparatus.

THEORY AND PROCEDURE

A detailed theory and procedure is found in your lab manual; **DO NOT COPY THIS INTO YOUR REPORT**. In your report, unless otherwise indicated, briefly discuss only theory or technique that differs from the manual.

DATA

The data section of your report should have a title, date and include the name of your lab partner. All data should be recorded directly into your notebook as the experiment is being performed. Whenever possible, data should be recorded in tables. Each table should have a title and column headings. Units and uncertainties, if required, should be included in the headings. If a mistake is made in entering data, draw one or two lines through the error(s) and record the correct data. Do not erase or cover errors in any way. The data recorded for each experiment should be accurate, detailed and concise. In some cases, it will be convenient to place the results of intermediate and final calculations in additional columns of your data table. The experiment must be performed and the data recorded in your notebook during the lab period.

ANALYSIS AND RESULTS

Briefly describe the analysis performed to accomplish the purpose of the experiment. It may be convenient to separate this section into parts corresponding to your manual. In each part, you may be required to show sample calculations for each type of calculation performed in your experiment. Include a complete error analysis, if required. The results of calculations may be stated as equations, placed in tables or in additional columns of your data table, if appropriate. Indicate where all graphs and the corresponding data tables may be found. Be sure all graphs have descriptive titles and clearly labelled axes. Show all slope and intercept calculations directly on your graph. Summarize the main findings from the graphs in your results section. Show numerical comparisons to accepted values.

CONCLUSION

A concluding discussion or the implications of your results is included in this section. Discuss the qualitative and quantitative results in relation to the expected behaviour or theory and try to explain any discrepancies. Discuss the accuracy and precision of your experimental results and any possible sources of error. You may also want to include suggestions concerning improvements to the experiment.

QUESTIONS

Answer any questions found at the end of the experiment. It is not necessary to re-write the questions.

PART II
EXPERIMENTS

Experiment 1

Force Vectors

Purpose

The objective of this lab is to measure unknown masses by balancing them with known masses on a force table.

Apparatus

The equipment required for this experiment consists of one Pasco force table (illustrated on Fig.1.1). The table has several components: a rim of which is marked so angles can be measured in degrees, three pulleys placed at set angles from which mass holders are hung. The equipment also includes a box of disks of known weight which can be added to the mass holders by sliding the disks down the shaft of the holders. Finally, you are also provided with two pairs of unknown cylindrical masses. Masses in one pair are of the same color.

Theory

Masses hanging from the table are subject to the gravitational force, which is proportional to the masses. When the forces sum to 0 as vectors, the table is balanced. Experimentally, this equilibrium is reached when the white plastic ring is at the center of the table, above the black target circle.

Figure 1.1: The Pasco force table.

The force on the plastic ring resulting from the suspension of a mass m is

$$\vec{F} = k\, m\, \vec{r} \tag{1.1}$$

Thus, if there are three masses hanging from the table, we have, at equilibrium:

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = 0 \Leftrightarrow m_1\vec{r}_1 + m_2\vec{r}_2 + m_3\vec{r}_3 = 0 \tag{1.2}$$

The vectors $\vec{r}_1$, $\vec{r}_2$ and $\vec{r}_3$ all have the same length r, so the vector equation (1.2) can be resolved in its $\hat{x}$ and $\hat{y}$ components:

$$\begin{aligned} m_1 r\cos\theta_1 + m_2 r\cos\theta_2 + m_3 r\cos\theta_3 &= 0 \\ m_1 r\sin\theta_1 + m_2 r\sin\theta_2 + m_3 r\sin\theta_3 &= 0 \end{aligned} \tag{1.3}$$

The length r cancels out of these equations. The angles θ_1, θ_2 and θ_3 required for the trigonometric resolution of the vectors can be deduced from the (fixed) angles α_1, α_2 and α_3 of the pulleys on the disk. Given a mass (say, m_1), the two equations (1.3) can be solved for the two remaining unknowns m_2 and m_3.

Procedure and Analysis

Important notice: The plastic holders have a mass of 5 g.

0: Pre-verify your setup by making sure you have the correct sets of unknown masses. Make sure the plastic screw in the center of the table is raised and that the white plastic ring is around this screw. Make sure the pulleys are free from the rim of the table and can move freely.

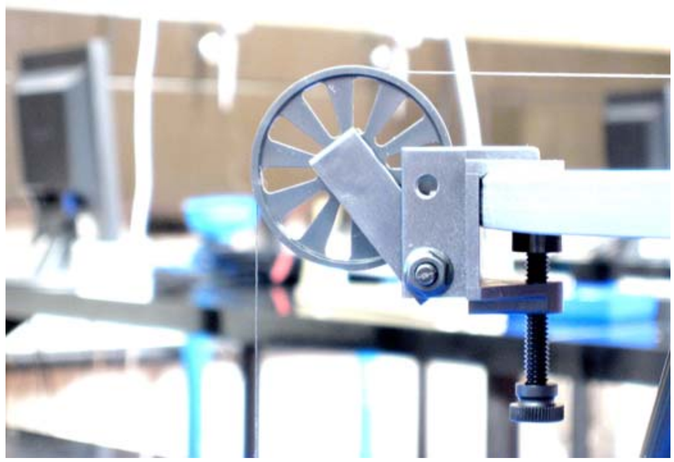


Figure 1.2: A pulley attached to the rim of the table. The pulley can rotate freely without touching the rim.

Part 1: balancing one known mass with two other masses.

a: Place a mass M_1 = 20 g in the first holder. Find the masses M_2 and M_3 that will balance your table. (Remember to include the mass of the holders). Have your TA verify the result.

b: Remove all masses and now place a mass M_2 = 20 g in the second holder. Find the masses M_1 and M_3 that will balance your table. Have your TA verify the result.

c: Remove all masses and place a mass M_3 = 20 g in the third holder. Find the masses M_1 and M_3 that will balance your table. Have your TA verify the result.

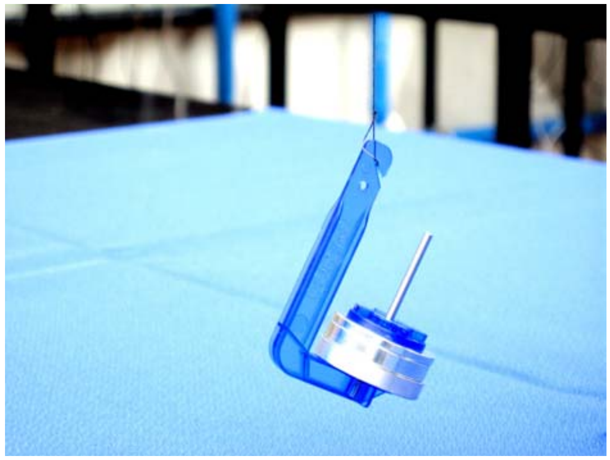


Figure 1. 3: A mass holder with some masses added.

Part 2a: Balancing two unknown masses with a variable mass.
Insert the **brass** unknown masses m_1 and m_2 in the appropriate holders. Find the mass m_3 that will balance your table. Have the TA verify the result.

Part 2b: Verifying your result. Double now the mass m_3 found in Part 2a. Add masses of known weights to the holders so the table is balanced again. Compare the masses added to m_1 and m_2 with m_1 and m_2. Discuss the result. Advise your TA that you are done with Part 2.

Part 3: Change setup. Set your pulleys at the set of angles specified for the aluminum masses.

Part 3a: Repeat Part 2a using this time the pair of **aluminum** unknown masses.

Part 3b: Verify the results of 3a by doubling the mass m3 found in Part 3a. Add masses of known weights to the holders so the table is balanced again. Compare the masses added to m_1 and m_2 with m_1 and m_2. Discuss the result.

Conclusion

Discuss why doubling the masses m_1 in Parts 2 and 3 allows you to obtain directly the values of M_2 and M_3. Provide final values for your unknown brass and aluminum masses. Explain why a set of masses is tied to a particular setup. Provide a table of the ratios M_2/M_1 (or m_2/m_1) and M_3/M_1 (or m_3/m_1) for Part 1a, 1b and 1c, and for parts 2a and 2b. Discuss any similarities or differences.

Required Angles

The unknown masses are in the mass kits provided with the force table. They are meant to be used in pairs corresponding to the same type of metal. That is, a given pair of aluminum or brass masses are to be used together. The following tables identifies the angles at which the unknown masses are to be placed as well as the angle required for the balancing mass $m_?$. Each mass has an identifier stamped on it. The identifier for aluminum masses begins with the letter A followed by a number. The brass masses are identified with the letter B followed by a number.

Table II.1.1: Required Angles

Mass Identifier & Angle	Mass Identifier & Angle	Mass Identifier & Angle
A1→ 223°	A2→ 130°	$m_?$→ 0°
B1→ 140°	B2→ 290°	$m_?$→ 343°
A3→ 134°	A4→ 234°	$m_?$→ 6°
B3→ 121°	B4→ 227°	$m_?$→ 359°
A5→ 143°	A6→ 228°	$m_?$→ 3°
B5→ 116°	B6→ 246°	$m_?$→ 13°
A7→ 188°	A8→ 250°	$m_?$→ 36°
B7→ 218°	B8→ 249°	$m_?$→ 50°
A9→ 130°	A10→ 225°	$m_?$→ 7°
B9→ 158°	B10→ 249°	$m_?$→ 25°
A11→ 111°	A11→ 0°	$m_?$→ 254°
B11→ 85°	B12→ 359°	$m_?$→ 216°
A13→ 111°	A14→ 170°	$m_?$→ 318°
B13→ 129°	B14→ 200°	$m_?$→ 341°
A15→ 115°	A16→ 261°	$m_?$→ 15°
B15→ 231°	B16→ 119°	$m_?$→ 7°
A17→ 282°	A18→ 161°	$m_?$→ 27°
B17→ 142°	B18→ 253°	$m_?$→ 9°
A19→ 160°	A20→ 240°	$m_?$→ 24°
B19→ 135°	B20→ 270°	$m_?$→ 31°

Experiment 2

Graphical Analysis

Purpose

The purpose of this experiment is to explore how graphical data analysis techniques can be used to determine functional relationships between experimentally measured quantities.

Apparatus

The apparatus for this experiment includes two masses having a total mass of 600 grams, a c-clamp, a safety block, two metre sticks, and a variety of mounts and rods.

Theory

Graphical Analysis

A functional relationship is a mathematical expression that describes the dependence between two or more experimentally measured quantities. An efficient and easy way to determine a functional relationship is to plot a graph of the experimental data and then analyze the graph.

In most cases, experiments are designed to look at how a given physical quantity changes when one other controllable quantity is changed while holding all other changeable quantities constant. This method allows for analysis using two-dimensional graphs.

The simplest graph to interpret is a straight line. Data that generates a straight line identifies a linear relationship between physical quantities. Assuming that we have assigned the symbol x to the independent physical quantity and the symbol y to the dependent one, we say that the functional relationship between y and x is described by the statement,

y is directly proportional to x

or

$$y \propto x$$

Relationships between experimental variables that do not generate a straight-line graph are said to be non-linear. How do we find the correct relationship? One method that we can use to analyze non-linear relationships involves the use of logarithms. Logarithms can be used to linearize relationships. Consider the functional relationship

$$y \propto x^z$$

where z is any Real number. This non-linear relationship can be linearized by taking the base 10 logarithm of both sides of the expression

$$\log(y) \propto z\log(x)$$

Plotting a graph of $\log(y)$ versus $\log(x)$ will yield a straight line with slope z.

Using logarithmic graph paper eliminates the need to calculate the logarithms of the data points. The construction of this graph paper allows the user to plot the data directly. Its scaling determines the logarithm. Logarithms need only be calculated when determining the slope of the graph.

Detailed information on logarithms and the use of logarithmic graph paper can be found in the logarithm section of chapter 2 beginning on page 120.

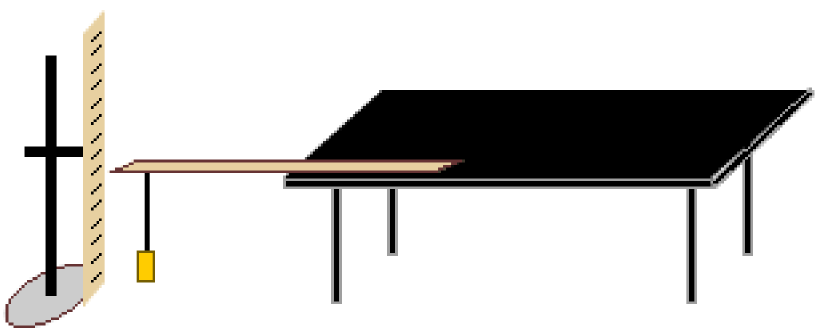
NOTE: Logarithmic graph paper is included at the end of this chapter and also in Appendix 2.

Bending of the Beam: Elasticity

Elasticity describes the ability of a system to spontaneously return to its original configuration after having been distorted. The modulus of elasticity is a parameter that describes this ability for a given material. Defined as the ratio of stress (applied force) to strain (resultant distortion), this number gives us a sense of how much pressure a given material can take before it deforms or breaks. For example, oak's modulus is about 14 GPa whereas that of soft biological tissue is about 2 MPa. The modulus does not by itself provide a complete picture since the response is also dependent on the geometry of the material being investigated.

When a small weight is suspended from the free end of a wooden metre stick of rectangular cross-section, the metre stick undergoes a small vertical deflection. The vertical deflection y is related to the length of the extension L of the free end by a power law relationship of the form $y \propto L^n$

Procedure



a. Determine and record the error in using the metre sticks as measuring devices.

b. Place the metre stick along one edge of the table carefully aligning the metre stick's length with the table.

c. Extend the metre stick the desired distance beyond the end of the table.

d. Place the safety block across the top of the metre stick and clamp the block and metre stick to the table.

e. Determine and record the extension of the metre stick.

f. Place the vertical metre stick near the end of the one to be deflected, then determine and record the initial position of the metre stick to be deflected.

g. Carefully hook the two mass combination to the end of the metre stick and allow the weight of the masses to bend the stick. Carefully support the hanging masses until the stick stops deflecting under the weight. As long as you are careful, any oscillations will die down quickly.

h. Determine and record the final position of the deflected metre stick.

i. Repeat until all required data has been acquired.

Table II.2.1: Sample Data Table

Initial Position (cm)	**Final Position** (cm)	**Extension** (cm)
$y_0 \pm \Delta y_0$	$y_f \pm \Delta y_f$	$L \pm \Delta L$

Follow the procedure outlined above and collect deflection versus extension data from 40 cm to 90 cm of extension inclusively. Collect data every 5 cm over this range. Record the metre stick extension, that is, the length that extends beyond the end of the table, the metre stick's initial vertical position without the addition of the masses and its final vertical position after the masses have been added. Make sure to check the initial position before each trial.

Analysis

Our analysis will determine the functional relationship between the deflection and extension of the metre stick. The Deflection for a given Extension is calculated from the initial and final position as shown in the equation

$$y = \left| y_f - y_0 \right| \tag{2.1}$$

Plot graphs of Deflection, y, versus Extension, L; y vs. L^2; y vs. L^3 and y vs. L^4 using Excel. (Appendix 2 has instructions for using Excel for scientific graphing). Can you determine the functional relationship between these physically observable values from these graphs? Record your initial guess at the functional relationship. Look at how the different curves change and support your guess.

