

**Houston Community College System
Physical Sciences Department
Northwest College**

**PHYSICS EXPERIMENTS IN
MECHANICS**

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Acknowledgements

In the sciences much more than the arts, most works cannot be accomplished by a single individual. This manual is no exception. Carol Monahan began to work in the Natural Sciences Department of HCC-NW in 2002, she held a degree in physics and hoped to “shake off the cobwebs” in her preparation in order to pursue graduate studies in physics. I am glad to report that she has succeeded in both regards. She is now a Texas A&M University graduate student. It has been Carol’s enthusiasm, her true concern for the students’ progress and her attention to the students’ learning processes that led to the constant revision of the lab exercises, which resulted in the present manual. Her motivating energy inspired other professors to collaborate in the development of the laboratory exercises. We were all beneficiaries of the work done by Professors Dwight Kranz and Bart Sheinberg who procured the state of the art lab equipment, and Dr. William Askew who has led the Natural Sciences Department at HCC-Northwest in constant growth and development.

Juan Carlos Reina, Ph.D.

And what a delightful collaboration it has been! Dr. Juan Carlos Reina has great energy and enthusiasm for the physics labs, and that enthusiasm is contagious! All of the professors at HCC have been a tremendous example in their competence and kindness, and I am forever grateful to all of them.

Most of the students at HCC who are enrolled in a physics course are at least pursuing a Bachelor’s degree, by completing the first two years of a four year program at HCC. Therefore, it is imperative to have a complete physics program that is comparable to any high quality four-year institution. Our hope is that this manual enables the success of the HCC physics program.

Above all, we wish the greatest success to the terrific students of Houston Community College!

Carol Monahan, B.S
June, 2004

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1.1 Introduction

*“Measure what is measurable and make
measurable what is not.”*

Galileo Galilei (1564-1642)

Since Antiquity and until the Renaissance in order to understand natural phenomena, it was only necessary in order to develop a model, to make observations, to present a hypothesis and *by reason alone* to arrive to the model. Galileo is considered the father of modern science due to his insistence in introducing measurements, i.e., data acquisition and its subsequent analysis by mathematical formulation, in order to arrive to a verifiable model.

Since then, at the core of all work in science lies a set of procedures that we call “**the scientific method**.” First there is an **observation** of natural phenomena, then a **hypothesis** is developed to explain it. In order to test this hypothesis an experiment is designed with the purpose of making precise and accurate measurements. The data obtained in the **experiment** is analyzed using the appropriate mathematical formulation. The main objective of the method is to arrive to a **conclusion** that is verifiable, a **theory** in which the observations and the mathematical formulation agree, hopefully a theory that would fit within a larger **model**.

This reliance in mathematics as a tool to understand experimental observations and measurements has led to a revolution in our understanding of nature. We are still in the midst of it. The purpose of the experiments outlined in this manual is that the student understands the scientific method thoroughly and that he or she is capable of applying it. **Physics** distinguishes itself from the other sciences by its strong emphasis and focus in precise and accurate measurements. Therefore, every experiment should follow this method. The corresponding laboratory report should also reflect the *scientific method*, as it will be explained in the following section.

It is our hope that the students will find that the concepts learned in the lecture part of the physics courses will be enhanced by the laboratory experience. The interplay between the abstract mathematical formulation and the practical simulations of natural phenomena will show how scientists of all fields try to discover the hidden laws in nature.

1.2 The Laboratory Report

Your instructor will indicate which of the experiments will require a full laboratory report. Some experiments will only require filling out a worksheet, graphs or tables.

You should use the format below when you are required to complete a full laboratory report. Whether it is a student report or a paper published in a scientific journal, the report's format usually consists of these five sections:

I. Introduction

Describe what the experiment is about, i.e., what are the phenomena being observed, and what are the current theories that may explain it. Include equations and definitions of symbols in this section that are relevant to the experiment.

II. Experiment Description

- a. Include the equipment and materials used. Be as specific as possible.
- b. Write down the procedure, step by step.

III. Data

Tables are usually the clearest way to record and present the data, and the tables will normally be provided for you. Record in ink to keep yourself honest. Be sure to use units for any measurement.

IV. Results

Calculations and graphs belong here. Again, include units.

V. Conclusion

The *most* important part: discuss the results. What do the calculations and graphs mean? Include a brief discussion of the types of error, the standard deviation and percent error or difference.

1.4 GRAPHING

The plotting of experimental data, generally a dependent variable versus an independent one, is a very effective way to determine trends and analyze the data. The system you will use in this course is the Cartesian system, with the exception of a polar system for rotational dynamics. The scales may be linear or logarithmic, or one axis linear with the other logarithmic (semi-logarithmic), or both scales can be logarithmic.

The criteria below will make your graph accurate and also easy to understand.

A. To construct a readable graph, the graph must have:

1. A title.
2. The independent variable as the abscissa (x-axis) and the dependent variable for the ordinate (y-axis).
3. A label on each axis indicating the quantity being measured and represented on that axis and the units associated with that quantity.
4. Data points that are readily visible. Any curve fit to the data should not hide the points. Use dots of a readily visible size, or draw a small circle around each data point. (O)

B. For an accurate graph, it must have:

1. The correct number of significant figures (the same number of significant figures as the data) on each axis.
2. The scales for both the abscissa and the ordinate chosen so that:
 - a. the plotted data fills over half the page in each direction.
 - b. the points are easy to plot and easy to read. This is accomplished by using a scale of 1,2,4,5, or 10 data units per division (scales of 3, 7, etc. units per division are difficult to plot and read).
 - c. each division on each axis is of equal size.

- C. The Pasco labs include a sophisticated program which may be used to obtain the curve which best represents the data, called simply, a “Best Fit” curve. However, you can obtain a representative curve manually with a simply visual analysis. The way to accomplish this is as follows:
1. With a pencil draw a light curve through the data such that, overall, it touches or comes close to the greatest number of points. Mentally add up the distances from the points to the curve. The distance to the data points on one side of the curve should be the same as the distance on the opposite side of the curve. Do not draw a straight line from data point to data point. If you are plotting a line, a flexible transparent ruler is a terrific aid in finding the best fit.
 2. Once you have determined the "best fit", fully pencil-in the curve (or ink-in the curve if the graph is part of a final report).
 3. Be faithful to the trend of the data; don't try to fit the data with a preconceived curve.

Once your graph is drawn, check the graph for all the details given in A. At the end of the exercise there are two examples of graphs for you to use as models.

THE SLOPE

In plotting linear relationships, you frequently will be asked to find the slope of the line you have fitted to the data (this slope usually has a physical meaning). To calculate an accurate slope, read a point on the line near each end of the line. **Do not** use data points unless they are on the fitted line!!!! That is, choose widely separated points only on the line for the calculation of a slope.

The slope is defined by:

$$\text{slope} = \frac{\text{difference in y-coordinates}}{\text{difference in x-coordinates}}$$

INTERCEPTS

The x-intercept of a line is that point on the abscissa, or x-axis, at which a line crosses that axis. The y-intercept is defined in the same manner.

1.4.2 GRAPHING: EXERCISE

You are to graph the following three sets of data and have them checked by your instructor.

1. The following data was collected on the position of a car as a function of time, as detected by a police radar detector:

<u>time (min)</u>	<u>position (km)</u>
0.00	2.51
0.67	3.33
1.17	6.43
1.80	7.58
2.37	8.83
3.05	12.18
3.59	12.65
4.18	13.78

- a. Make a graph of the above data.
 - b. Determine the slope and y-intercept of the above curve.
What is the *physical significance* of the slope?
2. The following data was taken for a glider on a level air track:

<u>t(s)</u>	<u>distance (cm)</u>
0.00	0.97
0.43	2.37
1.05	4.05
1.47	9.10
2.03	9.70
2.51	13.15
3.03	18.05
3.55	21.40
3.98	27.98
4.55	35.20
5.01	44.66
5.48	47.55

Make a graph for this data and the curve that best fits the data.

3. The following data was obtained for growth of bacteria experiment. N is the number of bacteria counted at time t and, N_0 is the number counted at $t = 0$. Use regular *and* semi-log paper to plot the data found below.

RADIOACTIVE DECAY DATA	
$t(\text{min})$	# counts/s.
0	80
20	133
40	245
60	455
80	763
100	1401
120	2643

2.1 The Experiments

You will be acquiring data in two different ways during this course: 1) **manually**, and 2) with **computer aided acquisition**. In our current technological world, much of the data that is obtained is with the aid of a computer, and we are excited at HCC to be able to offer this technology to you. Sensors combined with computers can acquire data faster, and often more accurately than we are able to do by hand. We must take care, however, not to allow the assistance of the computer to substitute for a deep understanding of the processes we are exploring. We continue to do some experiments without the aid of a computer because sometimes a computer doesn't help or can't even be used in some situations, and we need to stay connected with basic measurements of natural phenomena. Physics is, in essence, a study of nature in its beauty and magnificence, and sometimes computers can cloud that vision. We are attempting to understand the fascinating patterns and order that surrounds us, order which is often so predictable and precise that it can be expressed as a mathematical equation. Our sincere hope is that your appreciation and enjoyment of the natural world grows as a result of this course.

To help bring order out of chaos, we write lab reports. Writing and recording helps us make sense of the system we're investigating. The actual writing of a lab report, or doing error analysis and standard deviations may be tedious until practice makes them easy, but it all works together in building our understanding of the universe. So be patient with yourself and your partners, do your work with integrity, and have fun exploring!

Lab 1 Error Analysis

I.3.1 Introduction

Physical quantities, length, mass, time, etc., are constantly being measured in the laboratory. All experimentally determined quantities contain some degree of error or uncertainty. It is important that the experimentalist knows how to record the data and results so that it's clear just how precise the data is, and is familiar with the various sorts of error.

1.3.2 Types of Error

- A. Systematic or constant errors: These errors result from using an instrument that is not calibrated properly. For example, using a meter stick that is actually shorter in length than a meter or using a voltmeter, which has not been “zeroed”, would result in a systematic error being introduced into the experiment. Corrections can be made to the data to compensate for systematic errors if the type and extent of the error is known. Students should always be aware that systematic errors may exist and each lab report should contain a statement concerning possible sources of systematic error in the experiment.
- B. Random errors: These errors result from fluctuations of such parameters as temperature, pressure, humidity, line voltage, or magnetic and electrical interference which cause repeated measurements to disagree. In addition, most instruments require an estimate of the fraction of smallest scale division and the observer's estimate may vary from measurement to measurement. Most lab reports will require an estimate of the random error in measurements made.
- C. Human errors: These errors are caused by outright mistakes in reading instruments, performing the experiment, or recording data. Included in this category are mistakes made in calculations. Fortunately, these errors are usually apparent either as obviously incorrect data points or as results, which are not reasonably close to the expected results. These kinds of errors wreck your experiment and /or the lab report. It's *really* good to avoid these.

1.3.3 Estimating Random Error

The amount of uncertainty associated with a quantity, which has been measured “n” number of times, is estimated by calculating the *mean* and its *standard error*. No estimate of the random error can be deduced from only a single measurement!

The arithmetic mean, \bar{x} , (or average) of a series of n measurements (x_i) is defined by:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

The standard deviation of the quantities **x** are obtained by the following formula:

$$\sigma_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\bar{x} - x_i)^2} \quad (2)$$

The standard deviation of the mean or "standard error", $\sigma_{\bar{x}}$, is then:

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}} \quad (3)$$

Observe that the above formula for σ_x with n-1 in the denominator is the correct expression for the sample standard deviation when the mean is not known exactly. However, some calculators with a standard deviation key use a different definition of σ_x (with n in the denominator and not n-1). If you use your calculator to attempt to determine the standard deviation or error, figure out which quantity the program is using in the denominator (n or n-1).

For example, listed below are seven measured values of a quantity x measured in meters. The last two columns of the table help in calculating the standard deviation. The calculations are shown below the table. Each lab report should contain similar orderly and logical presentations of data and calculations.

Trial no.	$x_i(\text{m})$	$(\bar{x} - x_i) (\text{m})$	$(\bar{x} - x_i)^2 \times 10^{-6}(\text{m})^2$
1	7.364	0.0027	7.29
2	7.3710	-0.0043	18.49
3	7.363	0.0037	13.69
4	7.368	-0.0013	1.69
5	7.365	0.0017	2.89
6	7.366	0.0007	0.49
7	7.370	-0.0033	10.89
Total	$\Sigma = 51.567$		$\Sigma = 55.43 \times 10^{-6}$

Then:

$$\bar{x} = \frac{51.567\text{m}}{7} = 7.3667\text{m}$$

$$\sigma_x = \sqrt{\frac{5.543 \times 10^{-5} \text{ m}^2}{(7 - 1)}} = 0.0030\text{m}$$

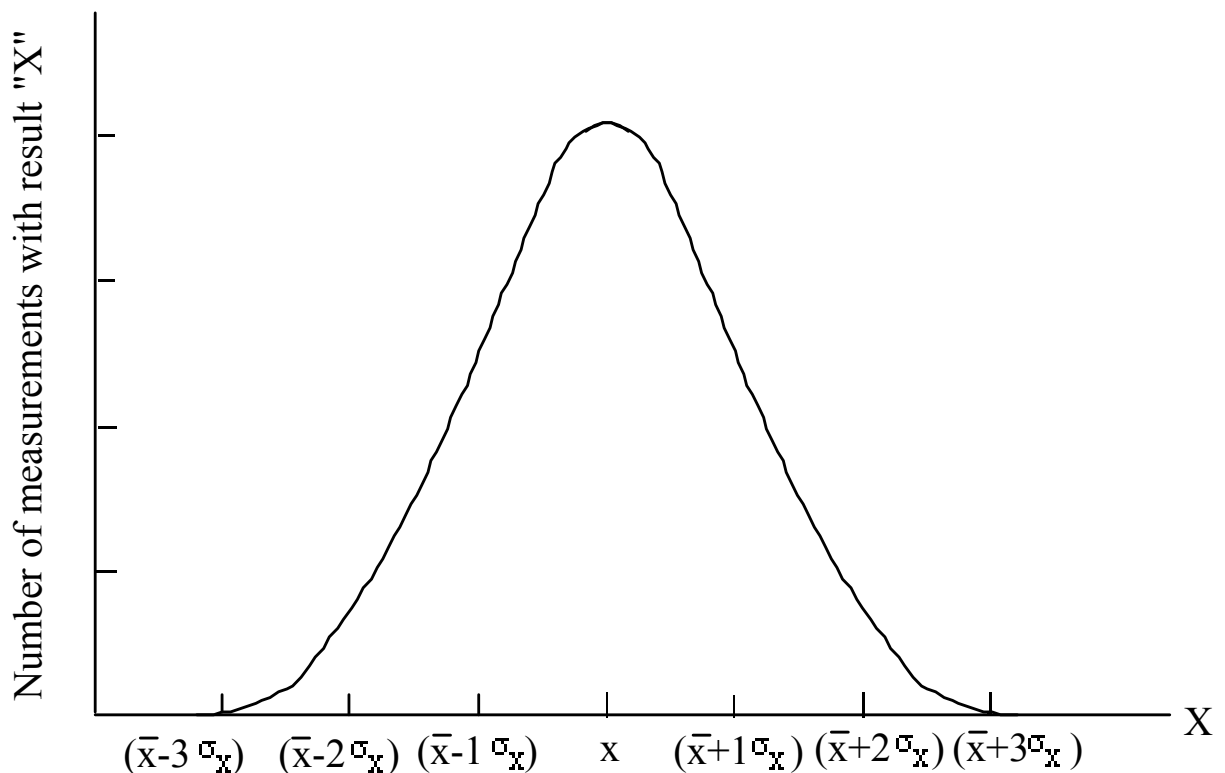
$$\sigma_{\bar{x}} = \frac{0.0030\text{m}}{\sqrt{7}} = 0.0011\text{m}$$

The standard deviation represents an estimate of the uncertainty due to random errors and can be interpreted as follows: If the experiment were to be repeated and the quantity x were measured again there is a 68% probability that the newly measured value would come within one standard deviation (0.003 m) of the mean. However, if an entirely new series of measurements were taken and another mean calculated, there is a 68% probability that the new mean will come within one standard error ($\pm/\sigma_{\bar{x}}$) of the previous mean. It is the mean and the standard error, which are recorded as the result of the measurements. Thus, the result of the above measurements would be written as $x = 7.367 \text{ m} \pm 0.001 \text{ m}$. The standard error is separated from the mean by a "+" (plus or minus) sign to emphasize that it is as an estimate of the uncertainty in the mean value reported. Consequently, there is a 68% probability that the true mean of all possible measurements of the quantity x lies between 7.366 m and 7.368 m.

It is customary to retain several additional digits as the mean, standard deviation, and standard error are computed. For the final reported values, however, **retain only one non-zero digit in the standard error and discard any digits in the mean that are in**

the decimal places to the right of the retained digit in the standard error. For example, in the previous calculation, the mean was determined to be 7.3667 m, the standard deviation was 0.0030 m, and the standard error was 0.0011 m. In reporting these results, the standard error was correctly rounded to 0.001 m and the mean was rounded to 7.367 m.

The standard deviation is only an estimate of the uncertainty due to random error because its interpretation is based on certain assumptions concerning the distribution of the measurements around the mean value. The 68% probability figure is calculated assuming a Gaussian (or normal) distribution about the mean. Shown below is a graph of the Gaussian distribution.



Frequency of the value of a quantity x obtained in a measurement vs the quantity x . The latter is given in terms of the mean \bar{x} and σ_x .

The most frequently obtained measurement is of course, the mean.