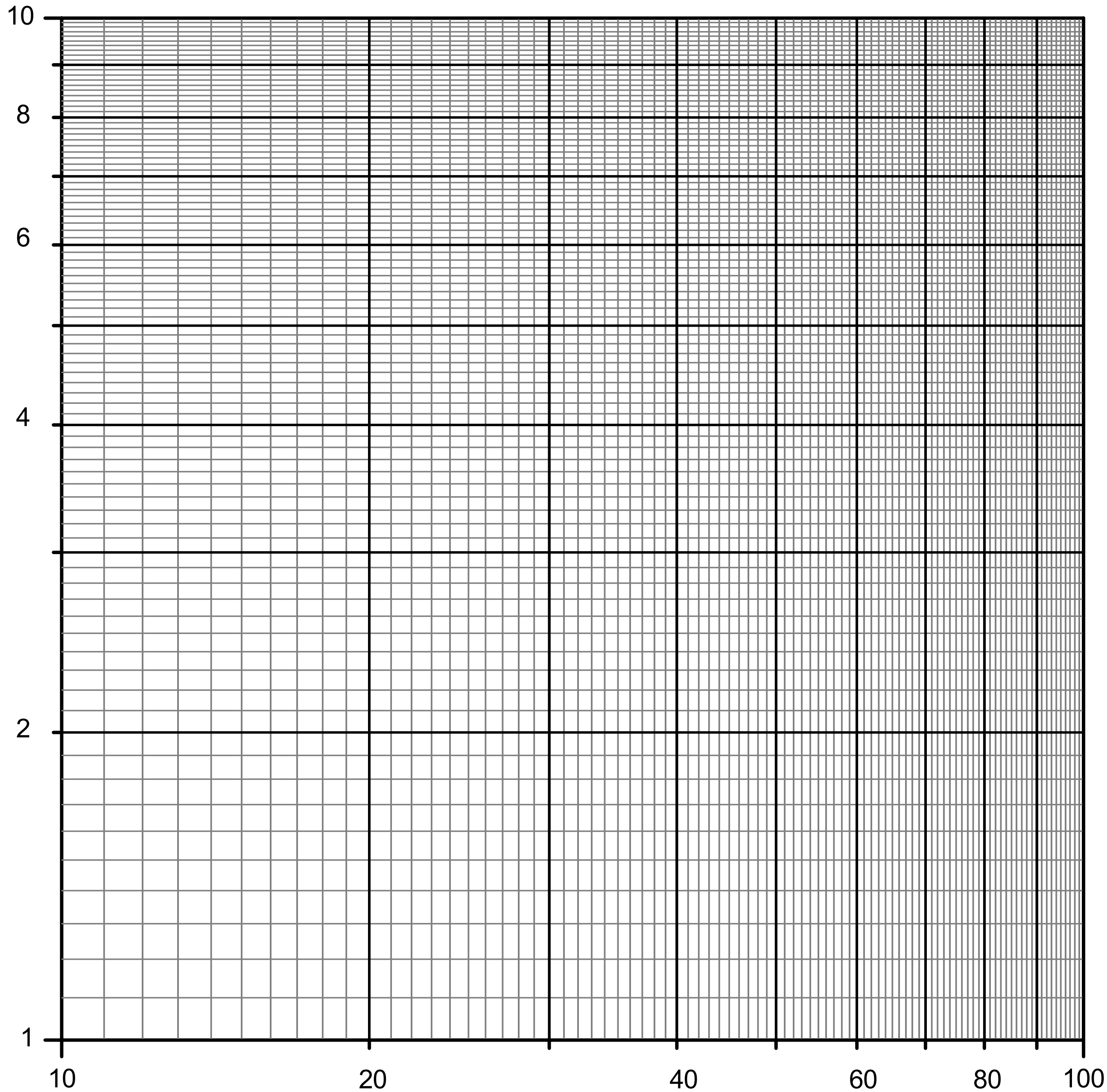
Plot the logarithm of the Deflection versus the logarithm of the Extension using logarithmic graphing paper. Determine the functional relationship between these observables by calculating the slope of the log plot.

How does the information determined from the log plot compare to your guess from graphing the Cartesian plots?

Conclusion

Discuss your findings.

NOTE: Single cycle Log-Log paper on next page.



Single Cycle Log-Log Paper

Experiment 3

Acceleration

Purpose

The purpose of this experiment is to analyze the displacement, velocity and acceleration of an object in motion.

Apparatus

The apparatus used in this experiment consists of a computer based data acquisition system, a sonic position sensor, a car, a track, a suspended mass and a spring. The car's wheels are designed such that its motion is essentially frictionless. The suspended mass is used to accelerate the car and the spring, once stretched, modifies this acceleration.

The sonic sensor and computer acquisition system determines and records the car's displacement at a rate of 20 samples per second.

Theory

Kinematics is the science of motion and is concerned with concepts such as displacement, velocity and acceleration independently from the cause of the motion.

In order to describe objects in motion we must first unambiguously specify their position. The position of an object can only be specified relative to some reference point. Our choice of reference position usually defines the origin of the coordinate system.

A single-axis or one-dimensional, coordinate system is sufficient when the motion being investigated is constrained to a straight line. Convention defines the positive direction to the right of the origin and the negative to the left. It is sometimes convenient to choose positive and negative directions opposite to convention.

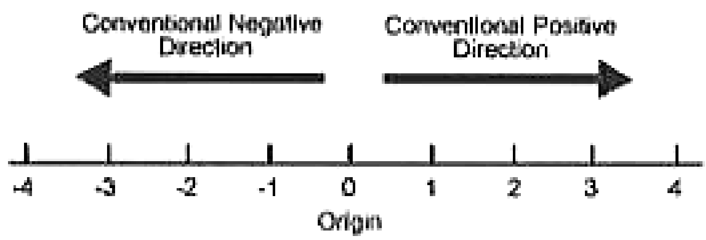


Figure 3.1: Position is specified with respect to a graduated axis that extends infinitely in both directions.

An object's change in position from its initial position, x_0, to its final position, x_f, is called the object's **displacement**. Displacement along the x-axis is denoted Δx where

$$\Delta x = x_f - x_0 \tag{3.1}$$

(The symbol Δ indicates a change in quantity.) Displacement is a **vector quantity**, meaning that it has both a magnitude and a direction. In the case of linear motion, the sign of the displacement gives the direction.

A measure of the rate with which the position of an object is changing is called the object's **velocity**. Velocity is also a vector quantity. The average velocity for a linear system is defined:

$$\bar{v} = \frac{\Delta x}{\Delta t} \tag{3.2}$$

When we ask, "How fast is the object moving?", the quantity that we are normally interested in is the object's instantaneous velocity. The instantaneous velocity is calculated from the average velocity by letting the time interval become infinitesimally small:

$$v = \lim_{\Delta x \to 0} \frac{\Delta x}{\Delta t} \tag{3.3}$$

This equation tells us that the instantaneous velocity is the rate at which an object's position is changing with time at a given instant.

Equation (3.3) has experimental ramifications that must be kept in mind when attempting to determine the instantaneous velocity of an object. If we choose time intervals so small that they approach zero then the displacements over those periods also approach zero. This significantly increases the error in the displacement measurement. We compensate for this by choosing a reasonably small time interval such that the average velocity is a good approximation of the instantaneous velocity in the middle of the time interval. This is justified by the fact that, for <u>constant</u> acceleration, the average velocity over any time interval is exactly equal to the instantaneous velocity at the halfway point in the interval. The car is not undergoing constant acceleration in the experiment at hand; however, the acceleration is nearly constant over the time interval determined by the sampling rate.

Procedure

1. Ensure that the all of the strings attached to the car and the one attached to the spring are secure.
2. Return the car to the back of the track. Ensure that the string between the car and the spring is not caught under the car and that it is free to extend.
3. Restrain the car and attach the 20 g mass to the string that passes over the pulleys.
4. Press the COLLECT button in the acquisition graphical user interface then release the car. The car must be released just after this button has been pressed. You should hear a clicking sound coming from the sonic sensor.
5. Print the data sheet. Select the “Print Data Table” command from the “File” drop-down menu. Choose the appropriate number of copies in the “Print” dialogue box. Each student must submit a copy of the data with their report.

Analysis

NOTE: You should check with the demonstrator about the permissibility of the use of Excel for graphing. Regardless of this, parts c & d must be done by hand.

a. Plot a graph of position versus time. You should note that the data provided by the system may show negative values for the position of the car. You can use these values as provided or you can translate the data. Make a careful choice for the location of the axes. (The bottom left-hand corner of the graph need not correspond to $(0,0)$.)

   To translate, simply add the magnitude of the position at time $t=0$ to all position values. For example, say our first data point corresponds to

$$t_1 = 0$$

$$d_1 = -1.98$$

   then, by adding $|d_1| = 1.98$ to all the position data we effectively translate the position so that it starts at zero. In either case, choose your vertical and horizontal scales such that the data extends over as much of the graph paper as possible.

b. Plot a graph of the instantaneous velocity as a function of time. You will need to make a discrete approximation for the value of the derivative. A reasonably accurate approximation can be calculated using

$$v(t_i) = \frac{d(t_{i+1}) - d(t_{i-1})}{t_{i+1} - t_{i-1}} \tag{3.4}$$

   It should be obvious from the formula that it is impossible to determine the velocity at the first and last time points being considered.

c. Another method for determining the instantaneous velocity consists of drawing a tangent to the position versus time curve at a point of interest. The slope of this tangent gives us the value of the instantaneous velocity. Choose three time points, one at the beginning, one in the middle and one at the end of your position versus time graph. Make sure that these points correspond to times for which you calculated the instantaneous velocity in part b. Graphically determine the instantaneous velocity at these points. Within experimental error, are the graphically determined values equal to the numerically derived ones? Would you expect them to be equal (within error)? If they are not the same, what reasons would there be to explain the difference?

d. Instantaneous acceleration, a, can be determined from the velocity data using the same two methods that we used to generate the data for the instantaneous velocity. Inspect your velocity versus time graph and, without calculating acceleration values, sketch the qualitative manner in which the acceleration varies over the trip of the car. Label the time axis and indicate any regions where the acceleration is constant, increasing, decreasing, or zero.

Conclusion

What conclusions can be drawn about the nature of velocity and acceleration over the course of the car's trip? What insights do the graphs reveal about the changes in velocity and acceleration? Explain.

Describe the motion of the car using your graphs as guides. Support your observations of the changes in displacement, velocity and acceleration quantitatively.

Questions

1. Would it be correct to use your initial and final positions in equation (3.2) to determine the average velocity for the total trip of the car? Would it be correct to average the initial and final velocities to determine the average? Explain. Describe a graphical method for determining the average velocity of the whole trip using your position versus time graph.
2. Suggest a graphical method for determine the total displacement of the car using your velocity versus time graph.

Experiment 4

Ball Toss

Purpose

The purpose of this experiment is to measure the change in kinetic and potential energies as a ball moves in free fall. We will also explore how the total energy of the ball changes during the free fall.

Apparatus

The apparatus for this experiment consists of a computer data acquisition system, a sonic sensor, a soccer ball, a balance, an aluminum collar and a mounted wire frame.

Theory

The total mechanical energy, E, of an object is defined as the sum of the object's kinetic, KE, and potential, PE, energies. The total energy remains constant as the object moves, provided that the net work done by external non-conservative forces is zero.

Kinetic energy is the energy that an object has due to its motion. We can determine the kinetic energy of an object either from the total work done by conservative forces on the object or more simply, from the object's velocity. The equation that relates the kinetic energy of an object to its velocity is

$$KE = \frac{1}{2}mv^2 \tag{4.1}$$

where m is the mass of the object and v is the magnitude of its velocity.

The retrievable energy stored in an object by virtue of the object's position or configuration in relation to a force $F(U)$ is called the Potential Energy. Most forms of potential energy are named for the force to which they are related. The force of interest during this experiment is that of gravitation. The gravitational potential energy is determined from the equation

$$PE = mgh \tag{4.2}$$

where m is the mass of the object, g is the acceleration due to gravity, and h is the height of the object measured from the origin of our coordinate system. Since we can define the origin at any location, this tells us that the zero reference level of potential energy is arbitrary, that is, we are free to choose a convenient reference point for our experiment. In other words we are only able to measure changes in potential energy with respect to a convenient origin.

Procedure

1. Measure and record the mass of the ball. Use the aluminum ring to hold the ball on the balance. Measure the mass of the ring then of both the ball and ring.
2. Hold the ball about $0.5\ m$ directly above the Motion Detector. Have your partner click the **COLLECT** button on the computer acquisition interface.
3. Toss the ball straight up above the detector to a height of about $1.5\ m$ above it. Use both hands and make sure to take your hands quickly out of the way after releasing the ball.
4. Catch the ball before it falls onto the sensor.
5. Verify that your distance versus time graph is parabolic in shape without spikes or flat regions. You may need to repeat the procedure until you get a good graph.

6. Print the data table, the distance versus time graph and the velocity versus time graph.

Analysis

a. Identify the portion of each graph where the ball just left your hands and was in free fall. Record this time as your initial starting point.
b. Find a time where the ball was moving downward, but a short time before it was caught. Record this time as the final time point.
c. Plot Kinetic Energy, Potential Energy and Total Energy from the initial to final time on the same graph. Remember that the zero for Potential Energy is arbitrary. A convenient choice will minimize the amount of work you need to do.
d. How well does this experiment demonstrate conservation of energy?
e. Explain the shapes of the Kinetic Energy and Potential Energy graphs.
f. Does the total energy remain constant within reasonable error? Should it? Why? If it does not, what other sources of energy are there or where could the missing energy have gone?

Questions

1. What would change in this experiment if we used a very light ball like a Nerf Ball?
2. What would happen to the experimental results if you used the wrong mass for the ball?

Experiment 5

The Pendulum

Purpose

The purpose of this experiment is to determine the acceleration due to gravity at Lakehead University by investigating the relationships between the period of a simple pendulum and its initial displacement, mass and length.

Apparatus

The apparatus for this experiment consists of a simple pendulum suspended from a bench stand, a photogate attached to a computer acquisition system and a set of masses. Pendulum lengths are measured with a metre stick, angular displacements with a protractor and timing is determined using the photogate.

Theory: The Simple Pendulum

A simple pendulum consists of a small mass m attached to a light inextensible string of length L. Periodic motion occurs when the mass is displaced from its equilibrium position and released. The pendulum oscillates along a circular arc.

The displacement from equilibrium of the oscillating pendulum bob can be described by the angle θ as shown in Figure 5.1. The length of the pendulum L and the distance travelled along the arc s are related to the angle by

$$\theta = \frac{s}{L} \tag{5.1}$$

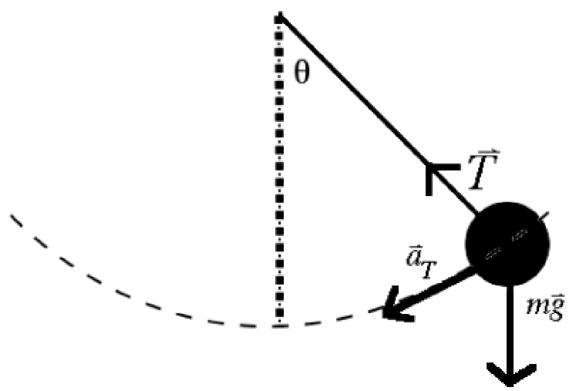


Figure 5.1: The Simple Pendulum

where θ is measured in radians.