Random error causes measurements different from the mean to be obtained but less frequently. Note that the curve is symmetric about the mean. Theory indicates that $\approx 68\%$ of all the measurements yield values between $+1\sigma_x$ and that $\approx 95\%$ of all measurements fall between $+2\sigma_x$.

1.3.4 Propagation of Error

Consider now computing involving numbers which all have standard errors associated with them. What is the standard error of *the result*? Consider two measured quantities $x \pm \delta_x$ and $y \pm \delta_y$, with a calculation yielding a result z whose standard error δ_z , is given by the following formulas: (a, b, and c are constants).

Addition or Subtraction:

$$z = ax + by \quad \sigma_z = \sqrt{b^2 \sigma_x^2 + b^2 \sigma_y^2} \quad (1)$$

Multiplication or Division:

$$z = a x^b y^c \quad \frac{\sigma_z}{z} = \sqrt{b^2 \left(\frac{\sigma_x}{x}\right)^2 + c^2 \left(\frac{\sigma_y}{y}\right)^2} \quad (2)$$

Exponentials:

$$z = ae^{\pm bx} \quad \frac{\sigma_z}{z} = \pm b \sigma_x \quad (3)$$

Logarithms:

$$a = \log_c (\pm bx) \quad \sigma_z = \pm b \frac{\sigma_x}{x \ln x} \quad (4)$$

For example, the length and width of a tabletop are found to be equal to $l = 0.9371 \pm 0.0002$ m and $w = 3.457 \pm 0.001$ m. The area is then:

$$\bar{a} = \bar{l} \bar{w} = (0.9371\text{m}) (3.457\text{m}) = 3.2396\text{m}^2$$

and

$$\frac{\sigma_a}{\bar{a}} = \sqrt{\left(\frac{\sigma_l}{\bar{l}}\right)^2 + \left(\frac{\sigma_w}{\bar{w}}\right)^2} = (3.2396\text{m}^2) \sqrt{\left(\frac{0.0002\text{m}}{0.9371\text{m}}\right)^2 + \left(\frac{0.001\text{m}}{3.457\text{m}}\right)^2} = 0.0012\text{m}^2$$

$$\text{and } a = \bar{a} \pm \sigma_a = 3.24\text{m}^2 \pm 0.001\text{m}^2$$

Note, the result and its standard error are always written with the same number of digits to the right of the decimal point and in the same units of measure. Thus both of the following are **incorrect**:

$$a = 3.2396\text{m}^2 \pm 0.001\text{m}^2$$

and

$$a = 3.2396\text{ m}^2 + 10\text{ cm}^2$$

1.3.5 Significant Digits

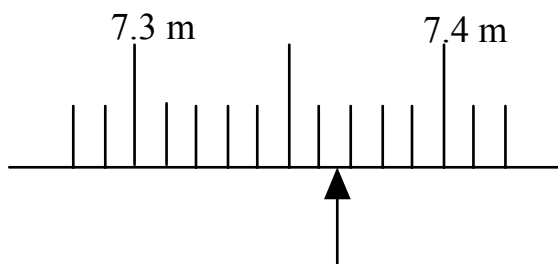
A further discussion of data and its analysis requires a knowledge of significant digits in a number.

- 1) All digits between and including the least and most significant digits are counted as significant digits.
- 2) The leftmost nonzero digit is the most significant digit, if there is no decimal point in the number.
- 3) The rightmost nonzero digit is the least significant digit, if there is a decimal point in the number.
- 4) The rightmost digit is the least significant digit even if it is a zero.

For example, in the quantity 0.00254 kg., the 2 is the most significant digit and the 4 is the least significant digit. Therefore, the number has 3 significant digits. The zeros at the beginning of the number are not significant; they only serve to locate the decimal point and can be omitted by a different choice of units, e.g., 0.00254 kg = 2.54 g.

The amount of uncertainty in both the data and the results is indicated by the way in which the number is written. Results (means of repeated measurements) are reported along with the standard error as an indication of the uncertainty, whereas, the uncertainty in each data point is indicated entirely by the number of significant digits. The least significant digit is considered to be the only uncertain digit.

For example, consider the enlarged portion of a metric tape measure shown below:



The measured length is indicated by the arrow. In recording this measurement, writing 7.36 m would be wrong. We are sure the reading is between 7.36 m and 7.37 m, consequently there is no uncertainty in the digit 6 and convention requires that the least significant digit be uncertain. Therefore, by estimating the next digit and writing 7.364 m, the uncertainty in the measurement has been correctly indicated.

1.3.6 Calculations and Significant Digits

Returning to the example given earlier, the mean of the seven measurements was calculated by dividing 51.567 m by 7, yielding on a calculator 7.366714286 m. Recording that number as the mean would be improper because it contains more than one uncertain digit. In fact, it is later discovered that the uncertainty in the mean is 0.001 m. Thus, the last six digits (714286) are insignificant and meaningless. Consequently, if a computation yields a number with more digits than are justified, the number should be rounded off. To drop insignificant digits from a number, use the following rules:

- 1) Drop all digits after the desired number of significant digits.
- 2) If the leftmost digit to be dropped is greater than 5, or 5 followed by other digits, increase the last retained digit by one.
- 3) If less than 5, leave the last retained digit unchanged.
- 4) If exactly 5, increase the last retained digit by one if it is odd and leave it unchanged if it is even.

The reason for rule (4) is that consistently incrementing the least significant digit if the leftmost digit to be dropped is exactly 5 would lead to a systematic error. In this way, the least significant digit is increased approximately half the time and left unchanged the other half.

However, how does one know how many digits should be retained in a calculation if the standard error has not yet been calculated? Use the following rules as a guideline:

- 1) For multiplication and division, compute first, then retain at most one more significant digit than the factor with the least number of significant digits. For example, $(9.8)(1.28) = 12.544$; 9.8 has only 2 significant digits so the result should be recorded with 3 significant digits, or 12.5.
- 2) For addition and subtraction, round each number to the same number of digits to the right of the decimal point as the number with the least number

of digits to the right of the decimal point and then compute. For example:
 $27.6499 + 0.1 + 63.04 = 27.6 + 0.1 + 63.0 = 90.7$.

These are to be considered general rules for calculations involving measured quantities which should be supplemented by the student's common sense. For example, one may ask why express the results of $51.567 \text{ m}/7$ with 5 significant digits when the 7 is the number with the least number of significant digits-one? The student should realize that the 7 *is not a measured quantity* and is considered infinitely accurate.

1.3.7 Percent Error and Percent Difference

Frequently it is desirable to compare the results of an experiment with accepted values known to be very accurate. The percent error is used as a measure of the agreement between the two numbers. It is defined as follows:

$$\text{percent error} = \frac{|\text{measured value} - \text{accepted value}|}{\text{accepted value}} \times 100\%$$

The vertical bars in the numerator indicate the absolute value. When a quantity is measured by two different techniques, the results are compared by calculating a percent difference. The percent difference is used when no accepted value for the measured quantity exists. It is defined as follows:

$$\text{percent difference} = \frac{|\text{measured value 1} - \text{measured value 2}|}{(\text{measured value 1} + \text{measured value 2}) \div 2} \times 100\%$$

Lab 1 Experimental Error and Data Analysis

Taken from Physics Laboratory Experiments, Jerry D. Wilson, 4th Edition.

1. Distinguish among the types and causes of experimental errors. Give a specific example of each.
2. How can each type of experimental error be reduced or minimized?
3. What is the difference between measurement accuracy and precision? Explain their general dependence on the various types of errors.
4. What determines the number of significant figures in reporting measurement values? What would be the effect of reporting more or fewer figures or digits than are significant?
5. In expressing experimental error or uncertainty, when does one use (a) experimental error and (b) percent difference?
6. What is the statistical significance of one standard deviation? Two standard deviations?
7. How could the function $y = 3t^2 + 4$ be plotted on a Cartesian graph to produce a straight line? What would be the numerical values of the slope and intercept of the line?

Lab 2: Measurements with Error Analysis

Equipment List Cabinet # 1 TC

Length Measurements:

- | | |
|-------------------------------|----------------------------|
| 1. Two meter sticks per group | 2. Paper |
| 2. Vernier Calipers | 3. Tape |
| 1. Clamps | 4. Various metal cylinders |

I. Introduction

To be a good scientist and nature explorer, a person must be able to make measurements of all sorts of physical quantities as accurately as possible. There are inherent limits of the devices used for measuring. The measurement of the accuracy with which one measures is determined by some statistical formulas called **standard deviation** and **standard error**. Error doesn't necessarily mean that one has made a mistake, rather, measuring devices have limits, and our ability to measure is constrained as well, for instance by our ability to see sharply. **Standard error** is another way of saying "degree of accuracy". A student can only measure to the tenth of a millimeter with a meter stick; the ruler can't be used to measure the wavelength of light! Also, nature itself imposes some restrictions.

II. Length Measurements

You and your lab partners will determine the distance between two parallel lines. This may seem quite simplistic, but the object of this simple experiment is to learn to make measurements as accurately as possible with the measuring devices you have available. In addition, this is the time to begin to learn to use the correct number of significant figures.

Procedure:

A. Using the Meter Stick

1. Draw a straight line (use a ruler!) with a thin tipped pencil or pen on each of two pieces of paper. Tape the papers perpendicularly to the edge of the lab bench about a half-meter apart.
2. One meter stick is clamped to the laboratory bench as a straightedge on top of the papers, while the other meter stick is placed on its edge so it can slide smoothly next to the first ruler.
3. Now you'll measure the distance between the lines, but don't align a mark on the meter stick with the lines on the paper. Do it this way so that the observers must estimate the last digit of each measurement.
 - a. Read the position of the line on the meter stick to the ten thousandth of a meter, estimating the last digit between two lines. The reading should look like this, with four digits to the right of the decimal (in meters): **0.1324 m**. The last digit, the fourth to the right of the decimal, is the limit at which a pair of good eyes can read the particular measuring device that has millimeter divisions as it's smallest markings. Record the reading on Table 1 for the line on the left as x_l , and then record the reading for the line on the right as x_r). Make the measurements independently of each other to reduce systematic errors... that means all eyes take the measurements independently!
4. Move the meter stick to a new position, once again making certain **not** to align the line of the paper with a scale marking, and then take new readings.

Repeat the measurement process in the same way until a total of ten measurements of the distance between the lines have been completed.

B. Length Measurements using the Vernier Caliper

The vernier caliper is a tool for measuring the *length* of an object *to the tenth of a millimeter*. The superior aspect (that means top) of the calipers has a screw which moves the jaw of the calipers. Be careful when closing the jaw! Don't tighten the screw. Only close the jaw to the point of contact with the object being measured.

Your instructor may teach you how to use the calipers by inspection, or to use to following method useful for any calipers:

These calipers have both English and metric measurements. We will discuss only the metric scale.

The 10- centimeter scale is called “the main scale”. Inside the window of the sliding scale are ten marks. The distance between any two adjacent marks is one millimeter. The measurement of the object can be made by sight with the aid of your instructor, or a measurement with any Vernier caliper can be made using the following method:

First, determine the “least count” of the Vernier:

The Least Count (**LC**) of the Vernier is determined as follows:

$$\text{LC} = \frac{\text{value of the smallest division on the main scale}}{\text{number of divisions on the Vernier or inset scale}}$$

With our calipers, $\text{LC} = \frac{1 \text{ mm}}{10} = .1 \text{ mm} = .01 \text{ cm}$

To read the measurement on the inset scale, locate the line on that scale which coincides exactly with a line on the fixed scale. The line on the fixed scale will be right on top of the line on the sliding scale. Then, on the sliding scale, count the number of lines from the left. This number will be multiplied by the LC.

$$\text{Total Reading} = \left(\begin{array}{c} \text{Main Scale} \\ \text{reading} \end{array} \right) + \left[\left(\begin{array}{c} \text{division on the vernier} \\ \text{scale that coincides with} \\ \text{the division on the main scale} \end{array} \right) \times \text{LC} \right]$$

Example: $2.4 \text{ cm (main scale)} + 8 (.01 \text{ cm}) = 2.4 + 0.08 = 2.48 \text{ cm}$

Procedure for Length Measurements using calipers:

5. Each person in the group will measure both the length and the width of a metal cylinder. Record the measurements in Table 2.
6. Find the Standard Deviation and Standard Error for these measurements.

Name _____ Date _____ Instructor _____

Partners _____

Table 1: Length between Two Lines

#	Right Reading $x_r(m)$	Left Reading $x_l(m)$	Difference $d_i = x_r - x_l (m)$	$(\bar{d} - d_i) (m)$	$(\bar{d} - d_i)^2 (m^2)$
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
			$\Sigma =$		$\Sigma =$
			$\bar{d} =$		$\sigma_d =$
					$\sigma_{\bar{d}} =$

The final result for the difference between the two parallel lines should be recorded in your report as:

$$d = \bar{d} \pm \sigma_{\bar{d}}$$

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Physics 1401

Table 2 Length Measurements with Calipers

Cylinder Color _____

	Length			Diameter		
	l_i	$\bar{l} - l_i$ (cm)	$(\bar{l} - l_i)^2$ (cm ²)	d_i	$(\bar{d} - d_i)$ (cm)	$(\bar{d} - d_i)^2$ (cm ²)
1						
2						
3						
4						
5						
	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$
	$\bar{l} =$		$\sigma_l =$	$\bar{d} =$		$\sigma_d =$
			$\sigma_{\bar{l}} =$			$\sigma_{\bar{d}} =$
	$l = \bar{l} \pm \sigma_{\bar{l}}$			$d = \bar{d} \pm \sigma_{\bar{d}}$		

Synopsis of Formulae for Statistical Error

The arithmetic mean, \bar{X} , (or average) of a series of n measurements (X_i) is defined by:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (1)$$

The standard deviation of the quantities x are obtained by the following formula:

$$\sigma_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\bar{X} - x_i)^2} \quad (2)$$

The standard deviation of the mean or "standard error", $\sigma_{\bar{X}}$, is then:

$$\sigma_{\bar{X}} = \frac{\sigma_x}{\sqrt{n}}$$

Propagation of Error Formula for Multiplication or Division:

$$z = a x^{+b} y^{\pm c} \quad \frac{\sigma_z}{z} = \sqrt{b^2 \left(\frac{\sigma_x}{x}\right)^2 + c^2 \left(\frac{\sigma_y}{y}\right)^2}$$

Physics 2125

Lab 2, Part II: Determining Density

Determining the density of a regular solid requires the knowledge of two things: the mass of the solid and its volume. The density ρ (a Greek letter pronounced “rho”) is then given by:

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

where m is the mass of the solid and V is its volume.

Procedure:

1. The instructor will give each group of students cylinders of unknown composition.
2. The mass will be measured with a mass balance by each person in the group. *Zero the balance before each mass measurement*, and after determining the mass independently, share your answer with your group. Record your measurements in Table 2.
3. By using a vernier caliper, each person in the group will measure the dimensions of the cylinder, the length and diameter. Record in Table 2.
4. In the case of a cylinder, the density is given by:

$$\rho = \frac{4m}{\pi d^2 l}$$

where d is the cylinder diameter and l its length. Find the averages and standard errors of the measured quantities as you did when measuring the length between the two lines. The tables provide a box for recording these calculations.

5. Repeat the measurements and calculations for two more cylinders.
6. Since each measurement you made contains a degree of error or uncertainty, the amount of error multiplies! You’ll determine this error with the “Propagation of Error” formula for Multiplication and Division found below, with further explanation in the introduction.

The instructor may announce the composition of the solid and its known density. If so, compare the result obtained with the known density using a percent error calculation. Discuss sources of random and systematic error that might contribute to any discrepancy between the experimental and known values.

Density Formulae

Density is defined as the mass per unit volume:

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{V}$$

The volume of a cylinder is:

$$V = \frac{\pi d^2 l}{4}$$

The density formula for a cylinder is, then

$$\rho = \frac{4\bar{m}}{\pi \bar{d}^2 \bar{l}} \pm \sigma_{\rho}$$

The measurements for the density of the cylinder require three measurements, each of which has an inherent error. To determine the total error for the density, use the *Propagation of Error* formulas.