The forces acting on the pendulum bob are the tension in the string $\vec{T}$ and the force of gravity $m\vec{g}$. The component of the gravitational force tangential to the arc at any point, $m\vec{g}\sin(\theta)$, provides the restoring force for the pendulum. From Newton's Second Law:

$$mg\sin(\theta) = ma_T \tag{5.2}$$

where a_T is the tangential acceleration. It can be shown that for small displacements $\sin(\theta) \approx \theta$. Using this approximation, equation (5.2) becomes

$$a_T = \frac{d^2 s}{dt^2} = \frac{-gs}{L} \tag{5.3}$$

Equation 5.3 is the equation of motion for a simple harmonic oscillator. A solution for this differential equation is

$$s = s_0 \cos(\omega t) \tag{5.4}$$

where

$$\omega = \sqrt{\frac{g}{L}} \tag{5.5}$$

is the angular frequency. The angular frequency is related to the period of oscillation by:

$$T = \frac{2\pi}{\omega} \tag{5.6}$$

Hence for the pendulum

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{5.7}$$

Procedure

You will notice that the pendulum is attached to the horizontal bar using a two-point mount. This helps to keep the pendulum swinging in a straight line and minimizes the chance of the pendulum hitting the photogate. The length of the pendulum is adjusted by loosening the setscrew on the horizontal bar and pulling the string. The length of the pendulum is the vertical distance from the midpoint between the strings to centre of mass of the bob. The centre of mass is located at the middle of the cylindrical part of the mass.

A pendulum possesses three adjustable parameters: initial displacement, mass and length. Equation (5.7) indicates that as long as the angle is small so that $\sin(\theta) \approx \theta$, then the period should not depend on the initial displacement or the mass of the pendulum bob. The first two experiments we perform investigate the accuracy if this conclusion. Our final experiment investigates the dependence of the period on the length of the pendulum.

A) Basic Instructions

1. Ensure that the pendulum is set to the required length and that the bob can swing through the photogate without hitting it.
2. Displace the pendulum and let it swing for at least two or three passes through the photogate.

3. Click the START button on the interface and allow the system to acquire the period of oscillation for at least 6 points.
4. Click on the STATISTICS button and record the mean value for the period in your data table.

B) Mass Dependence

You will use 3 different masses to determine if period is affected by changing the mass. Set the pendulum to about 1 metre in length. Use an initial displacement of 10 degrees for each trial. You need to ensure that each trial is performed using the same initial displacement. Determine the period using the same process as outlined in part A. Record your results in a data table.

C) Dependence on Initial Displacement

Determine the period for 5 initial displacements ranging from just enough to clear the photogate to about 30 degrees. Use the same length as you had in part B. Record your results in a data table.

D) Length Dependence

Equation (5.7) developed in the theory section shows that the pendulum's period depends on its length. Hang the 200 g mass from the string. Determine the period for 6 different lengths of the pendulum ranging from 0.5 to 1.0 metre. Use an initial displacement of about 10 degrees.

Analysis

Plot a graph of the period squared versus length using Excel. Use the *Scatter Plot* plot type and add a linear trend line with intercept 0 to the plot. Determine the slope of the trend line. Excel will display the equation for the trend line on the graph. Estimate the acceleration due to gravity from the slope of your trend line.

The actual value of the acceleration due to gravity at a given location depends strongly on the location's latitude and altitude above sea level. This value is easily determined using an equation that can be found in many sources. The CRC Handbook of Physics and Chemistry available in the reference section of the library or an online search are two possible sources. Thunder Bay is located at a latitude of 48°22’30” given in the standard form of degrees, minutes, and seconds. You will need to convert these numbers to their decimal equivalent in order to use the equation. Thunder Bay’s elevation is $199\ m$ above sea level.

Compare your experimental value for the acceleration with the accepted value. Account for any discrepancies between the experimental and calculated value for the acceleration due to gravity.

Conclusion

Our analysis suggests that the period of the pendulum is independent of both mass and initial displacement. Does your data in parts B and C support this? Explain.

Does the accepted value for the acceleration due to gravity agree, within error, with your experimental determination? Discuss the accuracy and precision of your result. How could accuracy and precision be improved?

Questions

1. Check the validity of the approximation $\sin(\theta) \approx \theta$ for angles θ=1°,2°,…,10°. Recall that this approximation is valid only for angles in radians.

Experiment 6

Momentum, Energy, and Collisions

Purpose

The purpose of this experiment is to observe collisions between two carts and to test for the conservation of momentum. You will also measure the energy changes during different types of collisions and classify the collisions as elastic, inelastic, or completely inelastic.

Apparatus

The apparatus to be used for the experiment includes a computer data acquisition system, a 1 metre track, two carts, two sonic sensors and a balance.

Theory

Momentum is transferred between objects involved in a collision. The total linear momentum of the system of colliding objects is conserved provided that the sum of any external forces acting upon the system is zero. Collisions are classified according to whether the total kinetic energy changes during the collision.

A) **Elastic Collision:** This is a collision in which the total kinetic energy of the system after the collision is the same as it was before.

B) **Inelastic Collision:** In this type of collision, the total kinetic energy of the system is different before and after the collision.

C) **Completely Inelastic Collision:** This is an inelastic collision in which the colliding bodies stick together at impact.

Procedure

Measure and record the masses of your carts. You will be using three different configurations of the apparatus for this experiment, one for each type of collision being investigated. You will need to measure the mass of the carts at each station.

Place one of the carts at about the centre of the track. To create the collision you will launch the other cart from one end of the track towards the cart at the middle. Try to launch the cart with just enough force that the collision occurs without the carts crashing into the sensors. Carts should be caught before they hit the sensors.

I) Magnetic Bumpers

a. Position the carts so that their magnetic bumpers face one another.

b. Have one partner click the *COLLECT* button on the interface while the other launches the other cart. Keep hands out of the way of the sensors after the launch. This will help to minimize errors.

c. You will see a position vs. time graph and a velocity vs. time graph on the computer screen. You can use the system to measure the average velocity for each cart before and after the collision. Drag the cursor across the velocity for the time interval of interest. Click on the Statistics button and a dialog box containing the required average velocity will appear. Record the average velocity for each cart, before and after the collision.

d. Perform a second trial recording the required information.

II) Velcro Bumpers

a. Position the carts so that their Velcro bumpers face each other.

b. Place one of the carts at about the middle of the track.

c. Press *COLLECT* on the interface and launch the other cart from one end of the track.

d. Measure the before and after cart average velocities using the Statistics button and record them in your data table.

e. Perform a second trial recording the required information.

III) Velcro to Magnetic Bumpers

a. Position the carts so that a Velcro bumper faces a magnetic bumper.

b. Place one of the carts at about the middle of the track.

c. Press *COLLECT* and launch the other cart from one end of the track. Ensure that opposite bumper types will participate in the collision.

d. Measure the before and after average cart velocities and record them.

e. Perform a second trial recording the required information.

Weigh each cart at each station and record these with the pertinent velocity data.

Analysis

For each run:

1) Determine and record the momentum of each cart before and after the collision and the total momentum of the system before and after the collision. Calculate and record the ratio of the before and after total momenta.

2) Determine and record the kinetic energy for each cart before and after the collision and the total kinetic energy both before and after the collision. Calculate and record the ratio of the total kinetic energy before the collision to the total kinetic energy after the collision.

Conclusion

Discuss the conservation of momentum for each of the six runs. Discuss the conservation of energy for each of the six runs. Classify each collision as elastic, inelastic or completely inelastic.

Experiment 7

Moment of Inertia

Purpose

The purpose of this experiment is to measure the moments of inertia of a number of objects about given axes and compare these with theoretical values computed from the masses and dimensions of the objects.

Apparatus

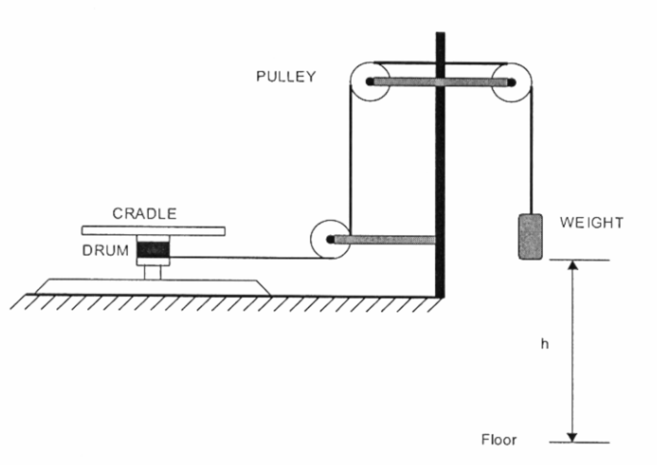


Figure 7.1: Experimental Apparatus

The apparatus used in this experiment consists of a rotating support connected to a system of pulleys, mounted on a table clamp and bar, by a length f thread. A variety of masses are suspended on the free end of the thread to provide the force required to rotate the support. Measuring devices used in this experiment include a computer-based stopwatch, vernier caliper, metre stick and a laboratory balance.

Theory

When a body is of a simple geometric form, its moment of inertia about an axis can be computed from its mass and dimensions. Irregular objects require a numerical determination of moments of inertia.

The Law of Conservation of Energy can be used to determine the moment of inertia of a body that can be placed on the experimental apparatus. The potential energy, mgh associated with the hanging mass m, except for a small amount, Δmgh, used to compensate for friction, is converted to the total kinetic energy of the system as the mass falls through a height h. The total kinetic energy is simply the sum of the translational kinetic energy, ½ mv^2 , of the downward moving mass and the rotational kinetic energy, ½ $I\, m\, \omega^2$ of the rotating system. Conservation of energy requires that

$$(m - \Delta m) g h_{initial} = \frac{1}{2} m v_{final}^2 + \frac{1}{2} I_{system} \omega_{final}^2 \tag{7.1}$$

where I_{system} is the moment of inertia, ω is the angular velocity acquired by the rotating object, and m is the mass of the suspended weight.

The weight experiences a constant acceleration thus its final velocity is $v_{final} = 2\overline{v} = \frac{2h}{t}$ and the final angular speed of the object is $\omega_{final} = \frac{v_{final}}{r}$, where *r* is the radius of the drum on which the string is wound. Substitution of these expressions into equation (7.1) gives

$$(m - \Delta m) g h_{initial} = \frac{m}{2}\left(\frac{2h}{t}\right)^2 + \frac{I}{2}\left(\frac{2h}{rt}\right)^2 \tag{7.2}$$

Solving equation (7.2) for I yields

$$I = mr^2\left[\frac{gt^2}{2h}\left(1-\frac{\Delta m}{m}\right)-1\right] \tag{7.3}$$

I is the moment of the inertia of the system comprising the object and the cradle. If I_C is the moment of inertia of the cradle alone, then the moment of inertia of the object, I_O, is given by

$$I_O = I - I_C \tag{7.4}$$

Procedure

The apparatus should be set up as shown in Figure 7.1. Ensure that the lower pulley is positioned such that the string is horizontal as it unwinds from the drum. The position of the upper pulley system should be such that the string is vertical as it comes off of the lower pulley and should allow about a 1m drop to the floor. Some care must be taken when rewinding the string onto the drum. Ensure that the string is wound evenly and that it does not cross over itself. See your lab instructor if you are having difficulty with the setup.

A: Moment of Inertia of the Cradle

Compensate for frictional forces. Use the hook and washers to determine the mass required to produce a slow uniform motion. Begin by hanging the hook and a single washer on the free end of the string. Continue adding washers until the hanging assembly just begins to drop. Determine the mass of the hook and washer combination using the laboratory balance. Record this mass as Δm. Remove the hook and washers from the string and add a weight large enough to produce a reasonable acceleration. Remember, the time of descent must be determined using the computer-based stopwatch. If the mass that you add is very large, it will drop very quickly and will be difficult to time accurately. Record the mass of the weight, the time it takes for the weight to touch the floor when dropped from rest and the initial height of the weight. (Measure the distance from the floor to the bottom of the hanging mass) Use 3 different masses and make two sets of measurements for each. Calculate and record the moment of inertia for each trial.

B: Moment of Inertia of Regular Geometric Objects

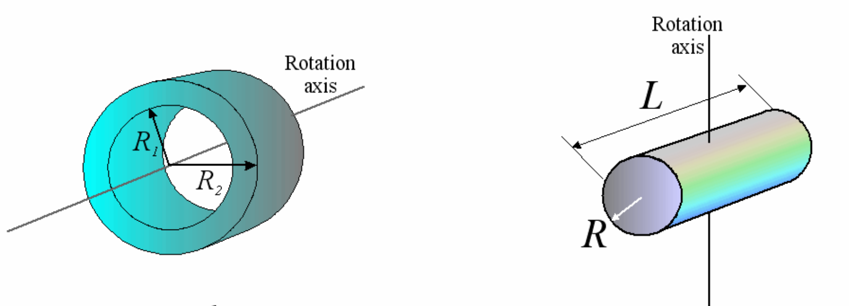
You have been provided with 2 regular geometric objects: a cylindrical ring and a cylindrical solid. The procedure to determine the moment of inertia for each of these is the same as that used for the cradle alone. Energy lost to friction is dependent on the mass of the rotating object. You must therefore make a new determination of the mass, Δm, for each change in the configuration of the system. Determine the moment of inertia of one of the objects. Perform the experiment using 3 different weights. Complete 2 trials for each weight.

C: Experiment vs. Theory

Compare your experimentally determined moments of inertia for the regular geometric objects with those predicted theoretically. (The equations are provided at the end of this experiment. Additional measurements may be required.)

Conclusion

Discuss your results. Pay attention to any discrepancies between experimental and theoretical values. Describe the importance of the moment of inertia of a rotating body. What is it a measure of?



$$I = \frac{1}{2}M(R_1^2 + R_2^2)$$

$$I = \frac{1}{4}MR^2 + \frac{1}{12}ML^2$$

Figure 7.2: Moments of Inertia for some Regular Objects

Experiment 8

Standing Waves

Purpose

The purpose of this experiment is to determine the wave speed on a stretched string and to investigate the relationship between string tension and the speed of the wave.

Apparatus

The apparatus for this experiment consists of a mechanical vibrator connected to a variable frequency sine wave generator. A pulley assembly and a set of masses is used to vary the tension in an elastic string. A metre stick is used to measure length and a balance is used to measure the mass of a sample of the string.

Theory

A wave is produced in an elastic medium when a periodic force is applied to it. A transverse wave is created in a string under tension when such a force is applied perpendicular to the direction of propagation. The wavelength λ of the wave is the distance between any two consecutive crests or troughs of a traveling wave. The frequency f of the wave is the number of complete oscillations made by the string per unit time. The speed

v at which the wave travels is related to the frequency and wavelength by the formula

$$v = f\lambda \tag{8.1}$$

As is true for all mechanical waves, the speed of the transverse wave depends on the properties of the medium through which it travels. For a wave on a stretched string, the speed of the wave depends on the linear density μ of the string and the tension T in the string as follows

$$v = \sqrt{\frac{T}{\mu}} \tag{8.2}$$

When two waves of the same frequency, amplitude and speed travel in opposite directions on the same string, interference produces a standing wave pattern. The standing wave wavelength and string length L are related by

$$L = \frac{n\lambda}{2} \tag{8.3}$$

where n is an integer that represents the number of antinodes .

The frequencies at which standing waves are produced are called resonant frequencies and are given by the formula

$$f = \frac{nv}{2L} \tag{8.4}$$

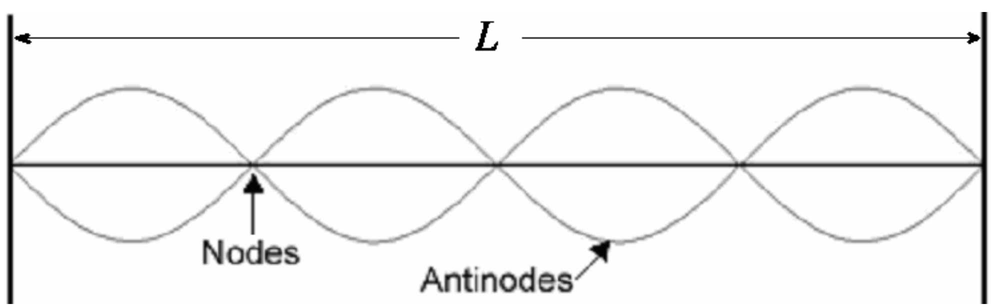


Figure 8.1: Standing Waves

The above assumes that the linear density of the string is unaffected by the tension. For the elastic string that you will use, this is not a good assumption.

The linear density can then be written as

$$\mu = \frac{m}{L_0 + \Delta L} = \frac{\mu_0}{1 + \Delta L / L_0} \tag{8.5}$$

where $\mu_0 = m / L_0$ and L_0 is the length without tension. Hooke's law relates the tension to the stretch via the spring constant k.

$$T = k\Delta L \tag{8.6}$$

Combining equations (8.2) and (8.5) and (8.6) we get

$$v^2 = \frac{T}{\mu_0}\left(1 + \frac{T}{kL_0}\right) \tag{8.7}$$

This is the equation of a straight line if we plot it as

$$\frac{v^2}{T} = \frac{1}{\mu_0} + \left(\frac{1}{\mu_0 k L_0}\right)T \tag{8.8}$$

Procedure

A) **Wave Speed on a Stretched String**

1. Provide tension in the string using a 400 g mass.
2. Carefully adjust the frequency on the function generator until a clear 3-antinode pattern occurs in the string. The antinodes will attain maximum amplitude at the correct frequency. It is advisable to increase the frequency until the antinodes begin to decrease in amplitude then decrease the frequency to get the maximum amplitude. Also, be careful not to overdrive the amplitude setting.
3. Measure the wavelength of the standing wave. This can be done by measuring the length, *L*, of the vibrating portion of the string (from the vibrating reed to the point where the string first touches the lower pulley) and using equation (8.3). Record both the wavelength and frequency in your data table.
4. Repeat steps 2 and 3 for the next four resonant frequencies.

5. Determine and record the length and mass of the unstretched sample string provided with the balance

B) Relationship between Tension and Wave Speed

1. Begin with a 400 g mass attached to the string. Determine the frequency at which a 3-antinode standing wave pattern occurs. Measure the wavelength of the standing wave. Record the mass, frequency, wavelength in your data table.
2. Repeat step one while varying the tension in the string in 50 g increments up to a total mass of 600 g. Set the tension in the string in the same way for each weight.
3. Measure the change in string length between the 600 g and the 400 g weights on the portion of string where the weights are attached.

Analysis

A) Wave Speed

a. Plot a graph of frequency f versus inverse wavelength $1/\lambda$ and determine the wave speed from the slope of the graph.

b. From the measurements of string mass and unstretched length determine the linear density, μ_0, of the string and use this and the tension produced by the 400 g mass to determine the wave speed using equation (8.2). Note that this may differ from the speed determined in point (a) above.

B) Relationship between Tension and Wave Speed

a. Calculate the tension and the wave speed using your experimental data.

b. Plot a graph of v^2/T versus T and determine both the slope and intercept.

c. Calculate μ_0 from the intercept and *k* from the slope (see equation 8.8) and compare to the direct measurement of μ_0 from part (A) and *k* from equation (8.6). In calculating *k* from eq.(8.6) use the difference in tension between the 400 g and 600 g masses.

Conclusion

Compare the wave speeds determined from your experiment in part A. Account for any differences. In part B does the theory correspond to the experiment? If not, why not?

Experiment 9

Electric Fields

Purpose

The purpose of this experiment is to draw equipotential lines and electric field lines in the region between charged conductors of various shapes.

Apparatus

The apparatus used in this experiment consists of a baseboard on which low conductivity paper with painted electrodes is positioned. A battery is used to establish a potential difference between the electrodes. Two probes connected to a voltmeter are used to map equipotential lines in the region between the conductors.

Theory

The interaction force between two point charges is determined by Coulomb's well-known law. This law, however, does not describe the interaction itself. A simple direct interaction model cannot explain why a change in the position of one charge does not instantaneously affect the other charge.

This indirect interaction can be explained by the concept of electric field. In this model, every charge produces an electric field in the surrounding space and it is this field that interacts with other charges. A change in the position of a charge results in a disturbance in the electric field that propagates as an electromagnetic pulse travelling at the speed of light. At any point in space the electric field is defined as the electric force on a charge q_0 divided by the magnitude of that charge:

$$\vec{E} = \frac{\vec{F}}{q_0} \tag{9.1}$$

Electric field lines, or lines of force, are a set of lines that point in the direction of the field with the density of the lines proportional to the field intensity. The electric field lines originate on positive charges and terminate on negative charges. The solid lines in Figure 9.1 below represent the electric field lines due to oppositely charged parallel plates.

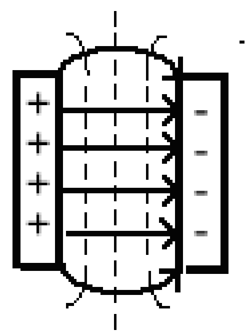


Figure 9.1: Electric Field Lines and Equipotential Lines

The relationship between the electric field and electric potential difference provides a method of mapping the electric field. The potential difference between two points in an electric field is given by

$$\Delta V = V_f - V_i = \frac{-W}{q_0} \tag{9.2}$$

where W is the work done by the field in moving a positive test charge q_0 from an initial position to a final position. Along an equipotential surface, the change in potential is zero; therefore, the electric field has no components tangential to the equipotential surface. Thus, at any point, the electric field is perpendicular to the equipotential surface or, in two dimensions, the electric field lines are perpendicular to equipotential lines as in Figure 9.1. In this experiment, points which are at the same potential will be located, equipotential lines drawn and the corresponding electric field lines sketched.

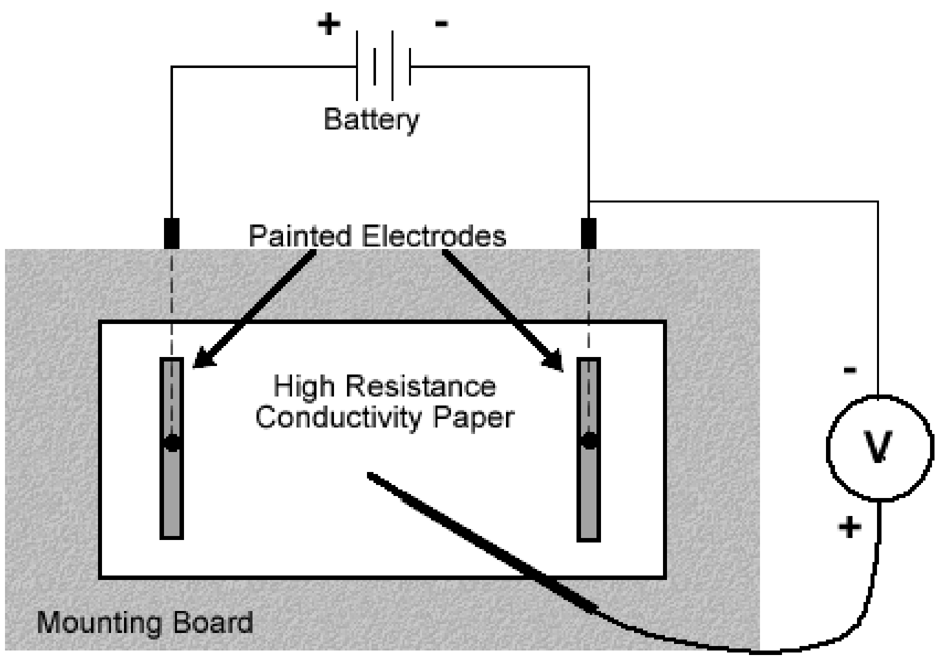


Figure 9.2: Experimental Apparatus

Procedure

1. Set up the apparatus as shown in Figure 9.2.
2. Position the low conductivity sheet with painted electrodes on the board and fasten it using the washers and fasteners.
3. Use the voltmeter to ensure good contacts exist between the terminals and electrodes then measure the maximum potential difference between the electrodes.
4. Map at least 7 equipotential lines between the electrodes. Some electrode configurations will require more than the minimum number of equipotential lines in order to get a good representation of the electric field. Mapping is accomplished by positioning the hand-held probe at points where the potential remains constant. The grid on the low-conductivity paper corresponds to the grid on the electrode printouts.

Use this grid to assist you in mapping the equipotential lines to the print out.

5. Record the potential of each line that you map and the potential at each electrode on your printout.
6. Sketch the corresponding field lines, ensuring that they are perpendicular to the equipotentials and are directed from (+) to (-).
7. Repeat this procedure for the following electrode arrangements:
    a. Parallel Plates
    b. Two Point Charges
    c. Parallel Plates with a Central Circular Conductor
    d. One of the other two arrangements.

Conclusion

Discuss the electric field for each electrode arrangement investigated. Use the density of the lines to determine where the electric field is the most/least intense, constant or zero. Do the lines of force point in the direction of increasing or decreasing potential? At what angle do the electric field lines meet the conductors? What is the electric field and electric potential inside the conductors?

Questions

1. How much work is done **by** the uniform electric field in moving an electron from the negative plate to the positive plate of the parallel plate conductors in this experiment? State your answer in both eV and joules.

2. If an electron was released from rest from the negative plate in vacuum, what would its speed be just before striking the positive plate? NOTE: 1 eV is the energy acquired by an electron when it is accelerated through a potential difference of 1 V.

Experiment 10

Electric Meters & Ohm’s Law

Purpose

In this experiment you will first study the galvanometer, which is a current measuring device, and investigate how the galvanometer can be converted into an ammeter and a voltmeter. You will also investigate the relationship between current and voltage for a number of conductors.

Apparatus

A galvanometer, several fixed resistors, a 10 $k\Omega$ decade resistor, a voltmeter, 1.5 V and 6 V batteries, a switch, two test conductors, a terminal board and connecting leads are used in the circuits described below.

Theory and Procedure

Part A: The Galvanometer

The galvanometer is a current sensitive device which may be used for detection of small currents. The type used in this experiment (see Figure 10.1) consists of a coil of wire mounted on pivots over a soft iron core. When a current is passed through the coil, the magnetic field created in the coil interacts with the uniform radial magnetic field of the permanent magnet. This produces a torque on the coil which is proportional to the current. This torque rotates the coil until it is balanced by the torque created in the spiral stabilizing spring. An indicating needle on the coil suspension makes a clearly visible display of this rotation. Since the restoring spring torque is proportional to the angle or rotation, the deflection of the needle is proportional to the current and the galvanometer has a linear scale.

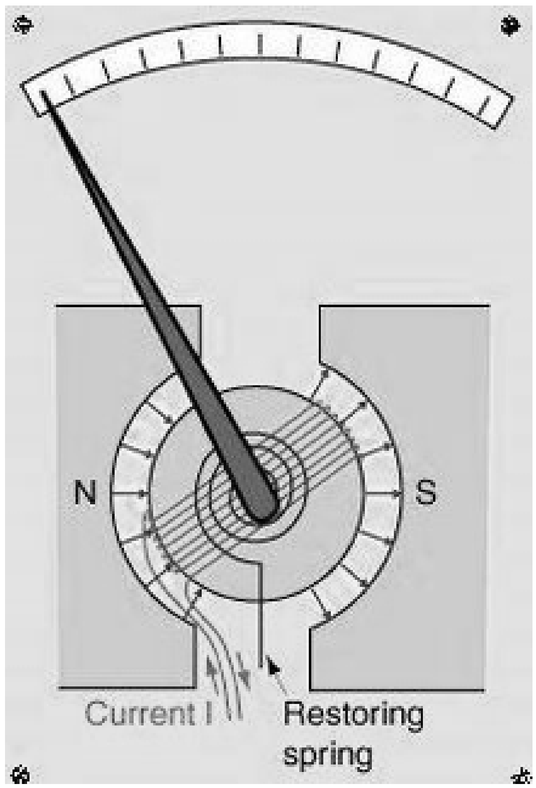


Figure 10.1: The Galvanometer

The galvanometer you are using has a bipolar scale that runs from -50 to +50 in arbitrary units. You are first to determine the current sensitivity of this device. Place the galvanometer in series with a 1.5 V battery and a 10 $k\Omega$ decade resistance box set at maximum resistance. Now reduce the resistance R of the decade box until the meter reads full scale. If we assume the resistance of the galvanometer R_g is much less than R, then the current in the circuit is $I_g = V_B / R$. Here V_B is the voltage of the battery which should be measured with the multimeter *while in the circuit*.

Since the galvanometer as a current measuring device is placed in series in a circuit it should have the smallest resistance possible to minimize its effect on the circuit. One could determine R_g by measuring the voltage across the galvanometer when in the circuit described above. However, this voltage would be quite small so we will use a different method. Replace the decade resistor in the circuit you have just constructed with a fixed resistor of the same value that gave full scale deflection of the galvanometer. If a shunt resistor R_{sh} equal to R_g were then placed in parallel with the galvanometer, half the current would pass through each. Place the decade resistor in parallel with the galvanometer as shown in Figure 10.2. Begin with R_{sh} at a maximum and decrease until the meter deflection is one-half full scale. Then $R_{sh} = R_g$.

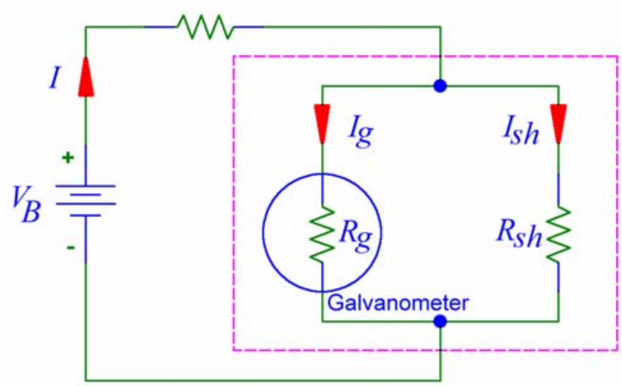


Figure 10.2: Galvanometer with parallel shunt resistance

Part B: The Ammeter

It is relatively simple to convert a galvanometer to an ammeter. In fact, you have already seen how to do this while investigating the resistance of the galvanometer. The parallel shunt in that case reduced the sensitivity of the galvanometer by one-half. The circuit within the dashed lines in Figure 10.2 is an ammeter. Use Kirchoff's rules to determine what value of R_{sh} would result in full scale deflection of the galvanometer for a total current of 5 mA. Construct a 5 mA ammeter by placing a resistor of this value across the terminals of the galvanometer. Set up a circuit which will provide 5 mA and test your new ammeter. Calculate the effective resistance of this ammeter.

Part C: The Voltmeter

The basic D.C. voltmeter consists simply of a galvanometer in series with a large resistor R_V as shown in Figure 10.3. A voltmeter is placed in parallel with the voltage V that is to be measured. Thus

$$V = I_g (R_V + R_g)$$
$$I_g = \frac{V}{R_V + R_g}$$

Determine the resistance R_V necessary to modify your galvanometer into a

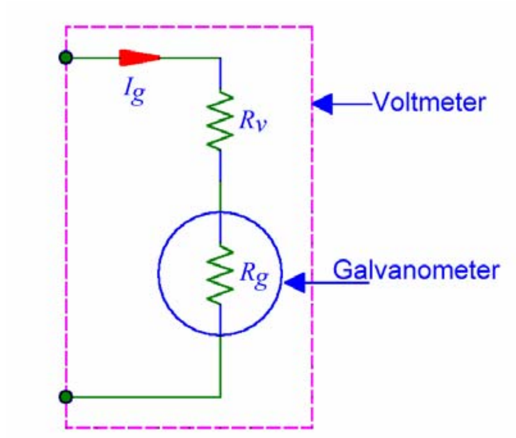


Figure 10.3: The Voltmeter

10 V full-scale voltmeter. Construct such a voltmeter using a fixed resistor for R_V. Test by measuring the voltages of a 1.5 V and 6 V battery. Construct the circuit shown in Figure 10.4 with a 6 V battery and with R_1 and R_2 of approximately 100 Ω and 360 Ω. Using the voltmeter you have constructed, measure V_1 and V_2, and the emf of the battery. Repeat this experiment with R_1 = 10 $k\Omega$ and R_2 = 20 $k\Omega$. Is $V_B = V_1 + V_2$ for both cases? In explaining any discrepancies consider the internal resistance of the voltmeter.