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Physics 2125

Determination of Density

Cylinder 1 Color _____

Mass				Length			Diameter		
#	m (g)	$\bar{m} - m_i$ (g)	$(\bar{m} - m_i)^2$ (g ²)	l (cm)	$\bar{l} - l_i$ (cm)	$(\bar{l} - l_i)^2$ (cm ²)	d_i (cm)	$(\bar{d} - d_i)$ (cm)	$(\bar{d} - d_i)^2$ (cm ²)
1									
2									
3									
4									
5									
	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$
	$\bar{m} =$		$\sigma_m =$	$\bar{l} =$		$\sigma_l =$	$\bar{d} =$		$\sigma_d =$
			$\sigma_{\bar{m}} =$			$\sigma_{\bar{l}} =$			$\sigma_{\bar{d}} =$
	$m = \bar{m} \pm \sigma_{\bar{m}}$			$l = \bar{l} \pm \sigma_{\bar{l}}$			$d = \bar{d} \pm \sigma_{\bar{d}}$		

Density of cylinder formula: $\rho = \frac{4\bar{m}}{\pi\bar{d}^2\bar{l}} \pm \sigma_{\bar{\rho}}$

Density of your cylinder: $\rho =$ _____ \pm _____

Name: _____ Date: _____

Cylinder 2 Color _____

	Mass			Length			Diameter		
#	m (g)	$\bar{m} - m_i$ (g)	$(\bar{m} - m_i)^2$ (g ²)	l (cm)	$\bar{l} - l_i$ (cm)	$(\bar{l} - l_i)^2$ (cm ²)	d_i (cm)	$(\bar{d} - d_i)$ (cm)	$(\bar{d} - d_i)^2$ (cm ²)
1									
2									
3									
4									
5									
	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$
	$\bar{m} =$		$\sigma_m =$	$\bar{l} =$		$\sigma_l =$	$\bar{d} =$		$\sigma_d =$
			$\sigma_{\bar{m}} =$			$\sigma_{\bar{l}} =$			$\sigma_{\bar{d}} =$
	$m = \bar{m} \pm \sigma_{\bar{m}}$			$l = \bar{l} \pm \sigma_{\bar{l}}$			$d = \bar{d} \pm \sigma_{\bar{d}}$		

Density of Cylinder 2: $\rho =$ \pm

Name: _____ Date: _____

Cylinder 3 Color _____

	Mass			Length			Diameter		
#	m (g)	$\bar{m} - m_i$ (g)	$(\bar{m} - m_i)^2$ (g ²)	l (cm)	$\bar{l} - l_i$ (cm)	$(\bar{l} - l_i)^2$ (cm ²)	(cm)	$(\bar{d} - d_i)$ (cm)	$(\bar{d} - d_i)^2$ (cm ²)
1									
2									
3									
4									
5									
	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$	$\Sigma =$		$\Sigma =$
	$\bar{m} =$		$\sigma_m =$	$\bar{l} =$		$\sigma_l =$	$\bar{d} =$		$\sigma_d =$
			$\sigma_{\bar{m}} =$			$\sigma_{\bar{l}} =$			$\sigma_{\bar{d}} =$
	$m = \bar{m} \pm \sigma_{\bar{m}}$			$l = \bar{l} \pm \sigma_{\bar{l}}$			$d = \bar{d} \pm \sigma_{\bar{d}}$		

Density of third cylinder: $\rho =$ \pm

Lab 3: Adding and Resolving Vectors: The Force Table

Equipment List Cabinet # 2 (T&C)

- | | |
|-----------------|---------------|
| 1. Force Tables | 5. Pulleys |
| 2. Weights | 6. Rings |
| 3. Graph paper | 7. Ruler |
| 4. Pins | 8. Protractor |

The Force Table

The force table is an apparatus that enables the experimental determination of the resultant of force vectors. The rim of the circular table is calibrated in degrees. Weight forces are applied to a central ring by means of strings running over pulleys and attached to weight hangers. The magnitude of a force (vector) is varied by adding or removing slotted weights, and the direction of the force is varied by moving the pulley.

Two forces (vectors) can be balanced with a third string and weight so that the ring is centered around the central pin. This balancing force is *not* the resultant **R**, but rather the *equilibrant* **E**, or the force that balances the other forces and holds the ring in equilibrium. **E** is the vector force that has an equal magnitude, but is in the opposite direction of **R** (i.e., $\mathbf{R} = -\mathbf{E}$). For example, if an equilibrant has a magnitude of 2 N (where 1 Newton = 1 kg m/s²) in a direction of 30° on the circular scale, the resultant of the forces has a magnitude of 2 N in the opposite direction, 30° + 180° = 210°. The resultant cannot be determined directly from the force table. (Why?)

The vectors in the problems are expressed as follows:

$$\mathbf{F}_1 = (0.200 \text{ kg}) \mathbf{g} @ \theta_1 = 30^\circ.$$

- The number in the parentheses is the mass in kilograms.
- **g** is the acceleration due to gravity, 9.8 m/s². The bold print indicates a vector.
- The magnitude of the vector is the absolute value of the mass x **g**.
- 1 kg x m/s² = 1 N or 1 Newton, the unit of force.
- The direction of the vector **F**₁ is indicated by the angle $\theta_1 = 30^\circ$.

Experimental Procedure

Set up the force table with strings and suspended weights and perform the following problems in vector addition. Do all of the experimental procedures on the force table first for each of the five problems before doing the graphical and analytical analyses.

1. Vector Addition 1: Given two vectors with magnitudes $\mathbf{F}_1 = (0.200 \text{ kg}) \mathbf{g}$ @ $\theta_1 = 30^\circ$ and $\mathbf{F}_2 = (0.200 \text{ kg}) \mathbf{g}$ @ $\theta_2 = 120^\circ$, find their vector sum or resultant $\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2$ by each of the following procedures: (Note: Orientation angles of vectors are given relative to the 0° reference line or positive X axis.)
 - a. Experimental:
 - i. On the force table, clamp pulleys at 30° and 120° and add enough weights to each weight hanger to total 0.200 kg, so as to give weight forces of $\mathbf{F}_1 = \mathbf{F}_2 = (0.200 \text{ kg}) \mathbf{g}$ in these directions. (The weight hangers have masses of 50 g or 0.050 kg.)
 - ii. Using a third pulley and weights, determine the magnitude and direction of the equilibrant force that causes the ring around the pin to be centered. Be certain the strings on the ring pull directly away from the center. Also, pulling the center ring straight up a short distance and releasing it helps adjust the friction in the pulleys as the ring vibrates up and down.
 - iii. *Record* the magnitude and direction of the equilibrant labeled as \mathbf{E} , then determine the resultant \mathbf{R} from \mathbf{E} , and *record* the magnitude and direction of \mathbf{R} in the same box.
 - b. Analytical:
 - i. Using the law of cosines or the Pythagorean theorem (since this is a 90° angle), compute the magnitude of the resultant force. Compute the angle of orientation from $\theta = \tan^{-1}(F_y / F_x)$.
 - ii. *Record* the magnitude and direction in the box.
 - c. Graphical: Using the parallelogram method of vector addition, draw a vector diagram to scale.
 - i. Try to determine a scale [such as 5 cm = 0.1 kg (times \mathbf{g})] such that *the finished* vector diagram fills *at least* a half sheet of graph paper.
 - ii. Draw the first vector on the graph paper, $\mathbf{F}_1 = (0.200 \text{ kg}) \mathbf{g}$ @ $\theta_1 = 30^\circ$.
After determining the scale, draw a straight line on the graph paper representing $(.200 \text{ kg}) \mathbf{g}$. The angle of the line with respect to the x axis will be at 30° .
 - iii. Now draw $\mathbf{F}_2 = (0.200 \text{ kg}) \mathbf{g}$, $\theta_2 = 120^\circ$. Draw the tail of the second vector at the head of the first vector. This vector will be the same length as the first vector, because the magnitudes are the same. To determine the direction of this second vector on the graph paper, set up another coordinate axes at the head of the first vector. Draw the second vector at 120° with respect to this new x axis.

- iv. Now draw the resultant vector. This vector will start at the origin, and the head of the resultant will meet the head of vector 2.
 - v. Find the magnitude of the resultant vector by measuring the length of the line on the graph with a ruler. Use your scale to determine the magnitude of the vector. Use a protractor to measure the angle of the vector with respect to the x axis. Measure the magnitude and direction of the resultant. *Record* the results in the data table.
2. Vector Addition 2: Repeat procedure in problem 1, this time with $\mathbf{F}_1 = (0.200 \text{ kg})\mathbf{g}$, $\theta_1 = 20^\circ$ and $\mathbf{F}_2 = (0.150 \text{ kg})\mathbf{g}$, $\theta_2 = 80^\circ$. Use the other half sheet of graph paper from problem 1 for the graphical analysis. Can you use $\theta = \tan^{-1}(F_y / F_x)$ in this case?
 3. Vector Addition 3: Repeat the procedure with $\mathbf{F}_1 = (0.200 \text{ kg})\mathbf{g}$, $\theta_1 = 0^\circ$ and $\mathbf{F}_2 = (0.150 \text{ kg})\mathbf{g}$, $\theta_2 = 90^\circ$. In this case, $\mathbf{F} = \mathbf{F}_x + \mathbf{F}_y$, where F_x and F_y are the x and y components of \mathbf{F} , respectively. That is, the resultant can be resolved into these components. Use at least one-half of another sheet of graph paper for the graphical method.
 4. Vector Resolution 4: Given a force vector of $\mathbf{F} = (0.300 \text{ kg})\mathbf{g}$, $\theta = 60^\circ$, resolve the vector into its x and y components and find the magnitudes of F_x and F_y by the following procedures:
 - a. Experimental: Clamp pulleys at 240° , 90° and 0° on the force table. Place a total of 0.300 kg on the 240° pulley string using a weight hanger. This force is the equilibrant of $\mathbf{F} = (0.300 \text{ kg})\mathbf{g}$, $\theta_1 = 60^\circ$ (since $60^\circ + 180^\circ = 240^\circ$), which must be used on the force table rather than the force itself. Add weights to the 0° and 90° hangers until the system is in equilibrium. The 0° and 90° forces are then the F_x and F_y components, respectively, of \mathbf{F} . Record their magnitudes in the data table.
 - b. Analytical: Compute the magnitudes of F_x and F_y . Record the results in the data table.
 - c. Graphical: Draw the vector $\mathbf{F} = (0.300 \text{ kg})\mathbf{g}$, $\theta = 60^\circ$ to scale on another sheet of graph paper. Determine and draw the components. Using the ruler, measure the length of the components, which are the magnitudes of the components of \mathbf{F} on the x and y axes. Record their magnitudes in the data table.

5. Problem 5: Given the force vectors $\mathbf{F}_1 = (0.100) \text{ g N}$, $\theta_1 = 30^\circ$, $\mathbf{F}_2 = (0.200) \text{ g N}$, $\theta_2 = 90^\circ$ and $\mathbf{F}_3 = (0.300) \text{ g N}$, $\theta_3 = 225^\circ$, find the magnitude and direction of their resultant $\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3$ by the following procedures:

- a. Experimental: Use the force table, this time using four pulleys.
- b. Analytical: Use the component method.
- c. Graphical: Use the polygon method.

Concluding: There are three different methods of determining a resultant vector from two (or more) initial vectors: experimental, graphical, and analytical. Use a percent error calculation to determine how close the graphical and experimental results are to the analytical method.

Name: _____ Date: _____
 Instructor: _____ Group Members: _____

The Addition and Resolution of Vectors: The Force Table

DATA TABLE

Purpose: To analyze results of different methods of vector addition.

	Forces	Experimental	Graphical	Analytical
Vector addition 1	$F_1=(0.200\text{kg})\mathbf{g}$, @ 30° $F_2=(0.200\text{kg})\mathbf{g}$, @ 120°	$\mathbf{E}=\mathbf{E}$ $\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$ % =
Vector addition 2	$F_1=(0.200\text{kg})\mathbf{g}$, @ 20° $F_2=(0.150\text{kg})\mathbf{g}$, @ 80°	$\mathbf{E}=\mathbf{E}$ $\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$
Vector addition 3	$F_1=F_x=(0.200\text{kg})\mathbf{g}$, @ 0° $F_2=F_y=(0.150\text{kg})\mathbf{g}$, @ 90°	$\mathbf{E}=\mathbf{E}$ $\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$
Vector resolution	$\mathbf{F}=(0.300\text{kg})\mathbf{g}$ @ 60°	F_x @ 0° F_y @ 90° % =	F_x @ 0° F_y @ 90° % =	F_x @ 0° F_y @ 90°
Vector addition 4	$F_1=(0.100\text{kg})\mathbf{g}$ @ 30° $F_2=(0.200\text{kg})\mathbf{g}$ @ 90° $F_3=(0.300\text{kg})\mathbf{g}$ @ 225°	$\mathbf{E}=\mathbf{E}$ $\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$ % =	$\mathbf{R}=\mathbf{R}$

1. \mathbf{E} = Equilibrant or balancing force of the weights. \mathbf{R} is the resultant. $\mathbf{R} = \mathbf{E} - 180^\circ$.
2. \mathbf{g} is the acceleration due to gravity, 9.8 m/s^2
3. Attach graphs and analytical calculations to Laboratory Report.
4. $\text{N} = (\text{kg})(\text{m})/(\text{s}^2)$ The Newton, N, is the unit of force. Don't forget to label units!
5. % means percent error.

Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab 4 Projectile Motion

I. Purpose

The purpose of this experiment is to study the projectile motion of a ball launched horizontally and at an angle. The height and length the ball travels will be measured and the velocities of the balls from the horizontal and angled launches will be calculated. Finally, the percent difference of the velocities will be calculated.

II. Equipment Needed

- Projectile Launcher and plastic ball
- Plumb bob
- Meter stick
- Carbon paper
- White paper
- Tape

III. Theory

A. Horizontal Launch

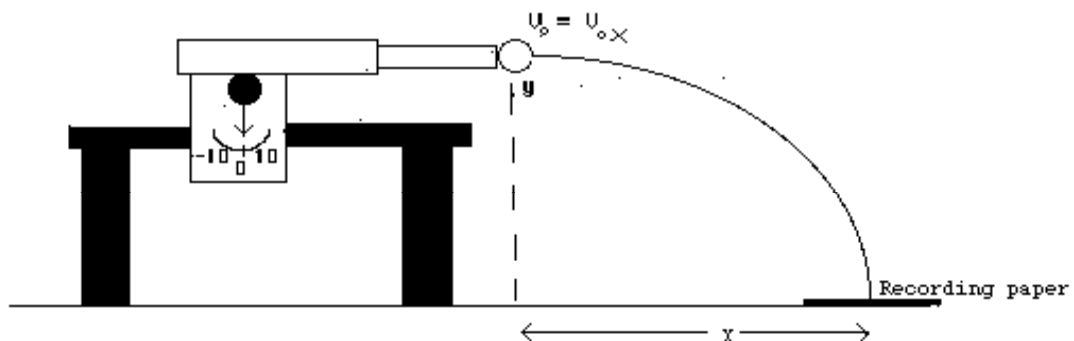


Fig 1- Set up for a speed - range experiment

The initial velocity v_i of a ball launched horizontally off of a table can be determined using the Constant Acceleration Equations of Motion. You will be measuring the values for x and y . Remember that horizontal

and vertical motions can be determined independently. Using the equation of motion for the *horizontal* displacement,

$$\mathbf{x_f = x_i + v_{ix} t + \frac{1}{2} a_x t^2}, \quad x_i \text{ is zero and } a_x \text{ is also zero; there is no}$$

component of acceleration horizontally.

Therefore,

$$\mathbf{x_f = v_{ix} t}.$$

The **time t** is determined from the vertical displacement:

$$\mathbf{y_f = y_i + v_{iy} t + \frac{1}{2} a_y t^2}.$$
 For this equation, both y_f and v_{iy} are zero.

y_f is zero due to the way the coordinate system is set up, and v_{iy} is zero since the initial velocity vector has only an x component and no y component; the initial motion is horizontal. Then:

$$\mathbf{0 = y_i + \frac{1}{2} a_y t^2}.$$

The acceleration a_y is the acceleration due to gravity, so $a_y = -g$, and y_i is the height h . Then,

$$h = \frac{1}{2} g t^2 \quad \text{Solving for } t,$$

$$\mathbf{t = (2h/g)^{1/2}}$$

Knowing t , the initial velocity for the horizontal launch can now be found:

$$\mathbf{v_i = x_f / t = x_f / (2h/g)^{1/2} = x_f (g/2h)^{1/2}}$$

B. The Angled Launch

The angled launch calculations are a little more complex since the velocity vector v_i will have both x and y components. The x and y values will be found by measuring the displacements of the ball horizontally and vertically. Instead of determining t for this part, t is eliminated in the displacement equation of motion by substitution.

$$\mathbf{y_f = y_i + x \tan \theta - (g x^2 / 2v_i^2 \cos^2 \theta)}$$

With $y_f = 0$, $y_i = h$ and x the mean horizontal displacement of the ball,

$$0 = h + x \tan \theta - (g x^2 / 2v_i^2 \cos^2 \theta) \text{ You need to solve for } v_i! \text{ Then,}$$

Using algebra and the measured values of x and h , determine v_i .

IV. Procedure

A. Horizontal Launch: Determining the Velocity

1. Clamp the Projectile Launcher to a sturdy table near one end of a table. Adjust the angle of the launcher to zero degrees so the ball will be launched horizontally.
2. Put the plastic ball in the launcher and push it in deeply using the black stick. Don't put your face in front of the launcher! And have about 5 meters cleared in front of your launcher. *Gently* pull the trigger on top, and see where the ball lands. At this position, tape a piece of white paper to the floor, the nearest end measured in whole numbers of meters from the muzzle of the launcher. Place a piece of carbon paper (carbon side down) on top of the white paper and tape it down on one side. When the ball hits the floor, it should hit the carbon paper, leaving a mark on the white paper.
3. Several things are important to get solid, repeatable results: make sure the launcher is level each time it is shot, measuring the angle at 0.0° . Use the level. Try keeping a meter stick propped under the launcher to prevent the barrel from moving during the shot. Measure the height of the launcher to the nearest millimeter. Fire ten shots, numbering the marks on the paper as they are shot. **There should be a cluster of dots, rather close together.** After all ten shots have been fired, measure the distance to the center of the mark, adding it to the measured whole number of meters to find the total distance x_i . Record these distances in Table 1.
4. Find the average or mean of x_i ; record in Table 1. Using the vertical distance and the average horizontal distance, calculate the time of flight and the initial velocity of the ball. Record (see last page).

B. The Ball Launched at an Angle

1. Adjust the angle of the Projectile launcher to an angle between 30 and 60 degrees and record this angle in Table 2.
2. Proceed with the experiment exactly as in Part 1. Measure the height before each time before the ball is shot in this part.

C. Analysis

1. Calculate the percent difference between the velocity v_{i1} of the horizontal launch and the velocity v_{i2} .
2. % Difference = $(v_{i1} - v_{i2} / v_{i1} + v_{i2}) \times 100$ The difference between velocities of the horizontal and angled launch, theoretically is zero for a nearly weightless ball. Experimentally, it may be around 5%.

Name _____ Date _____ Instructor _____

Partners _____

Table 1. Horizontal Launch

Trial Number	X	Y
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
Average		

Table 2. The Angled Launch $\theta =$ _____

Trial Number	X	Y
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
Average		

Horizontal Launch

Horizontal distance to
paper edge = _____

Calculated time of flight = _____

Initial velocity $v_{i1} =$ _____

Angled Launch

Horizontal distance
to paper edge = _____

Initial velocity $v_{i2} =$ _____

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 5A Position and Time: Understanding Motion 1

Concept	<i>DataStudio</i>
Linear motion	P01 Position and Time.ds

Equipment Needed	Qty	Equipment Needed	Qty
Motion Sensor (CI-6742)	1	Base and Support Rod (ME-9355)	1

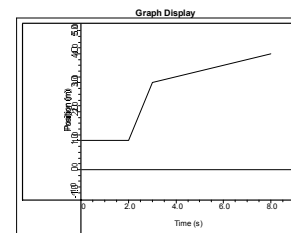
What Do You Think?

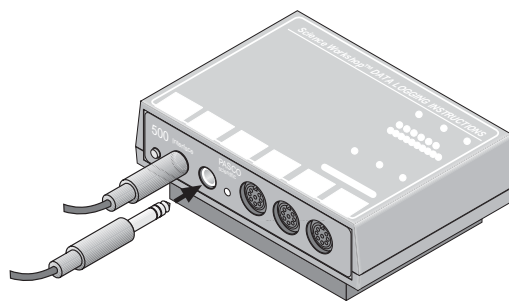
What is the relationship between the motion of an object – YOU – and a graph of position and time for the moving object?

Take time to answer the ‘What Do You Think?’ question(s) in the Lab Report section.

Background

When describing the motion of an object, knowing where it is relative to a reference point, how fast and in what direction it is moving, and how it is accelerating (changing its rate of motion) is essential. A sonar ranging device such as the PASCO Motion Sensor uses pulses of ultrasound that reflect from an object to determine the position of the object. As the object moves, the change in its position is measured many times each second. The change in position from moment to moment is expressed as a velocity (meters per second). The change in velocity from moment to moment is expressed as an acceleration (meters per second per second). The position of an object at a particular time can be plotted on a graph. You can also graph the velocity and acceleration of the object versus time. A graph is a mathematical picture of the motion of an object. For this reason, it is important to understand how to interpret a graph of position, velocity, or acceleration versus time. In this activity you will plot a graph of position in real-time, that is, as the motion is happening.





SAFETY REMINDER

- Follow all safety instructions.
- Keep the area clear where you will be walking.

**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

- **This activity is easier to do if you have a partner to run the computer while you move.**

For this activity, you will be the object in motion. Use the Motion Sensor to measure your position as you move in a straight line at different speeds. Use *DataStudio* to plot your motion on a graph of position and time.

The challenge in this activity is to move in such a way that a plot of your motion on the same graph will “match” the line that is already there.

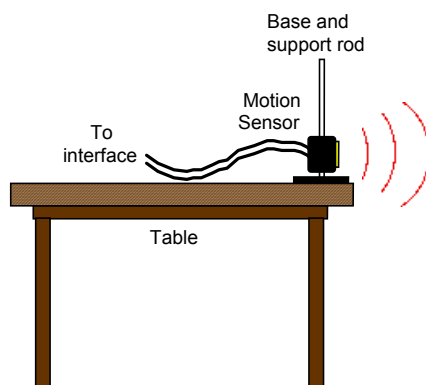
PART I: Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
 2. Connect the stereo phone plugs of the Motion Sensor to Digital Channels 1 and 2 on the interface. Connect the yellow plug to Digital Channel 1 and the other plug to Digital Channel 2.
 3. Open the Data Studio file entitled P01 Position and Time.ds
- The Graph shows Position and Time values that were entered into the Graph.
 - Data recording is set to stop automatically at 10 seconds. There is a three-second ‘countdown’ before data recording begins.

PART II: Sensor Calibration and Equipment Setup

- **You do not need to calibrate the Motion Sensor.**

1. Mount the Motion Sensor on a support rod so that it is aimed at your midsection when you are standing in front of the sensor. Make sure that you can move at least 2 meters away from the Motion Sensor.
2. Position the computer monitor so you can see the screen while you move away from the Motion Sensor.

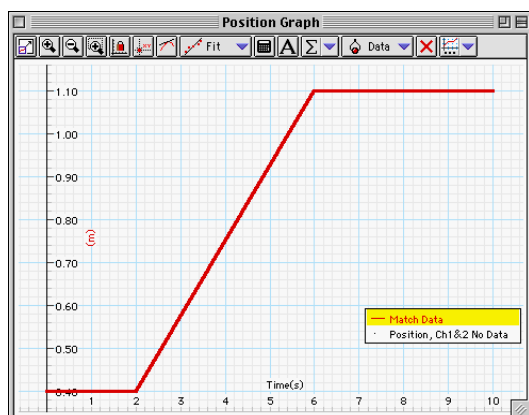


Understanding Motion 1: Position and Time

- **You will be moving backwards for part of this activity. Clear the area behind you for at least 2 meters (about 6 feet).**

PART III: Data Recording

1. Enlarge the Graph display until it fills the monitor screen.
2. Study the plot of Position versus Time in order to determine the following:
 - How close should you be to the Motion Sensor at the beginning?
_____ (m)
 - How far away should you move? _____ (m)
 - How long should your motion last? _____ (s)



3. When you are ready, stand in front of the Motion Sensor.
 - **WARNING: You will be moving backward, so be certain that the area behind you is free of obstacles.**
4. When everything is ready, start recording data.

In *DataStudio*, click 'Start'. There is a three-second countdown before data recording begins. The 'cursor' on the vertical axis of the Graph will move up and down as you move forward and backward relative to the sensor. Use the feedback from 'cursor' to find your best starting position.

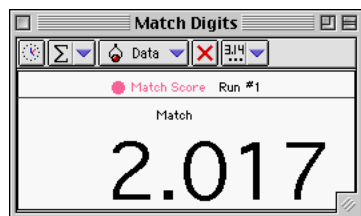
The Motion Sensor will make a faint clicking noise.

Watch the plot of your motion on the Graph and try to move so the plot of your motion matches the Position versus Time plot already there.

Repeat the data recording process a second and a third time. Try to improve the match between the plot of your motion and the plot already on the Graph.
- **The Graph can show more than one run of data at the same time.**

Analyzing the Data

1. Determine the slope of the best-fit line for the middle section of your best position versus time plot. You may want to resize the graph to fit the data.
 - The slope of this part of the position versus time plot is the velocity during the selected region of motion.
2. Determine how well your plot of motion fits the plot that was already in the Graph. (Hint: In *DataStudio*, examine the 'Match Data' calculation.)



Name: _____ Date: _____
Instructor: _____ Group Members: _____

Activity P01: Position & Time – Understanding Motion 1

What Do You Think?

Questions

1. In the Graph, what is the slope of the line of best fit for the middle section of your plot?
2. What is the description of your motion? (Example: “Constant speed for 2 seconds followed by no motion for 3 seconds, etc.”)
3. What would be the physical meaning of a steeper slope on the graph?
4. What would be different about the motion if the slope were negative?

Name: _____ Date: _____
 Instructor: _____ Group Members: _____

Lab 5B Velocity and Time – Understanding Motion 2

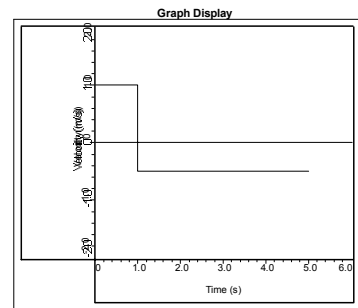
Concept	<i>DataStudio</i>
Linear motion	P02 Velocity and Time.ds

Equipment Needed	Qty	Equipment Needed	Qty
Motion Sensor (CI-6742)	1	Base and Support Rod (ME-9355)	1

What Do You Think?

What is the relationship between the motion of an object – YOU – and a graph of velocity and time for the moving object?

Take time to answer the ‘What Do You Think?’ question(s) in the Lab Report section.

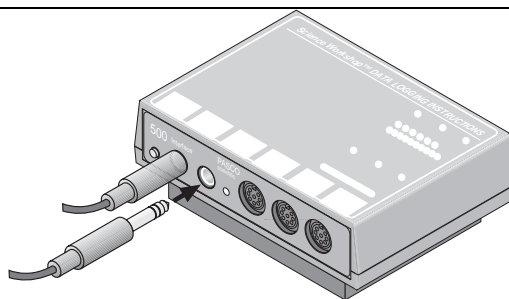


Background

When describing the motion of an object, knowing where it is relative to a reference point, how fast and in what direction it is moving, and how it is accelerating (changing its rate of motion) is essential. A sonar ranging device such as the PASCO Motion Sensor uses pulses of ultrasound that reflect from an object to determine the position of the object. As the object moves, the change in its position is measured many times each second. The change in position from moment to moment is expressed as a velocity (meters per second). The change in velocity from moment to moment is expressed as an acceleration (meters per second per second). The position of an object at a particular time can be plotted on a graph. You can also graph the velocity and acceleration of the object versus time. A graph is a mathematical picture of the motion of an object. For this reason, it is important to understand how to interpret a graph of position, velocity, or acceleration versus time. In this activity you will plot a graph of velocity in real-time, that is, as the motion is happening.

SAFETY REMINDERS

- Follow all safety instructions.
- Keep the area clear where you will be walking.



**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

- This activity is easier to do if you have a partner to run the computer while you move.

For this activity, you will be the object in motion. Use the Motion Sensor to measure your position as you move in a straight line at different speeds. Use *DataStudio* to plot your motion on a graph of position and time. The challenge in this activity is to move in such a way that a plot of your motion on the same graph will “match” the line that is already there.

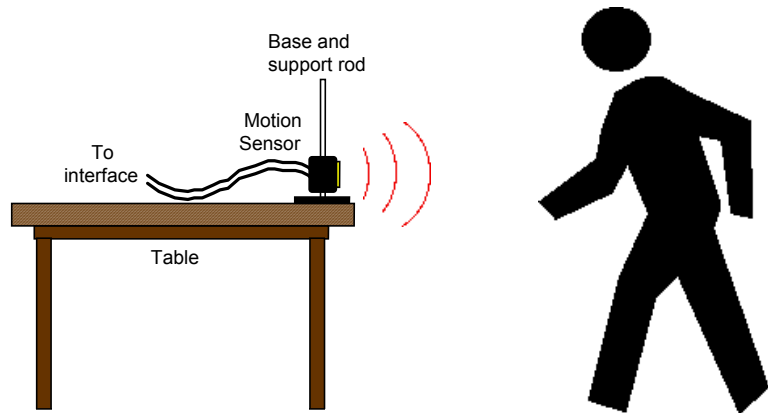
PART I: Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
 2. Connect the stereo phone plugs of the Motion Sensor to Digital Channels 1 and 2 on the interface. Connect the yellow plug to Digital Channel 1 and the other plug to Digital Channel 2.
 3. Open the Data Studio file entitled **P02 Velocity and Time.ds**
- The Graph shows Velocity and Time values that were entered into the Graph.
 - Data recording is set to stop automatically at 10 seconds.

PART II: Sensor Calibration and Equipment Setup

- **You do not need to calibrate the motion sensor for this activity. Moving away from the motion sensor is considered a positive velocity. Moving toward the motion sensor is considered a negative velocity.**
1. Mount the motion sensor on a support rod so that it is aimed at your midsection when you are standing in front of the sensor. Make sure that you can move at least 2 meters away from the motion sensor.

2. Position the computer monitor so you can see the screen while you move away from the motion sensor.
- **You will be moving backwards for part of this activity. Clear the area behind you for at least 2 meters (about 6 feet).**

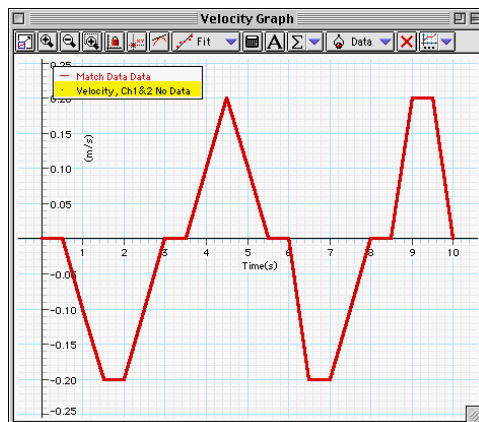


Understanding Motion 2: Velocity and Time

PART III: Data Recording

1. Enlarge the Graph until it fills the monitor screen.
2. Study the Velocity versus Time plot in order to determine the following:
 - Which direction (positive or negative) should you go at the beginning?

 - What is the maximum speed (positive or negative) you must achieve?
_____ (m/s)
 - How long should your motion last? _____ (s)

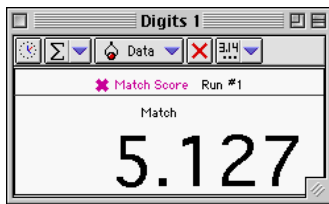


3. When you are ready, stand in front of the motion sensor.
 - **WARNING: You will be moving backward, so be certain that the area behind you is free of obstacles.**
4. When everything is ready, start recording data. Data recording will begin almost immediately. The motion sensor will make a faint clicking noise.
5. Watch the plot of your motion on the Graph, and try to move so that the plot of your motion matches the Velocity versus Time plot that is already there.

6. Repeat the data recording process a second and a third time. Try to improve the match between the plot of your motion and the plot that is already on the Graph.
- **The Graph can show more than one run of data at the same time.**

Analyzing the Data

1. Determine how well your best plot of velocity versus time matches the velocity versus time plot that was already on the Graph. You may want to resize the graph to fit the data.
- In *DataStudio*, check the 'Match Score' calculation in a Digits display..



Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab Report - Activity P02: Velocity & Time – Understanding Motion 2

What Do You Think?

Question

1. For your best attempt, how well did your plot of motion fit the plot that was already in the Graph?

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 6 Measuring the Acceleration due to Gravity

Concept	<i>DataStudio</i>
Linear motion	P07 Accelerate Cart.ds

Equipment Needed	Qty	Equipment Needed	Qty
Air Track	1	Air compressor and tube	1
Motion Sensor (CI-6742)	1	Rod and clamp	1
Glider with sail	1	Block (or book)	1
		Ruler	1

What Do You Think?



What happens to the acceleration of a cart as it moves up and down an inclined plane?

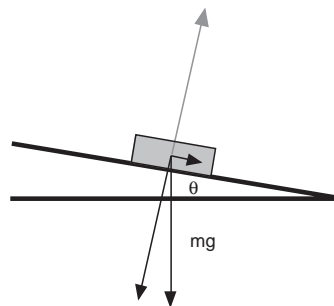
Take time to answer the ‘What Do You Think?’ question(s) in the Lab Report section.

Background

If a glider moves on a plane that is inclined at an angle θ , the component of force acting on the glider in a direction that is parallel to the surface of the plane is **$mg \sin \theta$** , where **m** is the mass of the cart, and **g** is the acceleration due to gravity.

The acceleration of the glider should be **$g \sin \theta$** , both up and down the inclined plane. The acceleration **$a = g \sin \theta = g \Delta d / \Delta h$** . Then

$$g = a \Delta h / \Delta d$$



SAFETY REMINDER

- Follow all safety instructions.

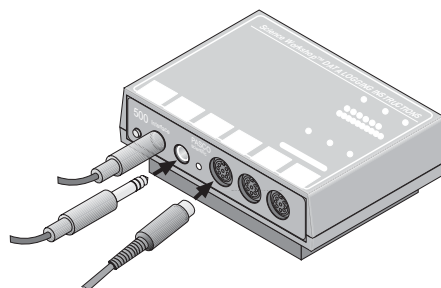
**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

Use a Motion Sensor to measure the motion of a glider or cart that glides down an inclined plane. Use *DataStudio* to record the motion and calculate the position and velocity of the cart as it moves. From the slopes of the graphs you will be able to determine the acceleration of the cart and then calculate g , the acceleration due to gravity.

PART I: Computer Setup

1. Connect the *ScienceWorkshop 750* interface to the computer, turn on the interface, and then turn on the computer.
2. Mount a Motion Sensor on a pole with a stand. Connect the Motion Sensor's plugs to Digital Channels 1 and 2 on the interface. Plug the yellow-banded (pulse) plug into Digital Channel 1 and the second plug (echo) into Digital Channel 2.
3. Open the file titled Data Studio: P07 Accelerate Cart.ds

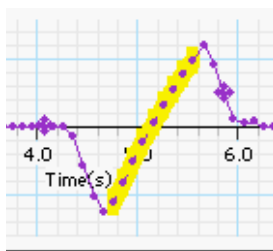


PART II: Sensor Calibration and Equipment Setup

- You do not need to calibrate the sensors for this activity.
1. Place the air track on a horizontal surface. Use a block or book at one end of the track to raise that end.
 2. You must measure the incline of the track. Measure the height at any two points along the track. The difference of these two heights is Δh . Measure the distance along the air track at the same two points where the heights were taken. This value is Δd . Record this data in the Data Table.
 3. Place the Motion Sensor at the high end of the track.
 4. Place the glider near the Motion Sensor on the high end of the track.
 5. Check the alignment of the Motion Sensor with the glider sail, and adjust if necessary.