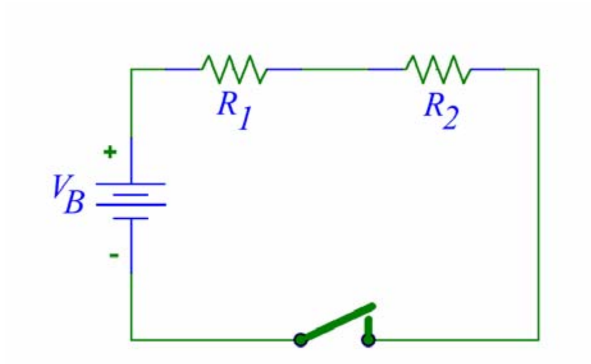


Figure 10.4: Test Circuit

Part D: Current-Voltage Relationships (Ohm's Law)

The resistance R of a conductor is defined as the ratio of the voltage V across the conductor to the current I through the conductor, that is

$$R = \frac{V}{I} \tag{10.1}$$

The metric unit of resistance, therefore, is the volt/ampere which is known as the ohm and given the symbol Ω.

Georg Simon Ohm (1787-1854) first investigated the I vs. V relationship for a large number of materials. He discovered that for many conductors R is a constant (the I-V curve is a straight line passing through the origin). A conductor for which R is constant is said to obey Ohm's Law or to be an ohmic conductor. A conductor for which R is not constant is called non-ohmic. Notice that in either case equation (10.1) still remains the definition of resistance. Sometimes, for non-ohmic conductors, the slope of the V versus I curve or differential resistance dV/dI is of more interest than the actual value of the resistance V/I. It is possible for the differential resistance to be negative, but the resistance never is. For an ohmic conductor, the differential resistance is the same as the resistance. In this experiment you are to investigate the I-V curve for two conductors: a low power light bulb and a carbon resistor. Construct the circuit shown in Figure 10.5 using the 6 volt battery. Measure the voltage drop across the two test conductors over the full range of the decade box settings. Take at least ten well spaced readings for each sample. Use the commercial multimeter to perform your measurements. Calculate the current through the load and its resistance for each reading. Use a well labeled table! From your data plot the *I-V* curve (current versus

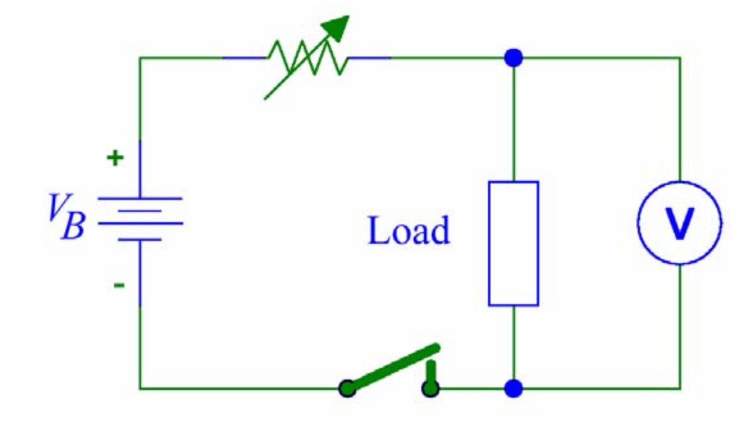


Figure 10.5: *I-V* Test Circuit

voltage) as well as the load resistance versus the current. For any ohmic device, determine the resistance from the *I-V* curve slope and compare this to the *R* vs. *I* plot. Discuss your results and explain any discrepancies seen. The results for both conductors should be plotted on the same two graphs.

Questions

1. How should two 100 resistors be connected so that the equivalent resistance is greater than the individual resistances? How do you connect them to make it less? Justify your answers with calculations.
2. Why is it advisable to connect car headlights in parallel rather than in series?

Experiment 11

AC Circuits

Purpose

The purpose of this experiment is to investigate the dependence of capacitive and inductive reactance on frequency and to demonstrate that the voltages across resistive and reactive circuit elements add as phasors rather than as scalars.

Apparatus

The apparatus for this experiment includes a function generator, an A.C. voltmeter, a 1.2 $k\Omega$ resistor, a 68 nF capacitor, a 100 mH inductor, and a circuit board. The tolerance of the resistor is 5 % (gold band) whereas the other two can be assumed to be 10 %.

Theory

A capacitor consists of two conducting plates separated by an insulator called a dielectric. The unit used to measure capacitance is the farad, where a capacitor of one farad holds a charge of one coulomb when charged to a voltage of one volt. The most commonly used units are actually the microfarad and the picofarad.

A capacitor in a D.C. circuit acts almost like a break in the circuit. Once it is charged, no current then flows. In an A.C., circuit the situation is different. The capacitor charges in one direction and when the voltage source changes polarity, the capacitor discharges and then charges in the opposite direction. Thus, an alternating current will flow in a circuit having capacity.

Just as the current in a D.C. circuit depends on the resistance in the circuit, the current in an A.C. circuit depends on the capacitance. In a D.C. circuit, the resistance as found from Ohm's Law is given by the ratio of voltage to current. For an alternating voltage VC applied across a capacitor, an alternating current I will flow. The quantity associated with the capacitance and analogous to resistance is called the capacitive reactance X_C and is given by the ratio V_C / I. If V_C is in volts and I in amperes, then X_C will be in ohms. In this experiment, the dependence of reactance on frequency will be examined. It can be shown that

$$X_C = \frac{1}{\omega C} \tag{11.1}$$

(11.1)

where C is the capacitance and is determined by the geometry of the capacitor and the materials of which it is constructed and is usually a constant for a particular capacitor. The angular frequency ω (in radians per second) is given by $\omega = 2\pi f$ where f is the frequency of the applied voltage (in Hz).

An inductor is usually made from a coil of wire. Its operation follows Faraday's Law of Induction. According to this law an inductor develops a voltage that opposes any change in current through the device. The current is constantly changing in an A.C. circuit. Faraday's Law can be used to show that the voltage across the inductor is given by IX_L where X_L is called the inductive reactance. It is directly related to the angular frequency of the current through the equation

$$X_L = \omega L \tag{11.2}$$

where L is the inductance of the device.

Procedure

1. Connect the experimental circuit as shown in Figure 11.1. This diagram shows the circuit with a capacitor. The same circuit is used for the inductor by replacing the capacitor with the inductor.

2. Measure the voltage across the resistor, the capacitor and the function generator for at least 9 frequencies from 400 Hz to 10 kHz. Record the frequencies and the voltages in your data table.
3. Repeat for the inductor circuit and use the multimeter to measure the resistance of the inductor.

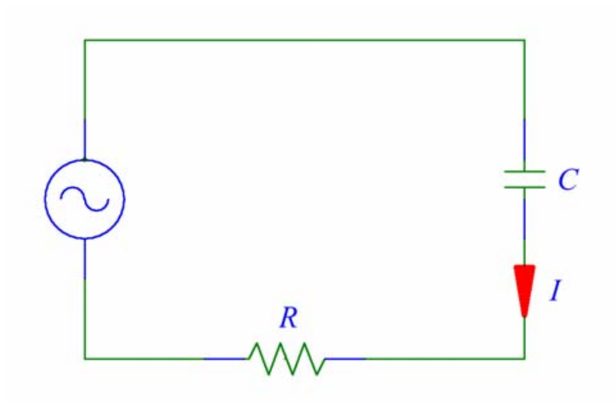


Figure 11.1: Experimental Circuit

Analysis

A) Calculate and record $\sqrt{V_R^2 + V_C^2}$, $\sqrt{V_R^2 + V_L^2}$ and the percentage errors for each frequency explored.

B) Calculate and record X_C and X_L at each frequency. Note that

$$X = \frac{V_X}{I} = \frac{RV_X}{V_R} \tag{11.3}$$

C) Plot graphs of X_C versus $1/\omega$ and X_L versus ω. Determine the capacitance and inductance from the slopes of the graphs.

Conclusion

For each circuit and at each frequency, compare and contrast the square root of the sum of the squares of the voltage drops to the output voltage at the function generator. Use a logically constructed table to facilitate this comparison. Discuss your findings. What does the result indicate about voltages in inductive and capacitive A.C. circuits?

Compare your experimentally determined capacitance and inductance to the given values for them. Account for any significant differences. What is the stated tolerances for the circuit elements? What is the significance of the inductor resistance?

Question

You will see that the percentage error calculated for the measured total voltage compared to the phasor calculation is much greater for the inductor circuit. What is the source of this error? Your explanation must also explain the frequency dependence of this error. There is a specific logical explanation for this. **DO NOT** say that it is a reading error!

Experiment 12

Thin Lenses

Purpose

The purpose of this experiment is to verify the thin lens equation and to determine the focal length of an optical thin lens.

Apparatus

The apparatus used in this experiment consists of an optical bench, a light source with built-in object, a thin lens, a screen and a small plastic scale.

Theory

A thin lens is an optical system with two refracting surfaces that are close enough to each other that we can neglect their separation. Light rays passing through a thin lens are refracted, changing their direction of propagation.

A converging thin lens is one that will focus a beam of parallel rays to a single point called the focal point of the lens. A common form of a converging lens is a double convex lens that consists of two convex curved surfaces having the same curvature

The distance from the focal point to the centre of the lens is called the focal length of the lens. Converging lenses are often used to form images of extended objects.

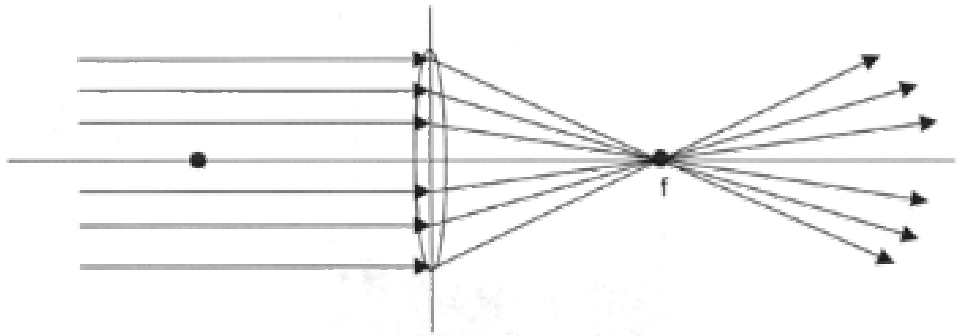


Figure 12.1: Rays from infinity converge at the focal point.

Consider the diagram in Figure 12.2. The distance from the object, of height y, to the centre of the lens is denoted with the letter p. The image, formed by the lens is located a distance q away and has a height y'.

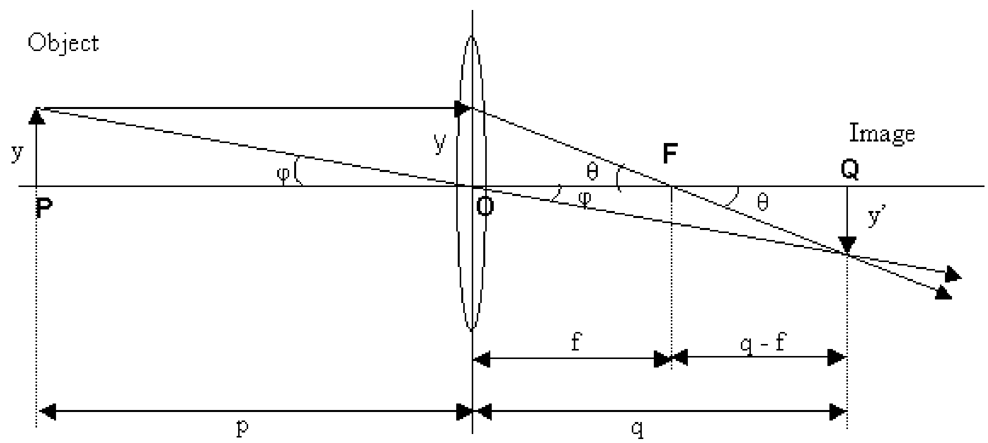


Figure 12.2: Image formation by a thin lens.

The ray parallel to the optic axis will pass through the focal point F after refraction through the lens. The ray that passes through the centre of the lens is undeflected. The intersection of the two rays defines the image height y'.

$$\tan(\phi) = \frac{y}{p} = \frac{-y'}{q} \tag{12.1}$$

The quantity on the right hand side of equation (12.1) is negative because y' lies below the optical axis and thus is a negative quantity, in accordance with our sign convention. We can also write

$$\tan(\theta) = \frac{y}{f} = \frac{-y'}{q-f} \tag{12.2}$$

The ratio of the height of the image to the height of the object is called the magnification and is denoted by the symbol M. From equations (12.1) and (12.2) we get

$$M = \frac{y'}{y} = \frac{-q}{p} = 1 - \frac{q}{f} \tag{12.3}$$

We can now derive the thin lens equation by dividing by q and rearranging the last two terms in equation (12.3)

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \tag{12.4}$$

Procedure

1. Your light source has the object built into it. The light bulb aligns with the pointer on the carriage and is situated in the centre of the housing. The object is stamped into one face of the housing. Be careful to take this into account when determining the position of the object on the scale.
2. Determine and record the location of the lens and screen. Both of these align with the pointer of their carriage.
3. The image height can be determined on the scale printed on the screen and the height of the object is fixed and can be measured with a small plastic scale.
4. Perform a minimum of 10 measurements. Use a fixed object location and move the lens to a new location for each one. Ensure that you obtain a good range of data and avoid data that clumps into a small area of your graph. Record all measurements in a clearly written table.

Analysis

A) Use the experimental data to determine the object distance, p, the image distance, q, and the magnification, M, for each trial and record the results in a new table. Calculate $1/p$ and $1/q$ in the same table.

B) Plot a graph of $1/q$ versus $1/p$ and determine the slope and both intercepts.

C) Plot the magnification, M or $-M$ versus q and determine this graph's slope and intercepts.

Conclusion

What is the significance of the slope of the graph in part B of the analysis? From the intercepts calculate the focal length of the lens.

Determine the slope and both intercepts of the part C graph as well. You can get two more values for the focal length. Compare all four values of the focal length that you have calculated from both graphs. If necessary rewrite the equations into the form of a straight line in your theory section to help with your analysis.

Questions

1. In this experiment we considered only real objects and real images and thus our data lies in the first quadrant of the cartesian plane. It is also possible to have virtual images or even virtual objects. Sketch the complete $1/q$ versus $1/p$ curve for all four quadrants.
2. Sketch the q versus p curve and show the asymptotes.

Part III

APPENDIX

Appendix 1

Graphing with Excel

To open Excel, choose the stylized X icon from the quick launch bar at the bottom of the desktop. You can also access the program through Finder by choosing the Applications option from the Go menu and navigating to the Microsoft Office folder. You are presented with a Document Type option once Excel opens. The default is Blank Documents/Excel Workbook. This is the type of spreadsheet that you need so choose OK.