PART III: Data Recording

1. When everything is ready, turn on the compressor. Then release the glider and immediately start recording data.
2. Stop recording when the glider reaches the bottom of the track.



Velocity vs. Time Graph

3. If the plot of data is not smooth, check the alignment of the Motion Sensor and repeat the above procedure until the plot is smooth. (The glider may wobble a bit as it begins to move.) If the data points do not appear on the graph, check the alignment of the Motion Sensor and try again.

PART IV: Analyzing the Data

1. To analyze the data, recall the Constant Acceleration Equations of Motion.

$$x = x_0 + v_0 t + \frac{1}{2} a t^2 \quad \text{and} \quad v = v_0 + a t$$

2. The graphs record the position of the glider and the velocity of the glider as it slides down the air track. Select the portion of the curve that corresponds to the movement of the glider down the track. (Click and drag the mouse in a rectangle around the salient portion of the graph.) You'll see the portion of the line you selected highlighted in yellow.
3. On the **position vs. time graph**, select the 'Quadratic' from the 'Fit' menu. You will see the letters A, B, and C. These are coefficients which correspond to the quadratic equation $A + Bx + Cx^2$. This generic quadratic equation corresponds to the position equation of motion (that you memorized already!!) $x = x_0 + v_0 t + \frac{1}{2} a t^2$. So the coefficient **C** in the generic equation corresponds to the coefficient $\frac{1}{2} a$ in the kinematic equation. Now you can calculate the acceleration of the glider from this graph.
4. On the **velocity vs. time graph**, selecting 'Linear' from the 'Fit' menu, the slope of the line is the acceleration.
5. The values of the acceleration from the two graphs should be very close to one another if the cart ran properly. **Average** the two values of the acceleration.

6. Set the track to a little steeper angle and repeat the data recording.
7. Calculate the theoretical value for the acceleration of the cart based on the track's angle and record it in the Data Table.

Record your results in the Lab Report section.

Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab Report - Acceleration of a Glider

What Do You Think?

Data Table

Item	Run #1	Run #2
$h_2 =$		
$h_1 =$		
$\Delta h =$		
$\Delta d =$		
From position graph: acceleration	m/sec ²	m/sec ²
From velocity graph: acceleration	m/sec ²	m/sec ²
Mean value of acceleration	m/sec ²	m/sec ²
Calculate 'g' (experimental)	m/sec ²	m/sec ²
'g' (theoretical)	m/sec ²	m/sec ²
% error	%	%

Questions

1. Describe the position versus time plot of the Graph display.
2. Describe the velocity versus time plot of the Graph display.
3. How does the acceleration determined in the plot of velocity compare to the value of acceleration from the plot of position?

4. What is the percent difference between the acceleration determined in the plot of velocity and the theoretical value for acceleration?

Remember, % error = $\frac{\text{abs. value (exp. Value - theoretical value)}}{\text{theoretical value}} \times 100$

5. How did the acceleration change when the track became steeper?

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 7 Conservation of Linear Momentum

Concept	<i>DataStudio</i>
Newton's Laws	P38 Linear Momentum.DS

Equipment Needed	Qty	Equipment Needed	Qty
Balance	2	Gliders for air track	2
Motion Sensor (CI-6742)	1	Air track	1
Posts for mounting motion sensors	2	Air compressor	1
Air compressor tube	1	Glider flag	1

What Do You Think?

How does the total momentum of two carts before an elastic collision compare to the total momentum of two carts after the collision?



Take time to answer the 'What Do You Think?' question(s) in the Lab Report section.



Background

When objects collide, whether locomotives, shopping carts, or your foot and the sidewalk, the results can be complicated. Yet even in the most chaotic of collisions, as long as there are no external forces acting on the colliding objects, one principle always holds and provides an excellent tool for understanding the dynamics of the collision. That principle is called the conservation of momentum. For a two-object collision, momentum conservation is easily stated mathematically by the equation:

$$m_1\vec{v}_1 + m_2\vec{v}_2 = m_1\vec{v}_1' + m_2\vec{v}_2'$$

If external forces such as friction are ignored, the sum of the momenta of two gliders prior to a collision is the same as the sum of the momenta of the gliders after the collision.

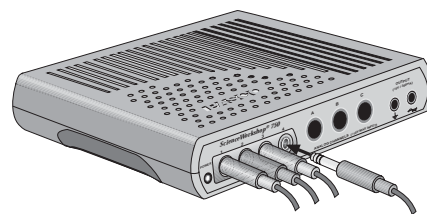
SAFETY REMINDERS

- Follow all directions for using the equipment.

**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

Use Motion Sensors to measure the motion of two gliders before and after an elastic collision. Use *DataStudio* to determine the momentum for both gliders before and after the collision. Compare the total momentum of the two gliders before collision to the total momentum of both gliders after collision.



PART I: Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
 2. Connect one Motion Sensor into Digital Channels 1 and 2 on the interface. Connect the yellow plug into Channel 1 and the other plug into Channel 2.
 3. Connect the second Motion Sensor into Digital Channels 3 and 4 on the interface. Connect the yellow plug into Channel 3 and the other plug into Channel 4.
 4. Open the Data Studio file entitled P38 Linear Momentum DS.
- The document will open with a Graph display of 'Position' for two objects.
 - The *DataStudio* file also has a Workbook display. Read the instructions in the Workbook.
 - The Motion Sensor 'Trigger Rate' is 20 Hz (20 times per second).

PART II: Sensor Calibration and Equipment Setup

- You do not need to calibrate the sensors for this activity.
1. Place the track on a horizontal surface.
 2. Attach one end of the air compressor tube to the air track and the other to the compressor.
 3. Turn on air compressor. Level the track by placing a glider on the track. If the glider slides one way or the other, use the adjustable feet at one end of the track to raise or lower that end until the track is level and the glider will not slide one way or the other.
 4. Insert the flag or sail into each glider.
 5. Use the balance to find the mass of each glider and record the values in the Data Table in the Lab Report section.
 6. Mount the Motion Sensor that is connected to Digital Channels 1 and 2 on the left end of the track on the post. Mount the other Motion Sensor on the right end of the track on the post.

7. Adjust each sensor so it can measure the motion of a glider as it moves from the end of the track to the middle and back again. Put the 'SWITCH SETTING' on the sensor to 'Narrow'.
8. Place a glider at each end of the track. Let the glider on the left be 'Glider 1' and the glider on the right be 'Glider 2'.

PART III: Data Recording

1. Prepare to measure the motion of each glider as it moves toward the other glider and then collides elastically.
2. Start recording data. (In *DataStudio*, click 'Start'.)
3. Gently push the gliders toward each other at the same time.
 - Continue collecting data until the gliders have collided and returned to the ends of the track.
4. Stop recording data.
 - 'Run #1' will appear in the Data list.


Troubleshooting Note: If your data are not smooth, check the alignment of the motion sensors. To erase a trial run of data, select "Run #1" in the data list and press the "Delete" key.

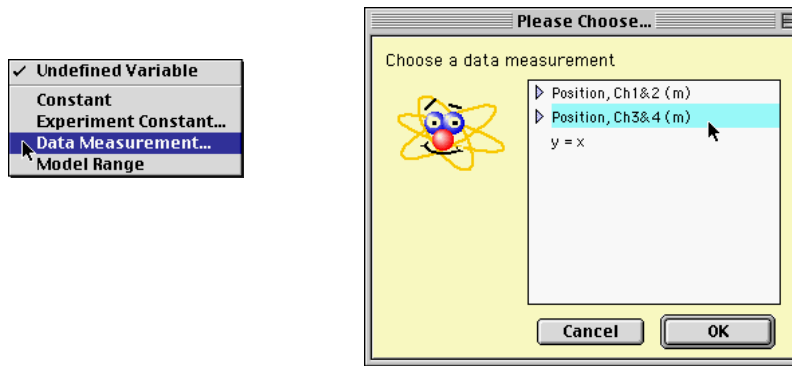
Analyzing the Data

Find the slope of the position versus time plot for each glider just prior to collision and the slope of the plot for each glider just after collision. The slope is the average velocity of the glider. Use the velocity and mass of the glider to calculate the momentum of each glider before and after collision. Compare the total momentum of the two gliders before the collision with the total momentum of the two gliders after the collision.

Momentum is a vector quantity. Since the gliders move in opposite directions, one glider's momentum is in the opposite direction to the other glider's momentum. However, each Motion Sensor measures motion away from it as 'positive' and motion toward it as 'negative'. Use the software's built-in calculator to "reverse" the directions of the motion of one of the gliders.

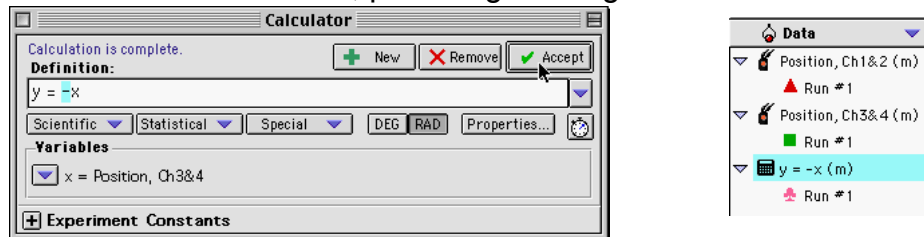
Create a Calculation for the Motion of 'Glider 2'

1. Click the 'Calculate' button ( Calculate) in *DataStudio*. Result: The Calculator window opens.
2. Create a calculation to 'reverse' the values of position for 'cart 2'.



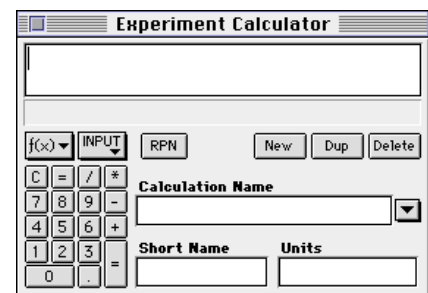
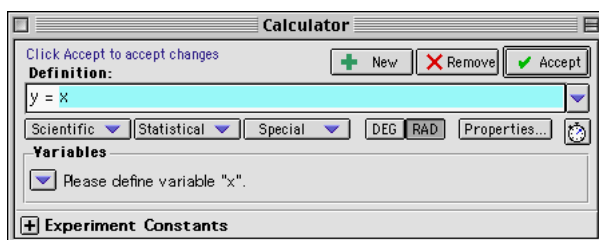
In *DataStudio*, do the following:

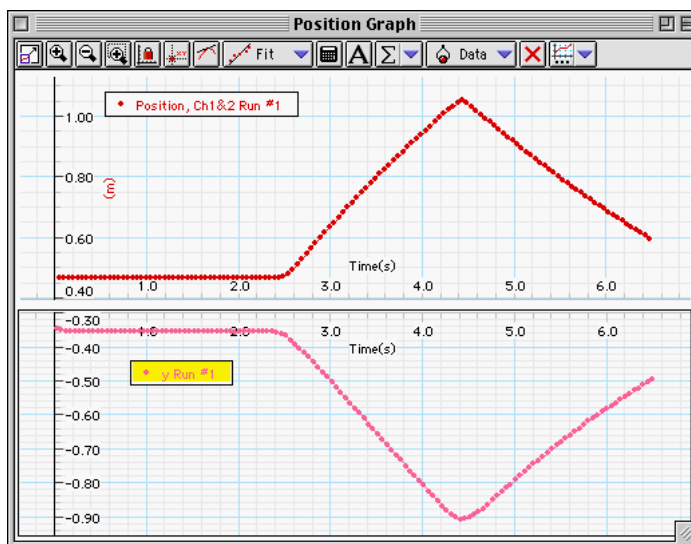
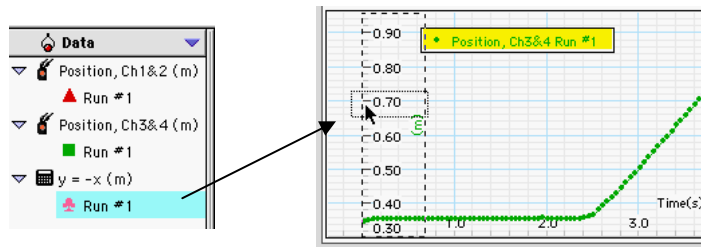
- Click the 'Variables' menu and select 'Data Measurement'. **Result:** The 'Choose a data measurement' window opens. Select 'Position, Ch 3&4' and click 'OK'.
- In the 'Definitions' text area, put a negative sign "-" in front of 'x'. Click



'Accept'. **Result:**

The calculation appears in the Data list.





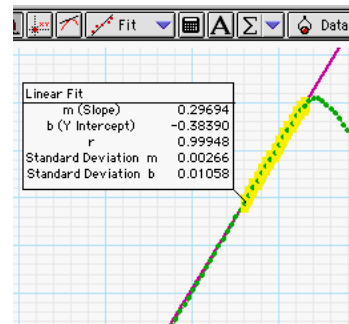
Display the Calculation of Motion for 'Glider 2' in the Graph

3. Display the calculation that shows the direction of motion for 'Glider 2'.
 - In *DataStudio*, click and drag 'Run #1' from the calculation in the Data list to the Y axis of the plot of 'Position' for the second cart.

Result: The Graph display shows 'Position' for Glider 1 and the calculation of position for Glider 2.

Find the Slope

1. Use the Graph display's built-in analysis tools to find the slope of the position vs. time plot just before and just after the collision for each glider.

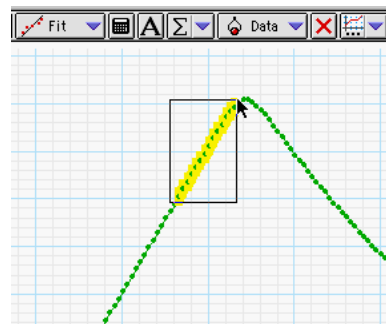


In *DataStudio*, do the following:

- In the plot for 'Glider 1', select a small portion just before collision (e.g., about 10 or 15 data points before the peak).
 - Click the 'Fit' menu and select 'Linear'. Record the slope as the 'Velocity Before Collision' for 'Glider 1'.
 - Repeat the process for a small portion of the plot just after collision and record the slope as the 'Velocity After Collision' for 'Glider 1'.
 - Do the same analysis for the plot of motion for 'Glider 2'.
2. Calculate the momentum before and after the collision for each glider. Calculate the total momentum before and after the collision.
 3. Calculate the percentage difference between the total momentum before and the total momentum after the collision.

$$\% \text{ difference} = \frac{p_{Total_Before} - p_{Total_After}}{p_{Total_Before}} \times 100\%$$

Record your results in the Lab Report section.



Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab Report - Conservation of Linear Momentum

What Do You Think?

How does the total momentum of two carts before an elastic collision compare to the total momentum of two carts after the collision?

Data Table

Item	Cart 1	Cart 2
mass (kg)		
velocity before (m/s)		
momentum before (kg•m/s)		
velocity after (m/s)		
momentum after (kg•m/s)		

total momentum _{before}	total momentum _{after}	percent difference

Questions

1. How does the total momentum before the collision compare to the total momentum after the collision?
2. What factors do think may cause there to be a difference between the momentum before and the momentum after collision?

Optional

Repeat the experiment for different speeds. Find the speeds for which the difference in momentum before and after collision is least. Repeat the experiment with different masses added to the carts.

Extension

Use the Calculator Window to create a formula for the momentum of each cart. Add a plot to the Graph or change one of the existing plots so it displays Momentum vs. Time. Compare the momentum before the collision to the momentum after the collision.

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 8 Atwood's Machine

Concept	DataStudio
Newton's Laws	P10 Atwood's.DS

Equipment Needed	Qty	Equipment Needed	Qty
Photogate/Pulley System (ME-6838)	1	String (SE-8050)	1
Mass and Hanger Set (ME-8967)	1	Universal Table Clamp (ME-9376B)	1

What Do You Think?

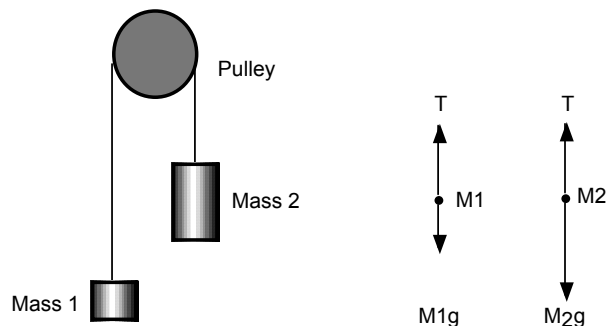


The purpose of this activity is to study the relationship among force, mass, and acceleration using an Atwood's Machine apparatus. What is a real world application of Atwood's Machine?

Take time to answer this question in the Lab Report section.

Background

The acceleration of an object depends on the net applied force and the object's mass. In an Atwood's Machine, the difference in weight between two hanging masses determines the net force acting on the system of both masses. This net force accelerates both of the hanging masses; the heavier mass is accelerated downward, and the lighter mass is accelerated upward.



Based on the above free body diagram, T is the tension in the string, $M_2 > M_1$, and g is the acceleration due to gravity. Taking the convention that up is positive and down is negative, the net force equations for M_1 and M_2 are:

$$T_1 - M_1g = F_{net} = M_1a$$

$$T_2 - M_2g = F_{net} = M_2(-a)$$

Assuming that the pulley is massless and frictionless, and the string has no mass and doesn't stretch, let $T_1 = T_2$. Solving for a , the acceleration of the system of both masses, the theoretical acceleration is g times the difference in mass divided by the total mass:

$$a = g \left(\frac{M_2 - M_1}{M_1 + M_2} \right)$$

SAFETY REMINDERS

- Follow all directions for using the equipment.

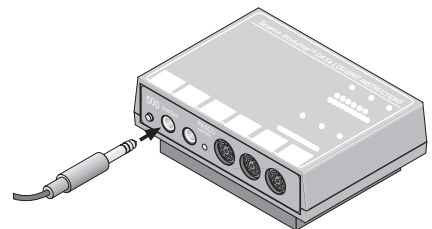
**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

Use the Photogate/Pulley System to measure the motion of both masses as one moves up and the other moves down. Use *DataStudio* to record the changing speed of the masses as they move. The slope of the graph of velocity vs. time is the acceleration of the system.

PART I: Computer Setup

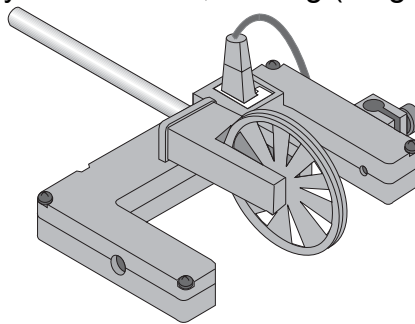
1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
2. Connect the Photogate's phone plug to Digital Channel 1 on the interface.
3. Open Data Studio to P10 Atwood's DS:
 - The *DataStudio* document has a Workbook display. Read the instructions in the Workbook.



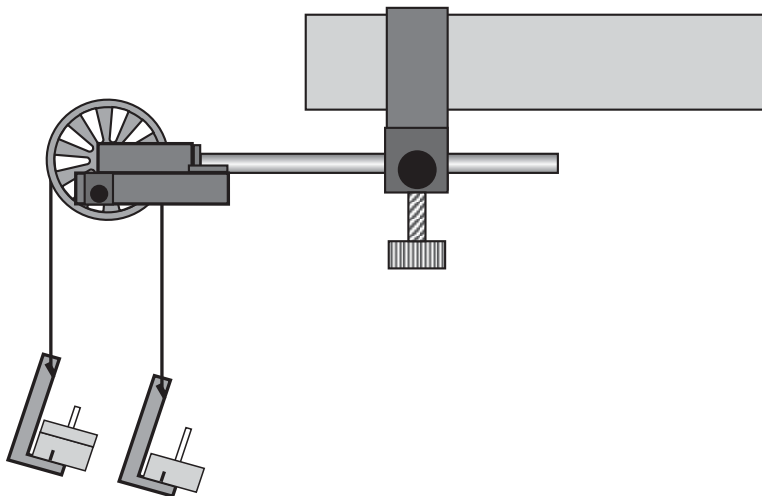
- Note: The spoke arc length for the Pulley is set at 0.015 m. If you are using a different pulley, change the spoke arc length in the sensor window by double clicking on the sensor's icon in the Experiment Setup window.

PART II: Sensor Calibration and Equipment Setup

- You do not need to calibrate the sensor.
1. Mount the clamp to the edge of a table.
 2. Use the Pulley Mounting Rod to attach the Pulley to the tab on the Photogate.
 3. Place Photogate/Pulley in the clamp so that the rod is horizontal.
 4. Use a piece of string about 10 cm longer than the distance from the top of the pulley to the floor. Place the string in the groove of the pulley.
 5. Fasten mass hangers to each end of the string.
- To attach the string to the hanger, form a loop at the end of the string and tie it back on itself to 'knot it' or wrap the string about 5 times around the notch in the mass hanger.
6. Place five to six masses from your mass set, totaling (roughly) 100 grams of mass on one mass hanger and record the total mass as M_1 in the Data Lab Report section. Be sure to include the hanger in the mass hanger, totaling Record this and mass Table in the



7. Move the M_2 mass hanger of upward until the M_1 mass hanger almost touches the floor. Hold the M_2 mass hanger to keep it from falling. Turn the pulley so that the Photogate beam is unblocked (the red light-emitting diode (LED) on the Photogate does not light).



PART IIIA: Data Recording – Constant Total Mass

1. Release the M_2 mass hanger and let it fall. Start recording data.
 2. Stop recording just before the M_2 mass hanger reaches the floor.
- Do not let the upward moving mass hit the Pulley!
- “Run #1” will appear in the Data list.
 3. For Run #2, move a mass from the M_2 mass hanger to the M_1 mass hanger. This process changes the net force without changing the total system mass. Record the new total mass for each hanger with masses in the Data Table in the Lab Report section. Allow the mass to fall. Begin data recording. Stop recording data just before the hanger reaches the floor.
 4. Repeat the above step to create three more mass combinations. For each run, the net force changes but the total mass of the system remains constant.

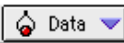


PART IIIB: Data Recording – Constant Net Force

1. Arrange the masses as they were for Run #1. Now, change the total mass of the system but keep the net force the same. To do this, add exactly the same amount of additional mass to both mass hangers.

- Make sure that the difference in mass is the same as it was for the beginning of Part IIIA.

2. Add approximately 10 grams to each mass hanger. Record the new total mass for each hanger with masses in the Data Table in the Lab Report section. Release the M2 mass hanger and let it fall. Start data recording. Stop recording just before the M2 mass hanger reaches the floor.
3. Repeat the above step to create three more data runs. For each data run, the net force remains the same, but the total mass of the system changes.

Analyzing the Data

1. Determine the experimental acceleration for each of the data runs.
 - Click in the Graph display to make it active. Find the slope of the velocity vs. time plot, the average acceleration of the masses.
 - In *DataStudio*, select Run #1 from the Data Menu () in the Graph display. If multiple data runs are showing, first select No Data from the Data Menu and then select Run #1. Click the “Scale to fit” button () to rescale the Graph axes to fit the data. Next, click the ‘Fit’ menu button () . Select ‘Linear’.
 - Record the slope of the linear fit in the Data Table in the Lab Report section. Repeat the above procedure for each of the remaining 9 data runs.
2. For each of the data runs, using the measured mass values, calculate and record the net force in the Data Table in the Lab Report section.

$$F_{net} = (M_2 - M_1)g$$

3. Calculate and record the total mass in the Data Table.
4. Using the total mass and net force, calculate the theoretical acceleration using:

$$a = \frac{F_{net}}{M_1 + M_2}$$

5. For each data run, calculate and record the percent difference between the experimental acceleration and the theoretical acceleration.

Record your results in the Lab Report section.

Name: _____ Date: _____
 Instructor: _____ Group Members: _____

Lab Report - Atwood's Machine

What Do You Think?

What is a real world application of Atwood's Machine?

Data Table: Constant Total Mass

Run	M ₁ (kg)	M ₂ (kg)	a _{exp} (m/s ²)	F _{net} (N)	M ₁ + M ₂ (kg)	a _{theory} (m/s ²)	Percent difference
Run #1							
Run #2							
Run #3							
Run #4							
Run #5							

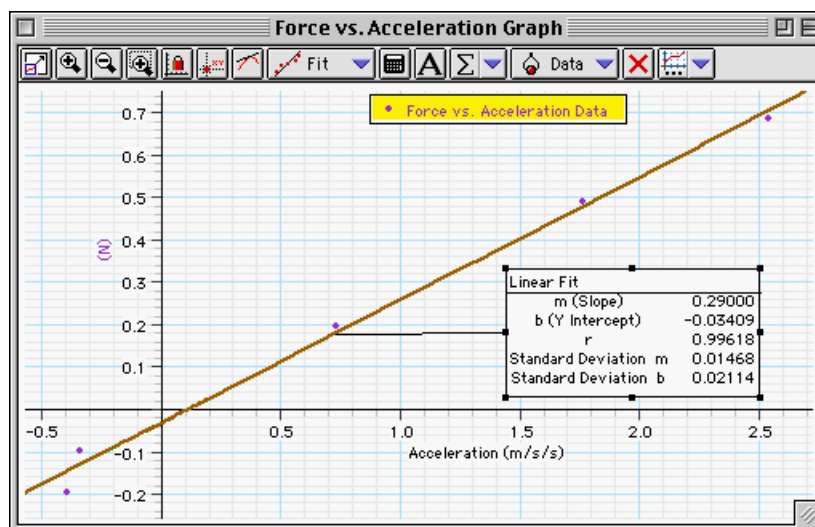
Data Table: Constant Net Force

Run	M ₁ (kg)	M ₂ (kg)	a _{exp} (m/s ²)	F _{net} (N)	M ₁ + M ₂ (kg)	a _{theory} (m/s ²)	Percent difference
Run #6							
Run #7							
Run #8							
Run #9							
Run #10							

Questions

1. Compare the experimental acceleration with the theoretical acceleration by determining the percentage difference. What are some reasons that would account for this percent difference?

2. For the Constant Total Mass data, plot a graph of F_{net} vs. a_{exp} . Note: Include a negative sign for acceleration values when $M_1 > M_2$. Attach your plot to the Lab Report.
3. Draw the best-fit line on your plot. What does the slope of the best-fit line represent?
4. How does the Force vs. Acceleration plot relate to Newton's Second Law?



Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 9 Kinetic Friction

Concept	<i>DataStudio</i>
Newton's Laws	P21 Kinetic Friction.DS

Equipment Needed	Qty	Equipment Needed	Qty
Photogate/Pulley System (ME-6838)	1	Mass and Hanger Set (ME-8967)	1
Balance (SE-8723)	1	String (SE-8050)	2 m
Friction Block w/ hook (003-04708)	1	Universal Table Clamp (ME-9376)	1



What Do You Think?

In relation to the direction of motion, in which direction does the kinetic frictional force act?

Take time to answer the 'What Do You Think?' question(s) in the Lab Report section.

Background

The block of mass M is placed on a level table connected by a string to a mass (m) hanging over a pulley. As the mass is released and starts to fall the block will slide across the table.

Treating both masses together as one system, the free-body diagram includes two forces: the force of gravity pulling on mass m and the kinetic friction acting on mass M . According to Newton's Second Law, the vector sum of the forces equals the total mass of the system times the acceleration of the system.

$$\sum F = mg - F_k = (M + m)a$$

where F_k is the force of kinetic friction which is given by:

$$F_k = \mu_k N$$

where μ_k is the coefficient of kinetic friction and N is the normal force acting on the block:

$$N = Mg$$

Solving for the coefficient of kinetic friction gives:

$$\mu_k = \frac{mg - (M + m)a}{Mg}$$

In general, the coefficient of kinetic friction for the block depends only on the type of materials that are rubbing together.

SAFETY REMINDER

- Follow the directions for using the equipment.

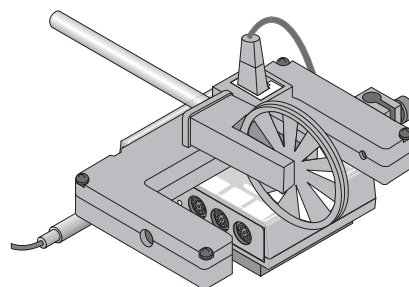
**THINK SAFETY
ACT SAFELY
BE SAFE!**

For You To Do

Use the Photogate/Pulley System to study how the coefficient of kinetic friction for an object depends on the normal force between the surfaces, the area of contact between the surfaces, the types of materials making contact, and the relative speed of the surfaces.

PART I: Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
 2. Connect the Photogate's phone plug to Digital Channel 1 on the interface.
 3. Open Data Studio to P21, Kinetic Friction.
- The *DataStudio* document has a Workbook display. Read the instructions in the Workbook.
 - Note: The spoke arc length for the Photogate/Pulley System is set at 0.015 m. If you are using a different pulley, change the spoke arc length in the sensor window by double clicking on the Smart Pulley icon in the Experiment setup window.



PART II: Sensor Calibration and Equipment Setup

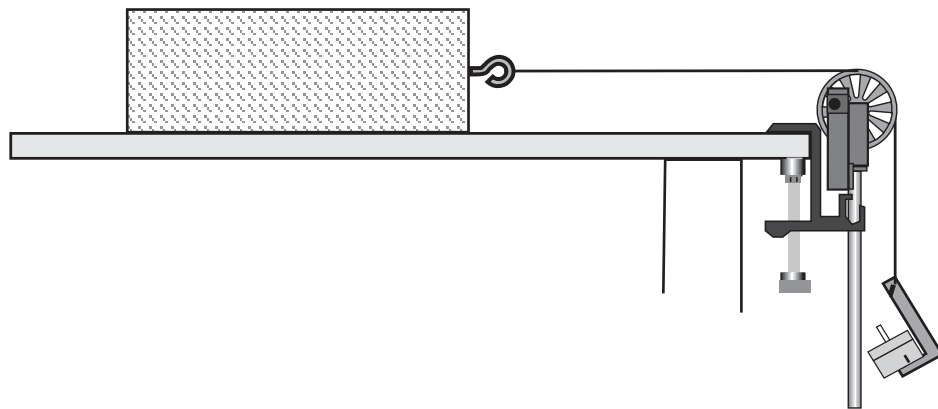
- You do not need to calibrate the Photogate/Pulley System.
1. Use the Pulley Mounting Rod to attach the Pulley to the tab on the Photogate.
 2. Use the Universal Table Clamp to mount the pulley rod vertically at the edge of a horizontal surface, such as a tabletop.
 3. Measure the mass of the Friction Block. Record the mass in the Data Table in the Lab Report section.

4. Use a piece of string that is about 10 centimeters longer than the distance from the top of the horizontal surface to the floor. Attach one end of the string to the block.
5. Put the string in the groove of the pulley. Attach the mass hanger to the other end of the string. Set up the block and Photogate/Pulley System as shown. If you are using a PASCO mass hanger, you can attach the string to the mass hanger by wrapping the string through the notch three or four times.

PART IIIA: Data Recording – Large, Smooth Surface

1. Place the block so its largest smooth side is on the horizontal surface.
2. Put enough mass on the mass hanger so that the block will slide on the surface without needing an initial push. Measure and record the value of the TOTAL hanging mass (remember to include the mass of the hanger).
3. Pull the block away from the Photogate/Pulley System until the hanging mass is almost up to the pulley. Hold the block in place. Turn the pulley so the photogate's beam is not blocked (light-emitting diode on the photogate is not lit).
4. Begin data recording.
5. Release the block.
6. End data recording before the block hits the pulley. Do not let the block hit the pulley.
 - The data will appear as Run #1.
7. Repeat the procedure to obtain a second run of data for the same hanging mass and surface.
 - The data will appear as Run #2.

PART IIIB: Data Recording – Different Mass of Block



1. Double the mass of the block by placing a mass approximately equal to the mass of the block on top of the block.

2. Measure and record the total mass (**M**) of the block and additional mass in the Data Table.
3. Double the hanging mass. Measure and record the total hanging mass (**m**) in the Data Table.
4. Record one run of data as before to see how the different mass affects the coefficient of kinetic friction.

PART IIIC: Data Recording – Different Surface Area

1. Remove the additional mass from the block and from the mass hanger to return the block and mass hanger to their original state from Part IIIA.
2. Place the block so its smallest smooth side is on the horizontal surface.
3. Record data. Compare this run to the data from Part IIIA.

PART IIID: Data Recording – Different Surface Material

1. Place the block so its **largest “rough” side** is on the horizontal surface.
2. Put enough mass on the mass hanger so that the block will slide on the surface without needing an initial push. Measure and record the value of the TOTAL hanging mass in the Data Table in the Lab Report section. Remember to include the mass of the hanger.
3. Record one run of data as before to see how the different material affects the coefficient of kinetic friction.
4. Place the block so its **smallest “rough” side** is on the horizontal surface.
5. Record data using the same hanging mass you used for the largest “rough” side so you can compare this run to the data for the largest “rough” side.

PART IIIE: Data Recording – Different Hanging Mass




1. Return the block to the original orientation as in Part IIIA (largest smooth side down).
2. Put an amount of mass on the hanger that is larger than the amount you used in Part IIIA. Measure and record the total hanging mass in the Data Table.
3. Record data as in Part IIIA.
4. Repeat the process using two larger totals for the hanging mass. Be sure to measure and record the total hanging mass for all three trials.

Data Recording Summary

Run #	PART & DESCRIPTION
1	IIIA, Largest smooth side of block
2	IIIA, Largest smooth side of block
3	IIIB, Larger mass of block and hanging mass
4	IIIC, Smallest smooth side of block
5	IIID, Largest rough side of block
6	IIID, Smallest rough side of block
7	IIIE, Larger hanging mass 1
8	IIIE, Larger hanging mass 2
9	IIIE, Larger hanging mass 3

Analyzing the Data

1. Determine the experimental acceleration for each of the data runs.
 - Click in the Graph display to make it active. Find the slope of the velocity vs. time plot, the average acceleration of the block.

In *DataStudio*, select Run #1 from the Data Menu () in the Graph display. If multiple data runs are showing, first select No Data from the Data Menu and then select Run #1. Click the “Scale to fit” button () to rescale the Graph axes to fit the data. Next, click the ‘Fit’ menu button () . Select ‘Linear’.

- Record the slope of the linear fit in the Data Table in the Lab Report section. Repeat the above procedure for each of the remaining data runs.
2. Using the mass values and the acceleration value, determine and record the coefficient of kinetic friction for each data run in the Data Table.

Record your results in the Lab Report section.

Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab Report - Kinetic Friction

What Do You Think?

In relation to the direction of motion, in which direction does the kinetic frictional force act?