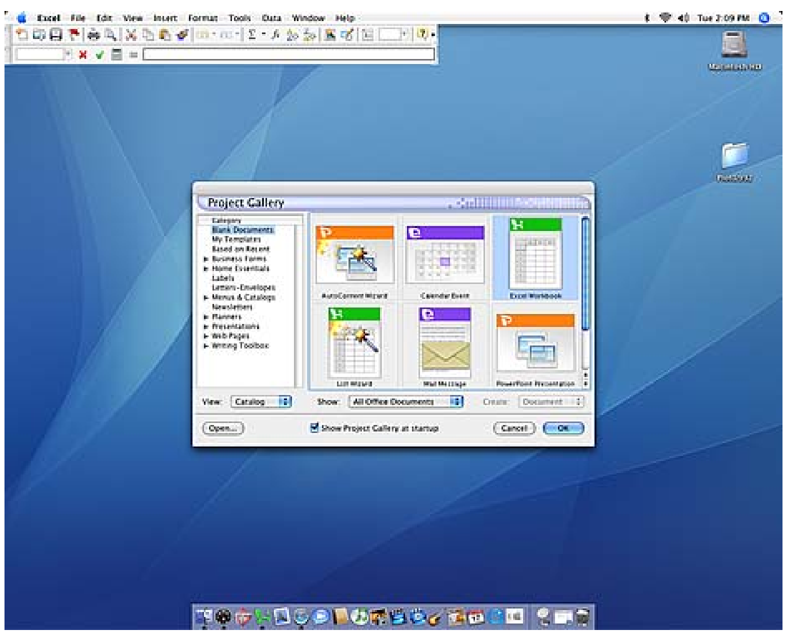


Figure 1.1: Screenshot 1

You will need to type your data to be graphed into the spreadsheet that opens. Your data needs to be input in column format. It is recommended, though not necessary to place all of the independent variable data into the leftmost column. You can then input the dependent variable data into the subsequent columns to the right. It is a good idea to place your raw data into the spreadsheet. You can then configure the spreadsheet to perform any calculations for you.

We provide an example using student-acquired data from a previous form of the non-uniform acceleration experiment. **NOTE: The experiment the data is from is very different from the one that you will be performing**.

It is useful to use column labels to identify your data. To create column labels, begin by selecting the cells that will contain the labels, then select Name->Label. . . from the Insert menu. This brings up a dialog box that should have the selected cells listed. Click Add then OK. You can now type in the column headings and input your data below them.

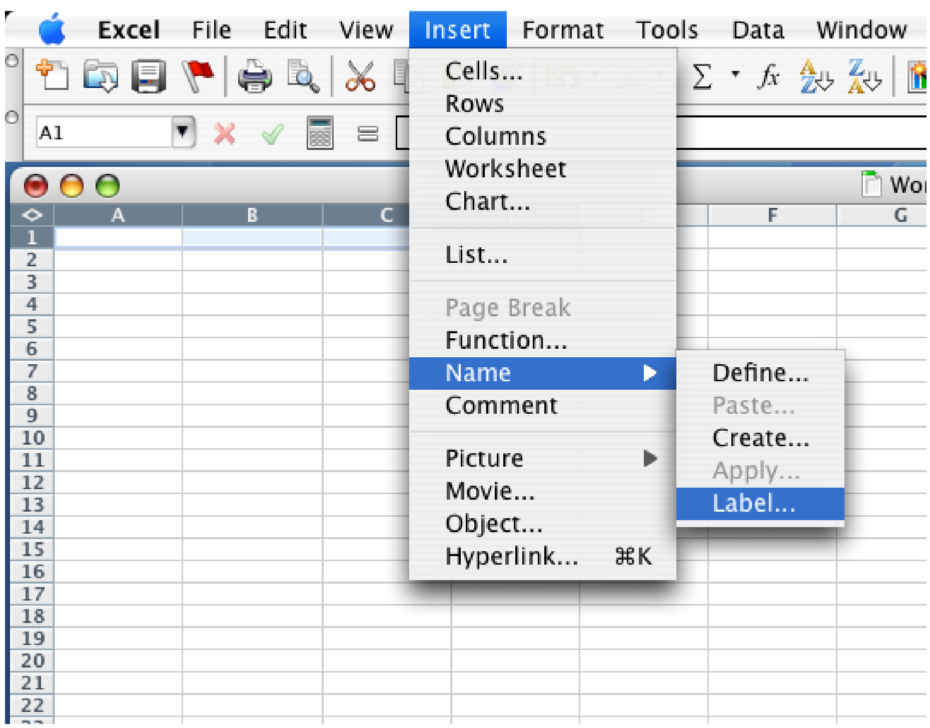


Figure 1.2: Screenshot 2

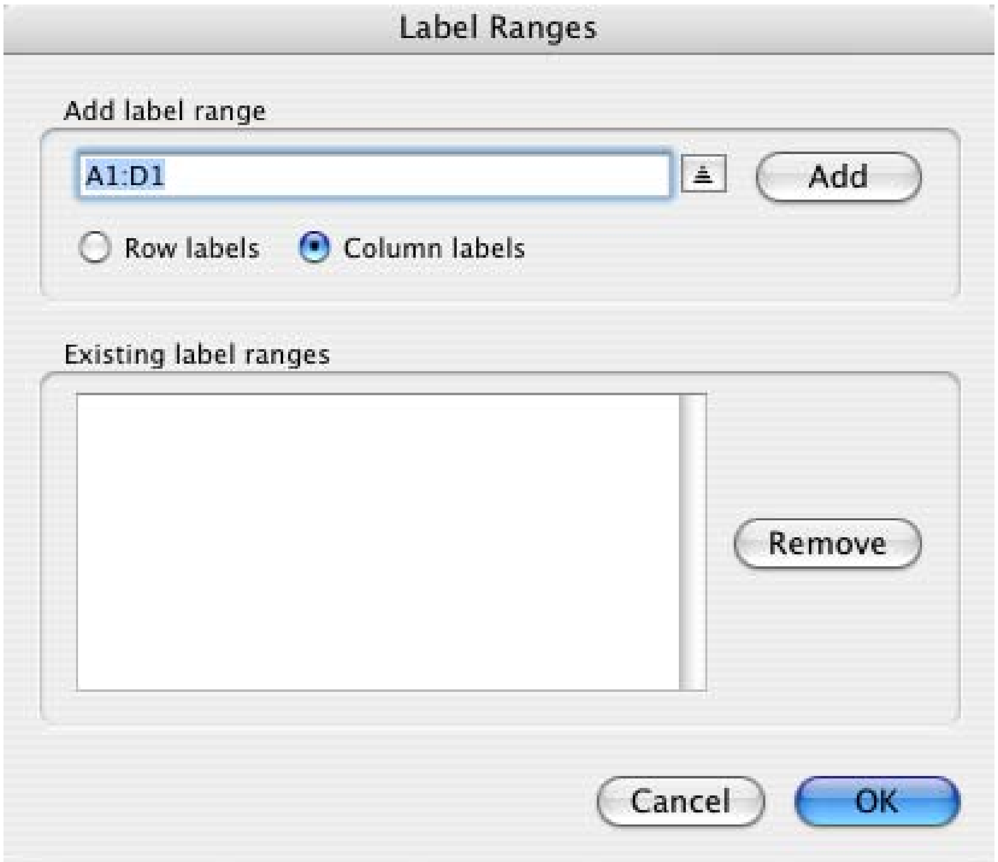


Figure 1.3: Dialogue Box

It is possible to have Excel perform calculations with your data. The experiment we are using as an example requires velocity be determined from displacement and time data. The time derivatives that give instantaneous velocity and acceleration are approximated using a finite approximation known as Euler's Method. To input the equation, click on the cell that will hold the result the type the equal sign and the equation. Cells are referred to by column letter and row number. For example, the velocity at time $t = 0.03s$ is determined as shown in the picture below (Figure 1.4. It is important to note that

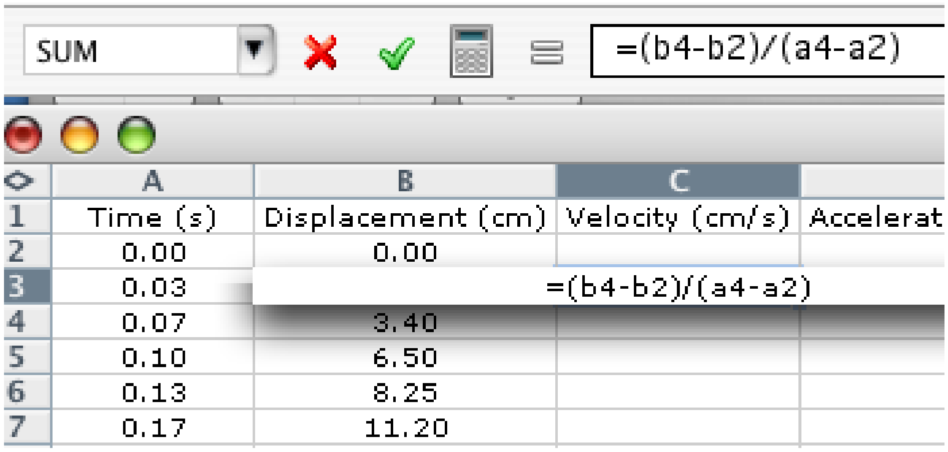
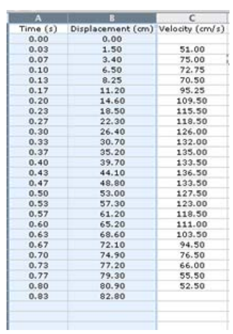


Figure 1.4: Euler's Method used in a Cell Calculation

Excel follows strict mathematical rules with respect to order of operations so the brackets in the expression are necessary for this calculation. The equation only needs to be typed once. To have Excel calculate the remaining values you need only copy the equation and paste it into the remaining cells. Excel will make the necessary adjustments to the equation automatically. NOTE: Key combinations on a Mac are different from those on the Windows version. To copy use Alt+C and to paste use Alt+V.

You are ready to begin graphing once all of the data has been input and the calculations are complete. Highlight the columns that you want Excel to graph.



A	B	C
Time (s)	Displacement (cm)	Velocity (cm/s)
0.00	0.00	
0.03	1.50	51.00
0.07	3.40	75.00
0.10	6.50	72.75
0.13	8.25	70.50
0.17	11.20	95.25
0.20	14.60	109.50
0.23	18.50	115.50
0.27	22.30	118.50
0.30	26.40	126.00
0.33	30.70	132.00
0.37	35.20	135.00
0.40	39.70	133.50
0.43	44.10	136.50
0.47	48.80	133.50
0.50	53.00	127.50
0.53	57.30	123.00
0.57	61.20	118.50
0.60	65.20	111.00
0.63	68.60	103.50
0.67	72.10	94.50
0.70	74.90	76.50
0.73	77.20	66.00
0.77	79.30	55.50
0.80	80.90	52.50
0.83	82.80	

Figure1.5: Highlighting Columns to use for Graphing

Choose Chart from the Insert menu. The Excel Chart Wizard pops up

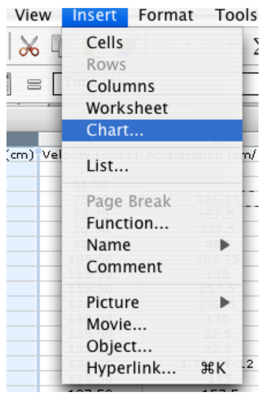


Figure 1.6: Selection from Menu

[Figure 1.7]. The default setting for graphs in Excel is the column type that is not very practical for scientific graphing. Select the XY (Scatter) type and choose the scatter type that plots data points without lines. This should be the default.

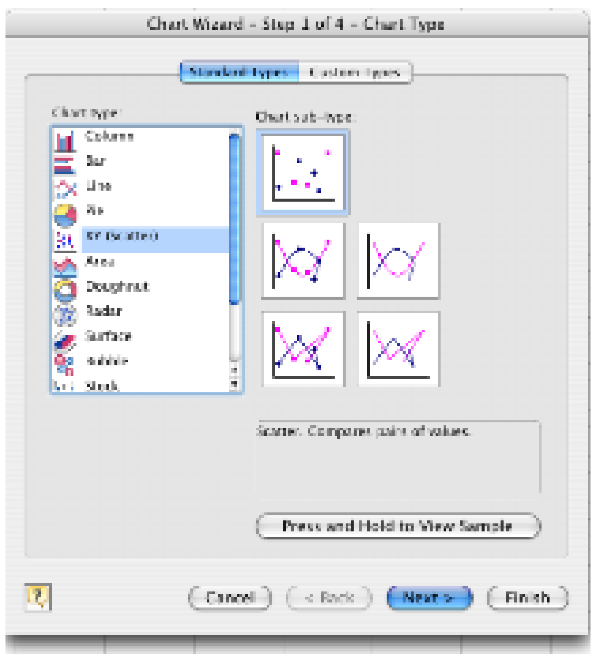


Figure 1.7: Chart Sub-Type Selection

Click Next. The dialogue that displays [Figure 1.8] presents a preview of your graph. Excel will automatically set the left-most selected column to the horizontal axis and the right most to the vertical one. You can always click on the Series tab to fix the selection if the data selection needs to be adjusted.

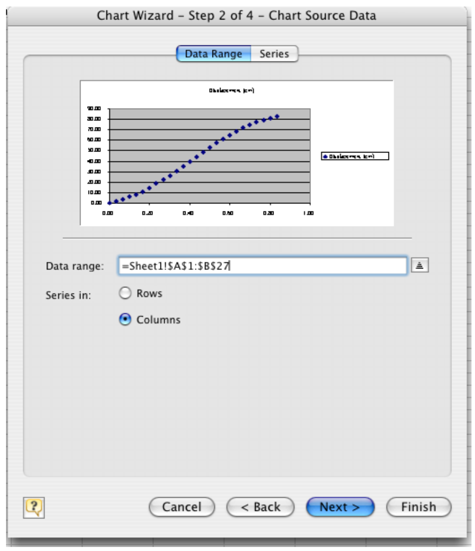


Figure 1.8: Data Range and Series Options Dialogue Box

Click Next to display the next set of Chart options [Figure 1.9]. The default title chosen by Excel is not adequate for your graph title. In this case, we are plotting Displacement vs. Time so that is the title that we choose. Axis labels should also be input in this dialogue. Select the Legend tab and deselect Show Legend.

You should also select the Gridlines tab and deselect the grid line check boxes. Click Next.

Choose Insert as New Sheet [Figure 1.10] with either the default title or one of your choice and click finish. Finally, once the chart is inserted into the workbook, right click in the blank area on the chart and choose Format Plot Area. Select the None radio button under the Area heading and click OK [Figure 1.11]. This will set the background colour to white that will provide a clearer copy when printing the graph.

The data we used for our example does not lend itself to a linear fit. That said, it will suffice to outline the process of fitting data using a linear trend line. Click on one of the data points displayed on the graph. This selects all

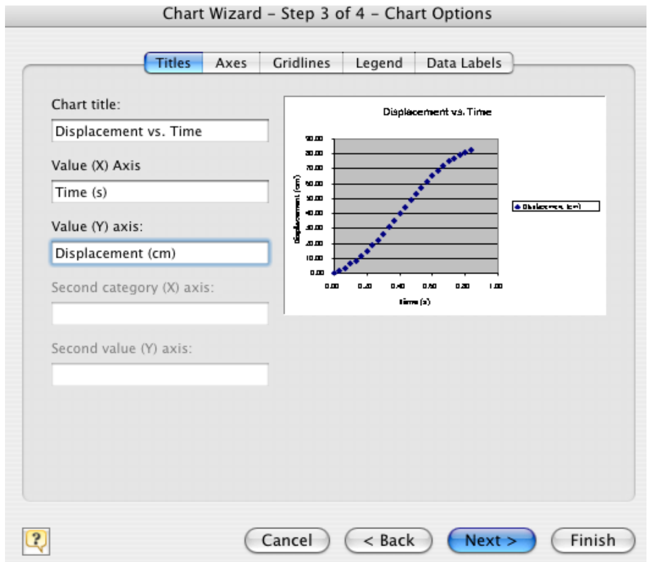


Figure 1.9: Labeling Options

Figure 1.10: Display Options

of the data points. Open the Chart menu and select *Add Trendline*. The trend line wizard opens up presenting a dialogue box [Figure 1.12] on the screen. The default Trend/regression type is linear. Excel usually selects the correct data to fit. You can correct this in the Based on Series edit box if necessary. Select the Options tab Figure 1.13 then select both *Set Intercept* = and *Display Equation on Chart*. The default intercept is zero. This is the value that would be expected in many cases however it is not always appropriate or expected.