Data Table:

Run	M total block mass (kg)	m total hanging mass (kg)	a _{exp} acceleration (m/s ²)	μ _k coefficient of friction
Run #1				
Run #2				
Run #3				
Run #4				
Run #5				
Run #6				
Run #7				
Run #8				
Run #9				

Summary:

Run #	Part and Description	μ _k
1	IIIA, Largest smooth side of block	
2	IIIA, Largest smooth side of block	
3	IIIB, Larger mass of block	
4	IIIC, Smallest smooth side of block	
5	IIID, Largest rough side of block	
6	IIID, Smallest rough side of block	
7	IIIE, Larger hanging mass 1	
8	IIIE, Larger hanging mass 2	
9	IIIE, Larger hanging mass 3	

Questions

1. How does the coefficient of kinetic friction vary with the mass of the block?
2. How does the coefficient of kinetic friction vary with the area of contact between the block and the horizontal surface?
3. How does the coefficient of kinetic friction vary with the type of material between the block and the horizontal surface?
4. When you used the different type of material, how does the coefficient of kinetic friction vary with the area of contact between the block and the horizontal surface?
5. How does the coefficient of kinetic friction vary as the speed varied due to the different hanging masses?
6. What is the relationship between the coefficient of kinetic friction and the mass, surface area, or speed of the object?
7. When the mass of the block is increased, does the force of kinetic friction increase? Why?

Lab 10 Angular Velocity

Introduction

In linear dynamics, Newton's second law ($F = ma$) describes the relationship between force, mass, and acceleration for an idealized point particle. No real object is a point particle, but this idealized relationship can be extended to real objects by defining a point called the center of mass of the object. Using this concept, a more generalized version of Newton's second law still holds. F is taken as the vector sum of all the external forces acting on the object, m is the mass of the object, and a is the acceleration of the center of mass.

However, an object can move while its center of mass remains stationary. In this experiment, you'll begin to study the simplest and most important motion of this type: rotation about a fixed axis through the center of mass of the object. This is an important kind of motion because any motion of a rigid body can be described as a combination of the motion of its center of mass, and rotation about its center of mass. Of course, a "rigid body" is an idealization, just like a point particle. Even a steel sphere is not perfectly rigid. But in studying the motion of a rigid body, rather than a point particle, you're investigating a model that can be used much more extensively in the real world.

Setup

► **NOTE:** If you have any questions about setting up the equipment, particularly about how to turn on or adjust the compressed air, see your instructor.

- ① Set up the equipment as shown in Figure 1.1. Use either the steel or aluminum disk as the top disk.
- ② Use the bubble level to check that the base of the apparatus is level. If not, adjust the leveling feet.
- ③ Plug in the AC Adapter to that the digital display comes on, and flip the switch on the display to UPPER, so the top disk is monitored by the optical readers. Then turn on the compressed air and adjust the pressure to approximately 9 psi.
- ④ Check that the valve pin for the lower disk is in the storage position, so that the lower disk rests firmly on the base plate.
- ⑤ Give the top disk a gentle spin, so that the digital display reads somewhere between 100 and 200 Hz. Watch the reading on the digital display for several minutes. Is it constant, or does the reading increase or decrease?

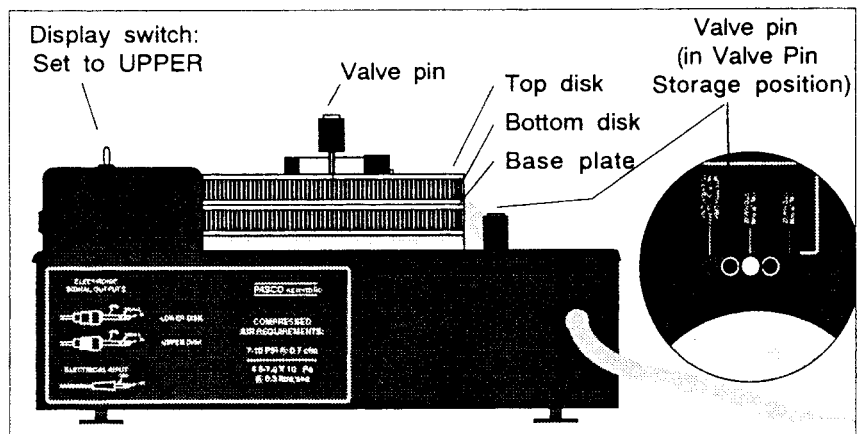


Figure 1.1 Equipment Setup

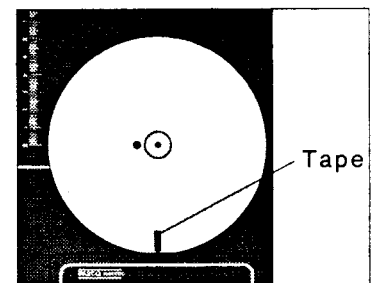


Figure 1.2 Placing the Tape

Procedure

Now perform the following experiment to see how the reading on the display relates to the angular velocity of the rotating disk. Record your measured values in Table 1.1

- ① Place a narrow piece of tape on the top of the top disk, at some point near the rim (see Figure 1.2).
- ② Give the disk a gentle spin (again to about 100-200 Hz), and record the initial reading on the digital display (R_i).
- ③ By watching the tape, count the number of revolutions of the disk in some specified time interval, about one minute. Record the number of revolutions as N and the time interval as t . At the end of the time interval, record the final reading on the digital display (R_f).
- ④ From your data, calculate the total angle θ , in radians, through which the disk rotated during the time t : $\theta = 2\pi N$. From this, determine the average angular velocity (ω_{avg}) of the disk during the time t ($\omega_{\text{avg}} = \theta/t$).
- ⑤ Calculate the average display reading during the time t : $R_{\text{avg}} = (R_f + R_i)/2$.
- ⑥ Using your calculated values, determine a constant κ , that relates the average display reading to the average angular velocity ($\kappa R_{\text{avg}} = \omega_{\text{avg}}$).
- ⑦ Repeat the experiment a few more times. How accurate does your measured value of κ seem to be?

The optical readers of the Rotational Dynamics Apparatus count the number of black bars that pass by them in one second. This is the number that is displayed. You can use this information to determine the value of κ using a more analytical approach.

- ⑧ Determine the number N of black bars on the circumference of the disk (count them, determine the number per centimeter and multiply by the circumference of the disk, or use some other method).
- ⑨ Divide 2π by N to determine the rotation of the disk in radians for each bar detected by the optical reader. This value is κ . (Convince yourself of this by comparing the units of the relevant variables: R (bars/second), ω (radians/second), N (bars), 2π (radians). Notice that $(2\pi/N)(R) = \omega$ gives the proper units.)
- ⑩ Compare your value of κ from step 9 with that from step 7. Are they the same? If not, which value do you have more confidence in? If necessary, experiment some more to determine a value of κ that you trust.

Optional

If you have time, try one or more of the following to get an idea of some of the factors that might effect your results in later experiments.

- ① Stop the disk from rotating. Hold it steady, then release it. Does it start to rotate? If so, let it rotate freely for a while and watch the display. In time, does the reading reach a steady value? If so, determine the angular velocity and record the value (including the direction). About how long did it take the disk to reach a steady angular velocity?
- ② Repeat step 1 using the other top disk (the aluminum disk if you were using the steel disk, the steel disk if you were using the aluminum disk). Are your results different for this disk?
- ③ Place a valve pin in the bottom disk valve. With one valve pin in this position, and another in the center of the top disk, the top and bottom disks should rotate independently. Design a few simple experiments to see if the motion of the two disks are truly independent. Discuss your experiments and your results.

Table 1.1 Data and Calculations

[illegible]

Lab 10B Angular Acceleration

Introduction

In linear motion, acceleration is defined as the rate of change of velocity with time. Average acceleration is calculated as, $a_{\text{avg}} = (v_f - v_i)/(t_f - t_i)$, where v_f and v_i are the final and initial velocities, and t_f and t_i are the corresponding times. If the motion is that of an object undergoing constant acceleration, then the average acceleration is equal to the instantaneous acceleration.

In rotational motion, the equation is analogous, with angular velocity (ω) and angular acceleration (α) replacing the corresponding linear variables:

$$\alpha_{\text{avg}} = (\omega_f - \omega_i)/(t_f - t_i).$$

In this experiment, you'll apply a constant force to the rotating disk under a variety of circumstances, in an attempt to determine how the force on the disk relates to its angular acceleration.

Procedure

➤ **NOTE:** If you have any questions about setting up the equipment, particularly about how to turn on or adjust the compressed air, see your instructor.

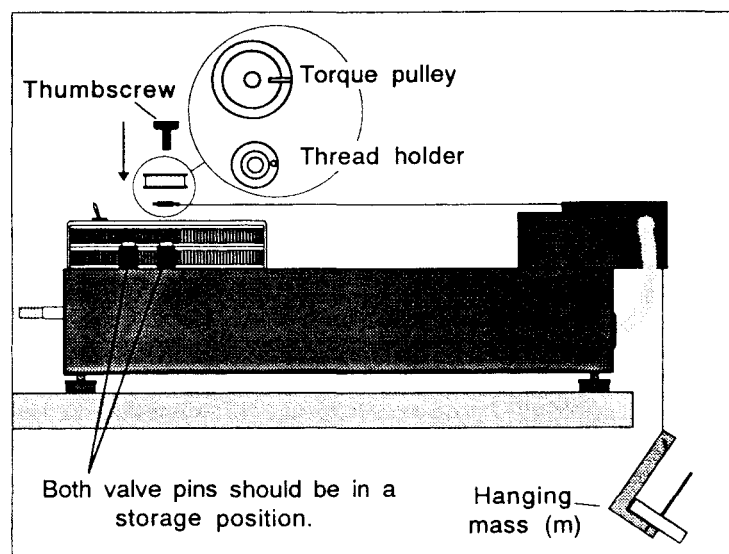


Figure 2.1 Equipment Setup

- ① Set up the equipment as shown in Figure 2.1. Use the steel disk as the top disk, and use the small torque pulley.
- ② Attach the mass hanger (with a 20g mass) to the end of the thread. With the thread extended, the mass should almost reach the floor.
- ③ Adjust the pressure of the compressed air to approximately 9 psi.
- ④ Check that the bottom disk sits firmly on the base plate (only the top disk should spin).
- ⑤ Record the hanging mass (m), the radius of the torque pulley (r), and the mass of the rotating disk (M) in Table 2.1. Be sure to include the mass of the hanger, 5g, in your value for m .

To measure the acceleration of the disk under the force applied by the hanging mass:

- ⑥ Wind the thread onto the torque pulley, until the hanging mass is almost against the air pulley.
- ⑦ Hold the disk still until the display reads zero.
- ⑧ Release the disk. As the disk rotates, record each successive, non-zero reading of the display in Table 2.1 ($R_1 - R_{10}$). Record these values as the hanging mass falls, and again as it rises back up. Do not record any values that appear after the mass has reached its highest point and started back down. You should get at least six different values. If you don't get that many, raise the apparatus and use a longer piece of thread.

Two of your recorded values will not be useable data. The first is R_1 (see *Notes on Timing* in the *Operation* section of this manual). The second is the value that was counted as the hanging mass reached its lowest point and then started back up. Leave these values in your data table, but mark them clearly so you do not use them in your later calculations.

- ⑨ Repeat steps 6-8 at least three times (the more the better).
- ⑩ The following can be performed by a single group, or divided between three groups:
 - a. Leaving all other experimental conditions the same, change the value of m , and repeat steps 6-9. Do this for at least three different values of m .
 - b. Leaving all other experimental conditions the same, change the value of r (use the large torque pulley), and repeat steps 6-9.
 - c. Leaving all other experimental conditions the same, change the value of M , and repeat steps 6-9. To do this, place a valve pin in the bottom disk valve position and remove the valve pin from the top disk, so both disks rotate together. For a third value of M , replace the steel top disk with the aluminum top disk.

Calculations

The display shows you the number of bars that pass by every second. However, there is a dead time of one second between each counting interval, so that the time between successive displayed values is 2.00 seconds. Therefore, if you convert all your display readings into angular velocities, you can use the equation at the top of the preceding page to calculate the average angular acceleration within each timing interval. For example, calculate α_2 as: $\alpha_2 = (\omega_3 - \omega_2)/(t_3 - t_2)$; where $t_3 - t_2 = 2.00$ seconds, and ω is determined using the conversion factor that you measured in Experiment 1 ($\omega_3 = \kappa R_3$, etc.).

For each trial of the experiment that you performed:

- ① Calculate the angular velocity within each counting interval ($\omega = \kappa R$).
- ② Use the above equation to calculate α , the average angular acceleration within each valid timing interval.

For each set of trials in which the experimental conditions were the same:

- ③ Determine the average of your measured values of α . Record this value as α in Table 2.2. For each value of α , also record m , r , and M , the experimental conditions under which α was measured.
- ④ Use your results to determine how each independent variable (m , r , and M) affects α , the angular acceleration of the disk(s). (For example, to determine the effect of m on α , examine your data for all your experimental runs in which m was varied and r and M remained constant. You might try graphing α as a function of m . Is α proportional to m ?)

Conclusions

- ① Is it reasonable to assume that your measured values of α are the same as the instantaneous angular acceleration within each counting interval? Explain your answer. (Hint: Is the angular acceleration constant?)
- ② Can you determine a mathematical relationship between α and the independent variables r , m , and M ?
- ③ In rotational dynamics, there is a quantity called torque that is analogous to force in linear dynamics. Figure 2.2 is a diagram showing how this quantity is measured. If a force (F) is applied to an object at a distance (d) from the axis of rotation of the object, then the torque can be calculated by the equation: $\tau = Fd_{\perp}$; where d_{\perp} is the component of the vector d that is perpendicular to the direction of the applied force. Discuss how the concept of torque relates to your results.

Table 2.1 Sample Data Table

$m =$ $r =$ $M =$

[illegible]

Table 2.2 Results

α	m	r	M

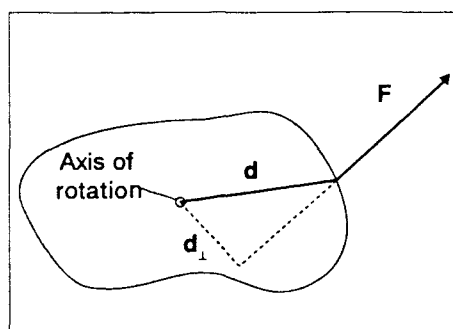


Figure 2.2 Torque Diagram

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Lab 11 Centripetal Force on a Pendulum

Concept: Centripetal Force P26 Centripetal Force.DS

Equipment Needed	Qty	Equipment Needed	Qty
Economy Force Sensor (CI-6746)	1	Clamp, right angle (SE-9444)	2
Photogate (ME-9204B)	1	Mass and Hanger Set (ME-8967)	1
Balance (SE-8723)	1	Pendulum bob	1
Base and Support Rod (ME-9355)	1	String (SE-8050)	1 m
Calipers (SF-8711)	1	Support Rod (ME-8736)	1

What Do You Think?

What are the factors that affect the centripetal force on a pendulum bob as the pendulum swings back and forth? Does the centripetal force depend on how fast the pendulum bob is swinging?



Take time to answer the ‘What Do You Think?’ question(s) in the Lab Report section.

Background

A pendulum bob follows a circular path. Therefore, it is acted on by a centripetal (“center-seeking”) force. In the case of the pendulum, the tension in the string causes the bob to follow the circular path. At the bottom of the pendulum’s swing the net force on the bob is the combination of the tension in the string and the force due to gravity.

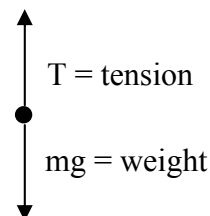
From Newton’s Second Law, $\Sigma F = T - mg = ma = F_c$

where T is the tension in the string, m is the mass of the pendulum bob, g is the acceleration due to gravity, and F_c is the centripetal force.

The Force Sensor will be zeroed when the pendulum is at rest in its equilibrium position (when $T = mg$). Thus the force measured by the Force Sensor when the pendulum passes through the lowest point of the swing is equal to the centripetal force F_c .

The centripetal force can also be found using the speed, v , of the bob as it passes through the lowest point of the swing using:

$$F_c = m \frac{v^2}{r}$$



where r is the radius of the circular path which, in this case, is equal to the length of the pendulum.

SAFETY REMINDER

- Follow the directions for using the equipment.

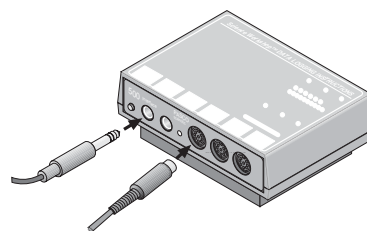
THINK SAFETY
ACT SAFELY
BE SAFE!

For You To Do

Use the Force Sensor to measure the centripetal force on a pendulum bob at the lowest point of its swing. Use the Photogate to measure the time that the pendulum bob blocks the Photogate beam. Enter the value for the diameter of the pendulum bob. For the bottom of the pendulum swing, *DataStudio* calculates and displays the speed of the pendulum bob and the centripetal force on the pendulum.

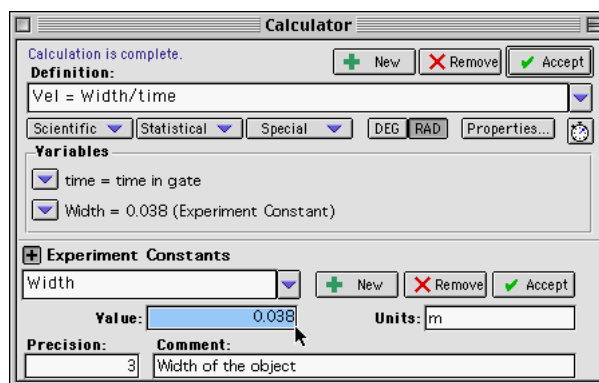
PART I: Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
 2. Connect the Photogate's phone plug to Digital Channel 1.
 3. Connect the DIN plug of the Force Sensor to Analog Channel A.
 4. Open the Data Studio document P26 Centripetal Force.DS
- The *DataStudio* document has a Workbook display. Read the instructions in the Workbook.
 - Data recording is set at 100 Hz for the Force Sensor.