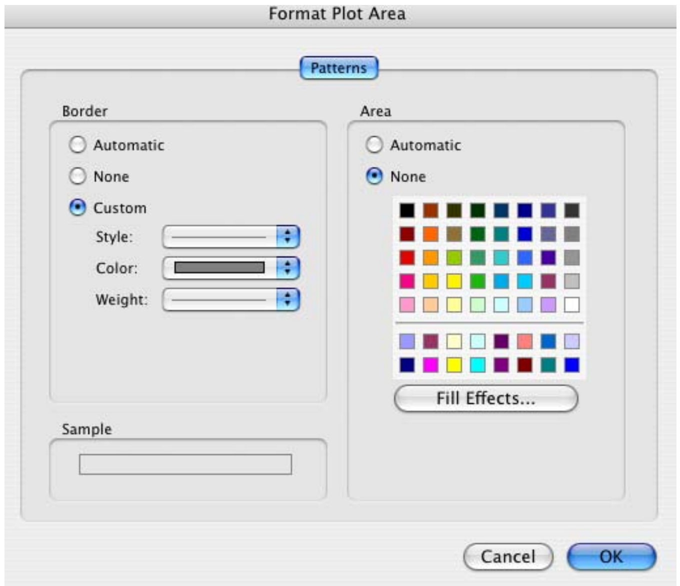


Figure 1.11: Adjust Background Colour

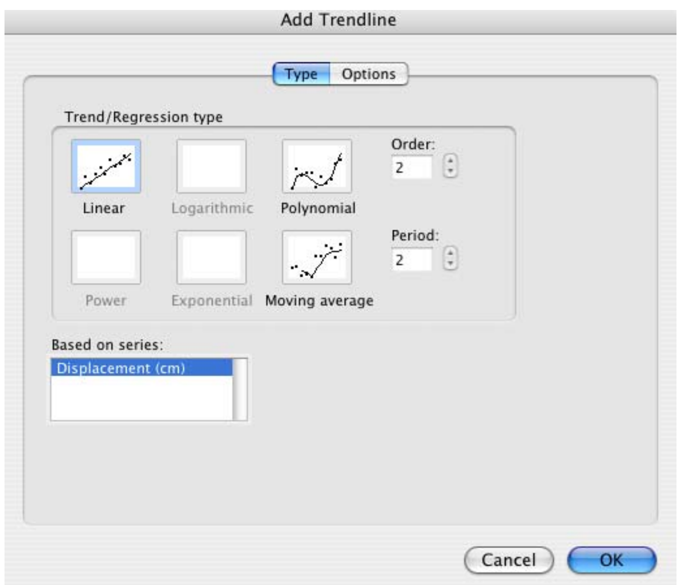


Figure 1.12: Inserting a Linear Fit Trend Line

The physics of the problem at hand should guide you to the proper selection of the expected intercept.

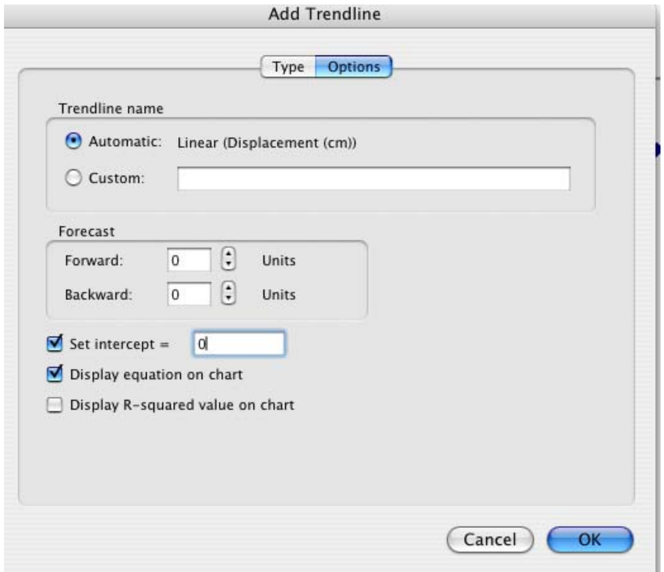


Figure 1.13: Trend Line Options

Appendix 2

Error Estimates and Measuring Tools

Error Estimates

The main sources of error that you will need to account for in this lab are observational errors, such as parallax and instrumental, such as the scale limitation of the measuring instrument at hand.

Parallax refers to the apparent displacement or difference in orientation of an object when it is viewed from different lines of sight. It is minimized when the observer and the measuring instrument being used are properly aligned with the object being measured. In Figure 2.1 we see that the observer's line of sight should be perpendicular to the measuring instrument. Error due to parallax can be minimized by a careful choice of measuring position and by keeping

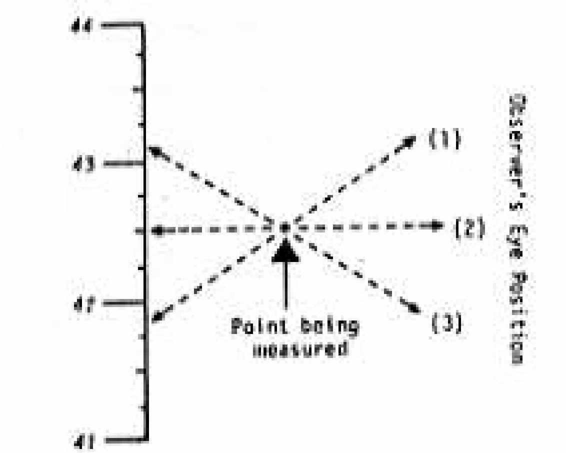


Figure 2.1: Parallax & the Viewer's Line of Sight

a minimum separation between the object being measured and the measuring tool. It can be very difficult to eliminate parallax from a measurement and its effect should be taken into account when estimating uncertainty.

Measuring tools and instruments are subject to two main sources of error, calibration and scale limitation. Calibration is the name given to the process in which a measuring instrument is brought into line with a given system of units. This is usually performed by comparing measurements made with the instrument with an accepted standard. In this lab we will assume, unless otherwise instructed, that the measuring instruments used are exact in comparison to a standard.

Every measuring instrument is limited by the smallest division which it is capable of resolving. As an example, the metre sticks in this lab have a smallest division of 1mm. Sometimes the point at which a measurement is being taken lies between the smallest divisions of the measuring scale. We then must estimate whether the object is closer to one division mark or the other. This leads to an error in accuracy due to the Scale Limitation of the measuring instrument. Any measurement in this lab, including those made with electronic equipment, is subject to a scale limitation error of one-half of the smallest division available on the instrument. For example, the metre sticks in this lab have a scale limitation of $0.5\ mm$.

Precision Measuring Tools

As was discussed in the introductory chapters in this manual, precision speaks to the reproducibility of measurements. The precision measuring tools you may be using in the lab, vernier calipers and micrometers, are both very precise and very accurate.

A vernier caliper makes use of a vernier scale to accurately measure fractions of a scale division. The calipers have both a fixed main scale and a sliding vernier scale. Most vernier calipers have two sets of jaws; one for measuring internal distances and one for measuring external distances.

When the jaws of the vernier are closed, the zero mark of the main scale (assuming the instrument has no zero error) and the zero mark of the vernier scale coincide. No other marks on the vernier scale will coincide with any marks on the main scale. Let us assume that the vernier caliper being considered has one millimetre as its smallest divisions. The vernier scale then

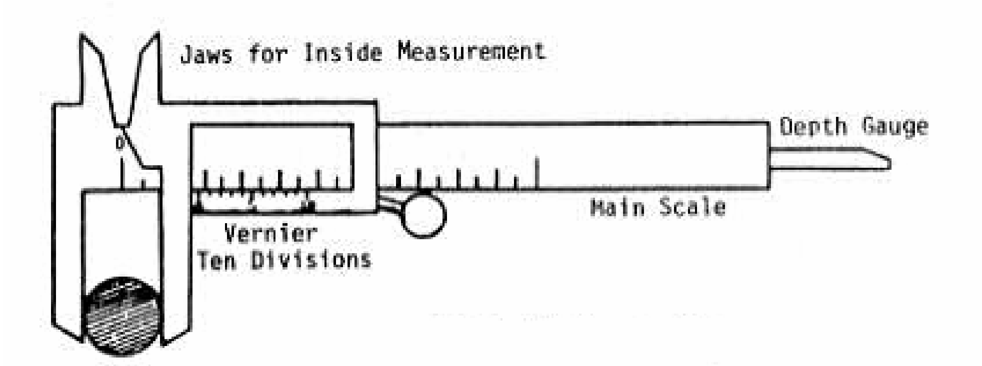


Figure 2.2: The Vernier Caliper

will allow us to accurately measure as small as $0.1\ mm$. Thus if we open the caliper by $0.1\ mm$ from closed we should find that the first vernier mark on the vernier scale will now coincide with the first millimetre mark on the main scale. Opening it by $0.2\ mm$ will find the second vernier mark coinciding with the second millimetre mark on the main scale. In practice, we would normally open the vernier caliper wide enough to go over (assuming an external measurement) the object in question then carefully close the caliper and read the measurement. To determine the measurement we first locate the zero mark on the vernier scale and read the main scale to the main scale mark closest to and before it. We then determine which of the vernier marks aligns most exactly with one of the main scale marks and add that to the previous determination. A vernier caliper becomes quite easy to use with a bit of practice.

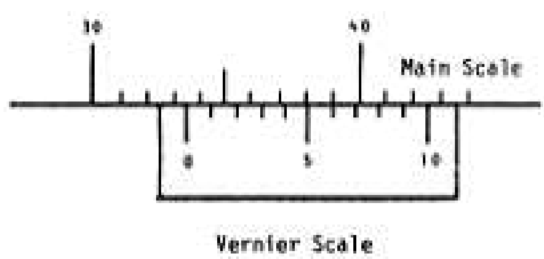
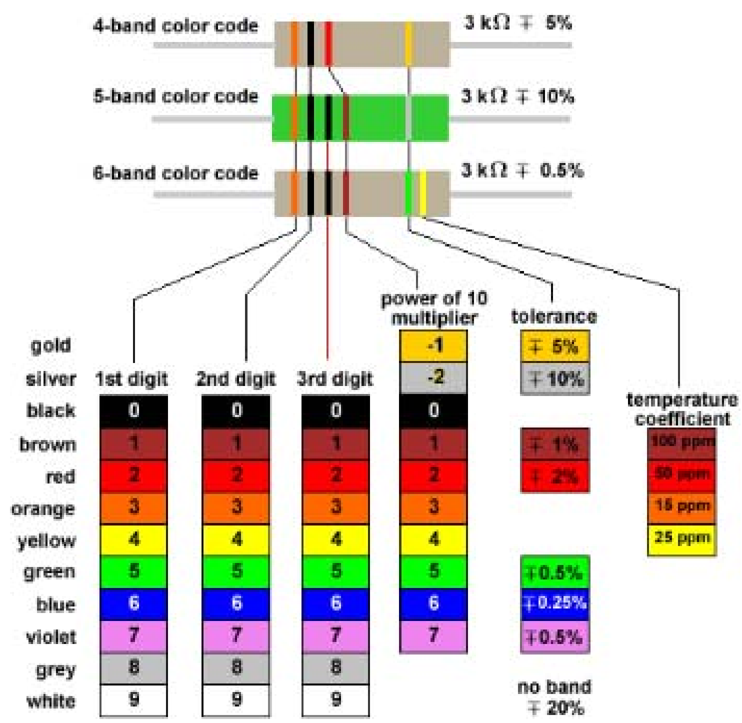


Figure 2.3: The Vernier Scale: A reading of 33.6 mm.

Consider Figure 2.3. The measurement shown here is $33.6\ mm$. The first $33\ mm$ is determined by the alignment of the zero bar on the vernier scale with the main scale. the $0.6\ mm$ is found by determining which vernier scale mark lines up with a mark on the main scale.

Appendix 3

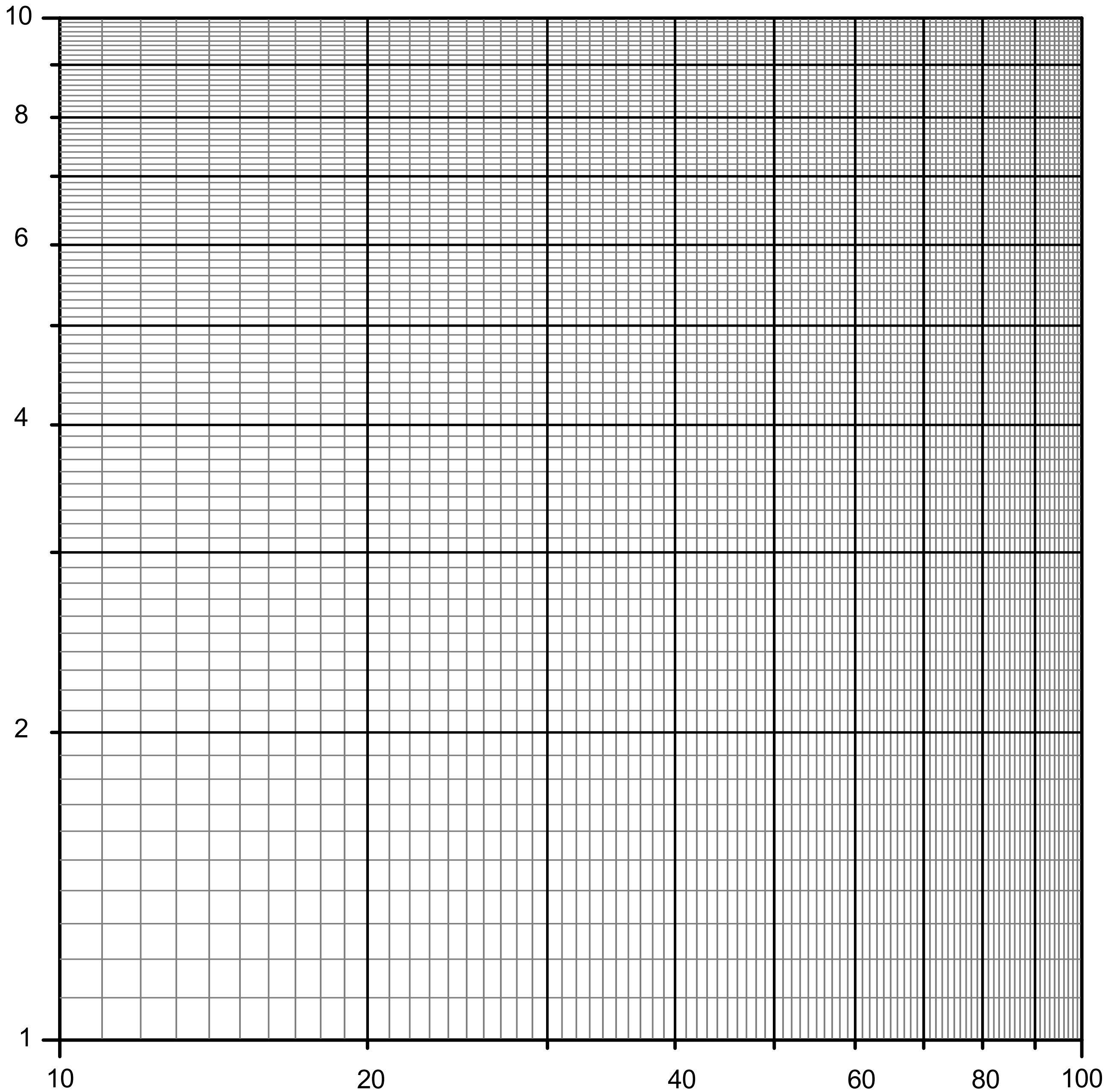
Resistor Colour Code



Appendix 4

Logarithmic Graphing Paper

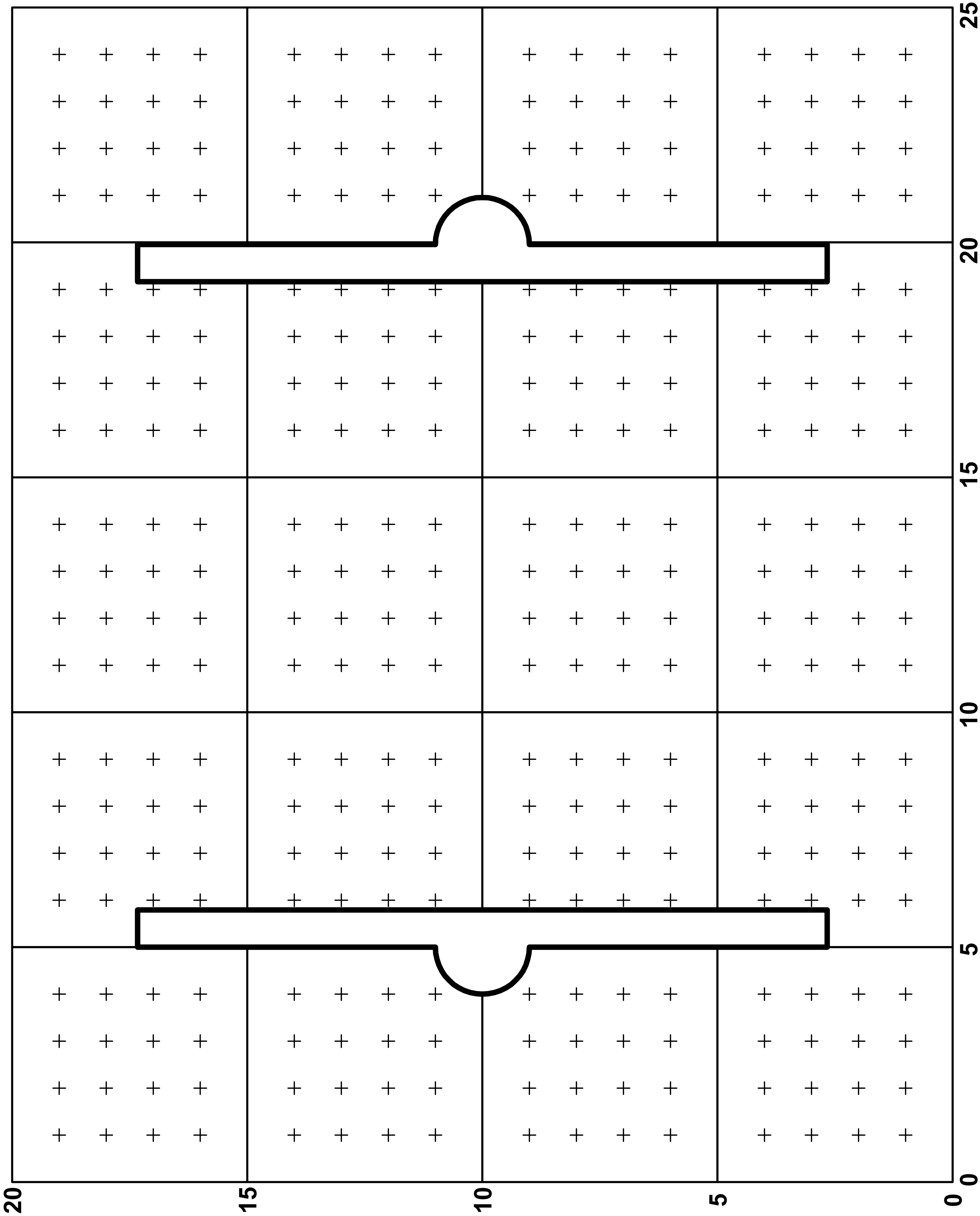
A4 – Logarithmic Graph Paper



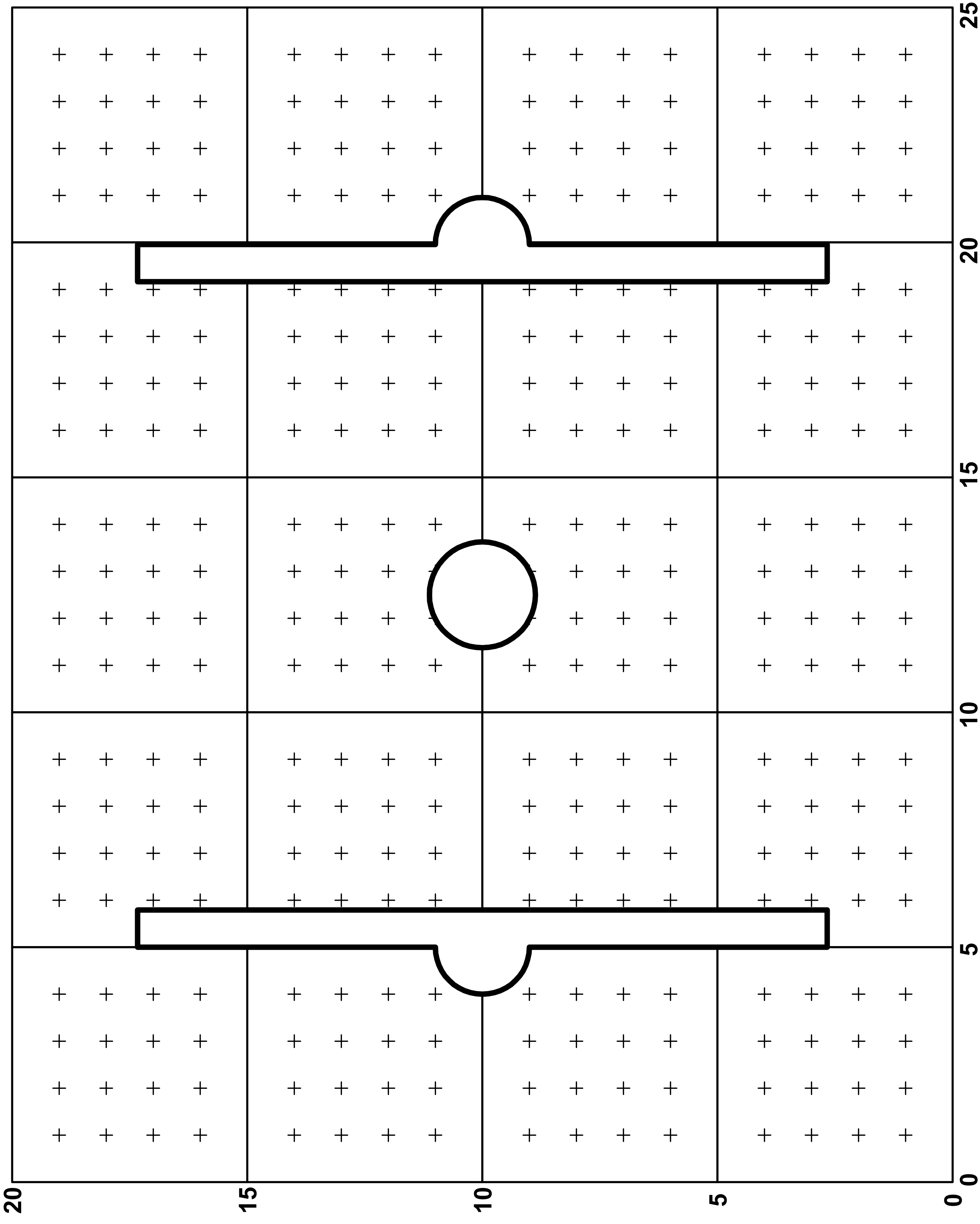
Appendix 5

Electric Field Graphing Paper

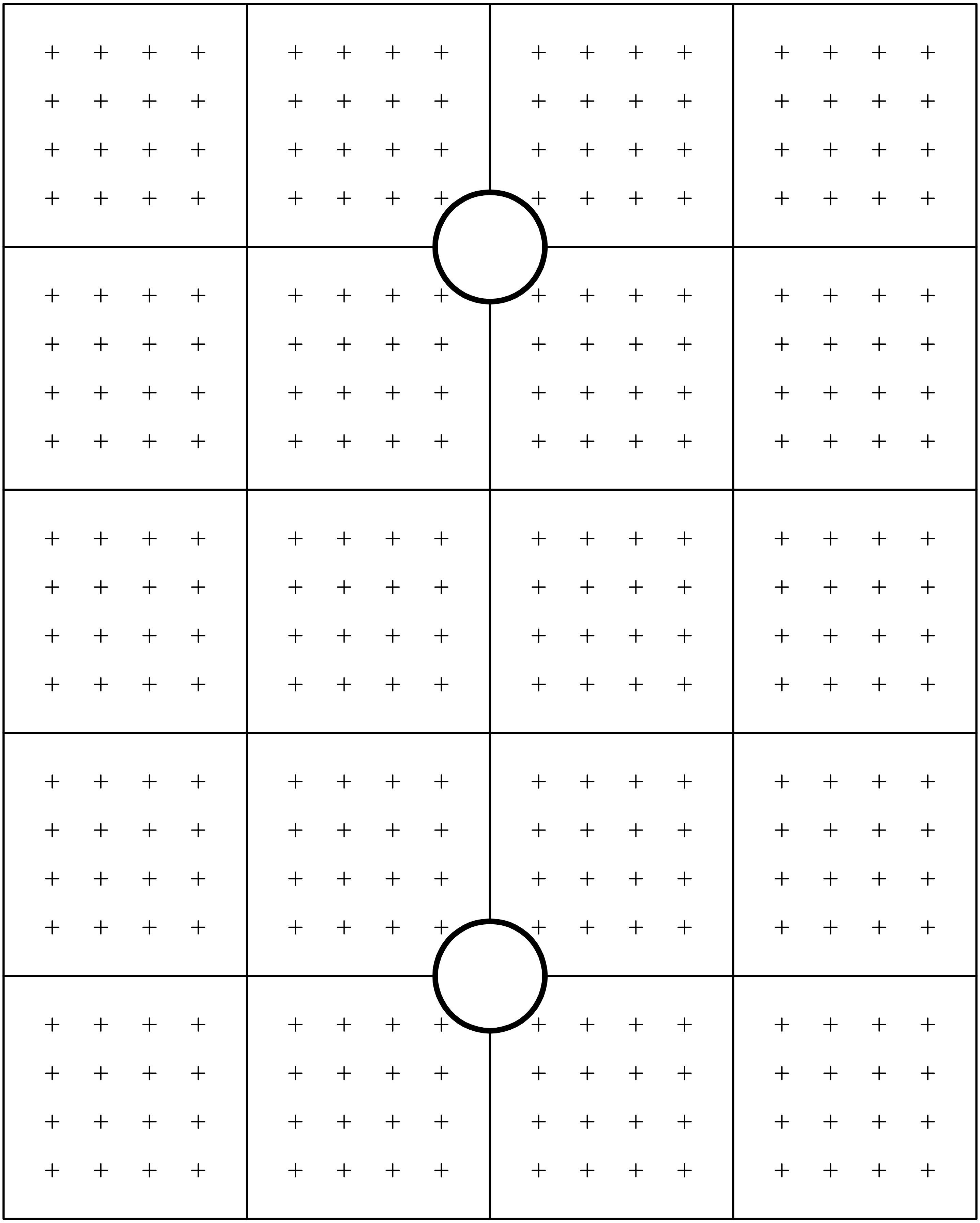
Electrode Printout-1



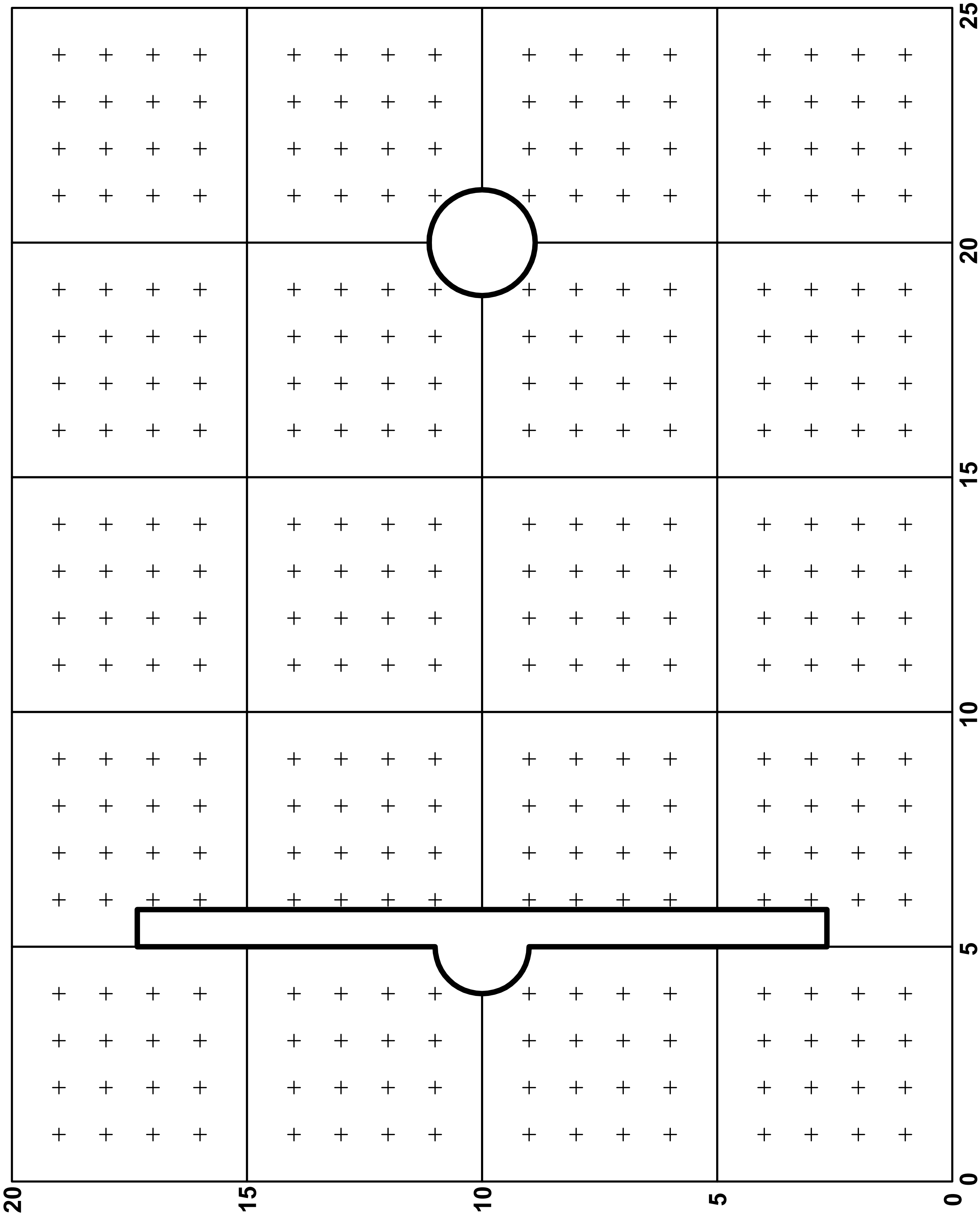
Electrode Printout-2



Electrode Printout-3



Electrode Printout-4



Electrode Printout-5