PART II: Sensor Calibration and Equipment Setup

- You do not need to calibrate the Photogate.
 - To calibrate the Force Sensor, refer to the description in the Force Sensor Manual.
1. Measure the value of the diameter of the pendulum bob. Record the diameter in the Data Table in the Lab Report section.
 2. Enter the diameter into the software.
- In *DataStudio*, double click on the Vel calculation in the Summary Window. The Calculator window will open. The window shows the calculation for velocity.

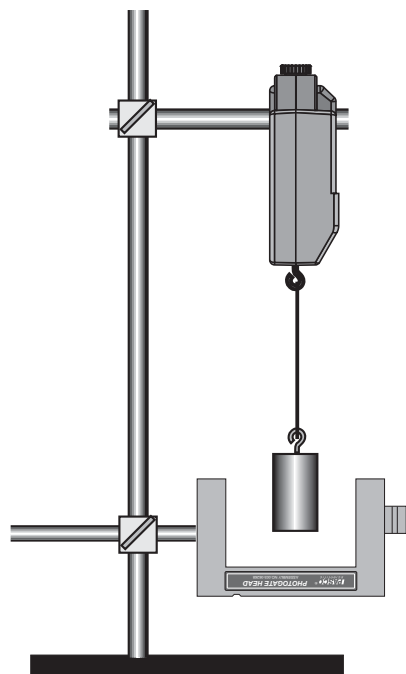


The pendulum width is stored as an 'Experiment Constant'. If the diameter for the pendulum is different than the value listed, highlight the width value in the 'Value' window and type in diameter of the pendulum.

Click the 'Accept' button to save your change.

Close the Experiment Calculator window.



3. Mount the Force Sensor on a horizontal rod with the hook end down.
 4. Measure the mass of the pendulum bob. Record the mass in the Data Table in the Lab Report section.
 5. To make the pendulum, use a piece of string that is about one meter long. Tie one end of the string to the hook on the Force Sensor and tie the other end to the pendulum bob.
 6. Arrange the Photogate so the pendulum bob blocks the Photogate's beam when the bob is at rest. The center of mass of the pendulum bob should be approximately at the same height as the Photogate beam.
 7. Measure the length of the pendulum from the bottom of the Force Sensor's hook to the middle of the pendulum bob. Record the length of the pendulum in the Data Table.
- Practice swinging the pendulum bob. Pull the pendulum bob to the side about 15 to 20 centimeters. Gently release the bob so it swings through the Photogate as smoothly as possible. The middle of the pendulum should break the photogate beam. Adjust the position of the Photogate if necessary.
 - Do not let the pendulum bob hit the Photogate.



PART III: Data Recording

1. When the pendulum bob is at rest, zero the Force Sensor by pressing the tare button.
2. Set the pendulum in motion. Let the pendulum swing back-and-forth several times to allow any oscillations to damp out.
3. Begin recording data.
4. Record data for about 20 seconds. End data recording.

Analyzing the Data

1. Click on the Graph Display to make it active. Rescale the Graph axes to fit the data.
 - In *DataStudio*, click on the 'Scale to Fit' button ().
 2. Find the maximum centripetal force and corresponding velocity value.
- In *DataStudio*, click the Force vs. Time plot to make it active. Click the 'Smart Tool' button (.
- Move the Smart Tool to the first trough in the plot of Force versus Time and read the value of force. Record the absolute value in the Data Table in the Lab Report section.
 - Click on the plot of Velocity vs. Time and click on the Smart Tool button. A second Smart Tool will appear. Place the tool at the velocity point that corresponds in time to the trough you measured in the plot of centripetal force. Record the value of speed in the Data Table.
3. Repeat the data analysis process for four more troughs on the plot of centripetal force. Record the maximum centripetal force and the corresponding speed in the Data Table in the Lab Report section.
 4. For each value of speed you measured, calculate the centripetal force using the mass, speed, and length of the pendulum. Record the calculated value of centripetal force in the Data Table.
 5. Calculate the percent difference between the measured centripetal force and the calculated centripetal force for each set of points. Record the percent differences in the Data Table.

Record your results in the Lab Report section.

Name: _____ Date: _____
Instructor: _____ Group Members: _____

Lab Report - Centripetal Force on a Pendulum

What Do You Think?

What are the factors that affect the centripetal force on a pendulum bob as the pendulum swings back and forth? Does the centripetal force depend on how fast the pendulum bob is swinging?

Data Tables

Item	Value
Diameter	
Mass	
Length	

Points	F_c , measured (N)	v (m/s)	F_c , calculated (N)	% difference
1				
2				
3				
4				
5				

Questions

1. How do your measured values of centripetal force compare to the calculated values of centripetal force?
2. What are possible reasons for the differences between the measured and calculated values of centripetal force?

Optional

- Try a different mass value for the pendulum bob or a different length for the pendulum or change the speed of the pendulum and repeat the data recording process.

Optional Data Tables

Item	Value
Diameter	
Mass	
Length	

Points	F_C , measured (N)	v (m/s)	F_C , calculated (N)	% difference
1				
2				
3				
4				
5				

Questions

1. How do your measured values of centripetal force compare to the calculated values of centripetal force?
2. How do the centripetal force values in the optional activity compare with the values from the original activity?

Lab 12 Calorimetry

Theory:

This is an experiment concerning energy exchanges, specifically energy in the form of heat. The total energy of the system is conserved. In this experiment, heat will be exchanged, moving from the hot water to the ice and to the calorimeter itself. Part of the heat transfer involves changing the temperature of both the hot water and the ice, bringing them into equilibrium, and some heat transfer occurs by changing the phase of the water from ice to liquid.

$$\Sigma Q_i = 0$$

$$m_{\text{ice}}c_{\text{ice}}\Delta t_1 + m_{\text{ice}}\lambda_{\text{ice}} + m_{\text{ice}}c_{\text{H}_2\text{O}}\Delta t_2 + m_{\text{hot H}_2\text{O}}c_{\text{H}_2\text{O}}\Delta t_3 + m_{\text{Al cup}}c_{\text{Al}}\Delta t_4 = 0$$

m_{ice} = mass of ice

c_{ice} = specific heat of ice

λ_{ice} = latent heat of fusion

$c_{\text{H}_2\text{O}}$ = specific heat of water

$m_{\text{hot H}_2\text{O}}$ = mass of hot water

$m_{\text{Al cup}}$ = mass of aluminum cup
insert

c_{Al} = specific heat of aluminum

$\Delta t = \Delta t_{\text{final}} - \Delta t_i$

t_{eq} = equilibrium temperature

$\Delta t_1 = 0^\circ$ - initial temp of ice

$\Delta t_2 = t_{\text{eq}} - 0^\circ$ (Temperature change of melted ice from zero to the final temp)

$\Delta t_3 = t_{\text{eq}} - \text{initial temp of hot water}$

$\Delta t_4 = t_{\text{eq}}$ of aluminum cup – initial temp of cup

Equipment:

Calorimeter (insulated flask)
Thermometer
Balance

Ice
Hot water Hot water heater
Thermoses for ice and hot water

Procedure:

I. Record the temperature of the aluminum cup insert.

II. Mass of calorimeter and calorimeter components.

1. Determine the mass of the calorimeter: just the metal, first the insert cup and then the outer flask. Record.
2. Record the mass of the stirrer.
3. Place the cup inside the larger aluminum flask.
4. Carefully place the thermometer through the stopper in the lid of the insulated flask. Push the stirrer through hole in the lid. Place the lid, with the thermometer and the stirrer, on the base.
5. Measure the mass of the calorimeter (flask, cup, lid, etc.). Record.

III. Ice.

6. Determine the temperature of the ice. Record. (The ice will be brought to you with the thermometer already in the ice.)
7. Add the ice you are given to the calorimeter. Close quickly. Measure the total mass. Record.

IV. Hot Water

8. Determine the temperature of the hot water. (The hot water will be brought to you with a thermometer already in the hot water.)
9. Measure the volume of the hot water in a warmed graduated cylinder; convert the volume to mass: $1.0 \text{ ml} = 1.0 \text{ g}$
10. Quickly add the hot water to the calorimeter. Cover immediately.
11. Gently stir the mixture with the stirring rod.

12. Determine the theoretical equilibrium temperature (see Analysis, below) while you're waiting for the mix to equilibrate.
13. Wait for the temperature of the mix to come to equilibrium. Record the final temp.
14. As soon as the ice has melted and the mix is stirred, record the final or equilibrium temperature.

Analysis:

While the mix is coming to equilibrium, determine the *theoretical* equilibrium temperature by using all the measurements you have taken and substituting them into the conservation equation (p. 1), solving for t_{eq} . (A Δt in Kelvin is the same as a Δt in Celcius, so it is not necessary to convert the temperature for the conservation equation.) Compare this value to the value you actually obtained. Why are the values different?

Use a percent error calculation. Convert the temperatures to Kelvin for the percent error calculation.

Name: _____ Date: _____

Instructor: _____

Group Members: _____

Calorimeter Data:

Temperature of calorimeter cup insert _____

Mass of calorimeter cup insert _____

Mass of calorimeter, metal only, outer flask _____

Mass of stirring rod _____

Mass of entire calorimeter: thermometer, thermos flask, cup, lid, plastic ring, stopper

Mass of entire calorimeter with ice _____

Mass of ice _____

Temperature of ice _____

Temperature of hot water _____

Volume of hot water _____

Mass of hot water _____

Final or equilibrium temperature of mix _____

$$c_{\text{ice}} = 2090 \text{ J/(kg K)}$$

$$c_{\text{H}_2\text{O}} = 4186 \text{ J/(kg K)}$$

$$c_{\text{Al}} = 900 \text{ J/(kg K)}$$

$$\lambda_{\text{ice}} = 33.5 \times 10^4 \text{ J/kg}$$

Calorimetry Questions

*Questions taken from Physics Laboratory Experiments, Jerry D. Wilson,
4th Edition*

1. The percent errors of your experimental values of the specific heats may be quite large. Identify several sources of experimental error.
2. Why does it improve the accuracy of the experiment if the final temperature of the system is near room temperature?
3. The specific heat of aluminum is $0.22 \text{ cal/g-}^{\circ}\text{C}$. What is the value of the specific heat in (a) $0.22 \text{ kcal/kg-}^{\circ}\text{C}$; (b) $\text{Btu/lb-}^{\circ}\text{F}$? (Show your calculations.)

4. Explain how the unknown temperature of a hot piece of metal may be determined by the method used today with the calorimeter.

(Assume c_m , the specific heat of the metal, is known.)

5. Explain why specific heat is *specific* and how it gives a *relative* indication of molecular configuration and bonding.

Simple Harmonic Motion

The Simple Pendulum

Purpose: To determine the value of g using a simple pendulum and empirical analysis.

Equipment:

- Two meters of string
- Weight
- Timer
- Meter stick
- Ring stand with perpendicular rod for hanging string

Procedure:

1. Tie string tightly to rod.
2. Tie weight to other end of string so that the weight clears the floor.
3. You'll need to know and record the length of the string to the nearest millimeter from the knot at the rod to the center of the weight.
4. Pull the weight away from its rest position to about four centimeters. This should be less than 10° . Let it swing once or twice to be certain the swing is in a straight line, not in a circular pattern. Also be certain that the string is swinging from the knot at the bottom of the rod, and that the string that encircles the rod is not moving.
5. Turn on the timer at the same instant the weight comes to the top of its swing, which is the greatest displacement from rest position

6. The pendulum has made one complete swing or cycle when the weight has moved from one side to the other *and back*. Count “one” when it has made one complete swing.
7. Continue to count the oscillations for thirty oscillations, stopping the stopwatch precisely when the weight comes to the top of its swing.
8. Record both the time and the number of oscillations.
9. Shorten the string and repeat the above steps. (Do this for ten different lengths.)

Analysis: Have you wondered how all the formulas in your textbook were determined? After researching a phenomenon and collecting data, the relationship between the variables can be determined by graphing them in a variety of ways. You will get to determine the mathematical relationship of g to L and T .

$$T^n = 4\pi^2 L / g$$

1. Determine the formula by plotting $4\pi^2 L$ vs T^n where n is:
 - a. $1/2$
 - b. 1
 - c. 2

The graph which yields the straight line gives the correct formula.

Alternate Procedure

1. Use thread that is nearly as long as the distance from the floor to the ceiling. Insert thread through a dense ball or tie around the ball (more dense than a tennis ball: massive enough to keep the string taut.)
2. Tie or affix the string to the ceiling or rod near the ceiling.
3. Repeat the procedure as above.

Other Possibilities:

1. Have the students investigate the relationship of the mass to the period. Offer several different masses.
2. Investigate the consequences of using angle greater than 10° .

Name: _____ Date: _____

Instructor: _____ Group Members: _____

The Simple Pendulum							
	Length (of string to center of weight) (m)	Time t	# of cycles	Period T	$T^{1/2}$	T^2	$4\pi^2 L$
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							
9.							
10.							

Lab 14

Sound Waves: Harmonics in an Open-Ended Pipe

Purpose: To determine the speed of sound in air using a water-filled, open ended pipe, a tuning fork, and the knowledge of harmonics.

Theory:

Sound waves are longitudinal waves, meaning that the direction of the displacement or movement of the particles is in the *same direction* as the propagation of the wave. Interference can occur in sound waves: when there is **constructive interference** of reverberating waves, the result is increased sound intensity.

If a tuning fork is struck, the fork vibrates, causing a compression of the air particles moving spherically outward from the fork. When the fork oscillates inward, it creates an area of rarefied air particles. A region of compressed air followed by a region of rarefied air constitutes one wavelength.

If the fork is struck over a tube filled with water, a sector of this wave will be captured by the tube. When the air particles hit the surface of water, most of energy is reflected at the water's surface due to the differences in the densities of the air and the water.

With each vibration of the tuning fork, another spherical wave front moves out from the fork, and a part of the new wave is also captured by the tube. When the height of the water is adjusted so that an *incoming* (compressed air) wave front is just meeting a *reflected* (compressed air) wave front at the open end of the tube, the waves will interfere constructively. When this happens over and over again each second, our ears can detect this constructive interference as increased sound intensity: it gets loud!

Using our simple tube and a tuning fork, we can discover the speed that sound travels in air. We know that:

$v = f \lambda$ The velocity of any wave is directly proportional both to the **wavelength λ of the sound wave** created by the tuning fork and **f , the frequency of vibration of the tuning fork**. The frequency is printed on the tuning fork. We can determine the wavelength by knowing a little about harmonics, and by creating harmonics with our tube and tuning fork.

Harmonics: The surface of the water is considered a *node*. In transverse waves, the node occurs when the displacement is zero. Likewise, at the water's surface at which the wave is reflected, the net displacement of the wave is zero. At the open end of the tube, the air is free to move, and this point is an *antinode*. Multiple nodes and antinodes will exist in the tube.

L is the distance from the top of the tube to the surface of the water, which we will measure with a meter stick. The first harmonic is the case in which there is only one node and one antinode in the tube, and this is also called the fundamental *mode*. In the case of an open ended tube, one wavelength of the fundamental *mode* is four times the length of the tube from the top of the tube to the water's surface:

$$\lambda = 4L$$

Substituting into $v = f \lambda$,

$$f_1 = v / 4L$$

The frequencies of the third and fifth harmonics are $3f_1$, $5f_1$... That is, in a pipe closed at one end and open at the other, only odd harmonics are present. These are given by

$$f_n = n v / 4L \quad n = 1, 3, 5, \dots$$

*Note: The diagrams in the textbook are helpful, but also somewhat misleading, as the diagrams are drawn as though the waves are transverse. Imagine regions of compressed air molecules followed by rarefied air moving through the tube to get a better visual picture.

Equipment:

Transparent Open-Ended
Tube

Meter stick

Ring stand and clamp

Water

Bucket

Tuning forks

Pitcher

Procedure:

1. Secure the tube vertically to the ring stand. Clamp the tuning fork just above the tube. Attach amplifier to the tube, if an amplifier is available.
2. Fill pitcher with water. If your tube does not have a valve, have one partner hold their thumb over the bottom of the drain tube. Pour water into the tube to within 5 cm of the top.
3. Strike tuning fork over the top of the tube.
4. First run: Drain water quickly from the tube, and listen closely for the sound intensity to increase. Make note of the approximate height of the water when that first “harmonic” is heard.
5. Continue to drain the water rather quickly, and a second harmonic will be heard. Make note of the approximate height of the water.
6. Second run: Refill the tube with water.
7. Quickly run the water out to five or six cm above where the first harmonic was heard. Then allow the water to slowly drain, listening for the amplitude of the sound to maximize. Record the height of the water when the sound peaks.
8. You may strike the tuning fork again.
9. Again, run the water down quickly to within five or six cm of the point of the second harmonic. Then drain the water slowly, and record the height of the water when the amplitude of the sound peaks again.
10. If you are careful, you may be able to find a third harmonic.
11. Repeat the procedure using two other tuning forks.

Name: _____ Date: _____

Instructor: _____ Group Members: _____

Harmonics Tables

Table 1

F	T	L		λ	
Frequency of Tuning Fork		Length from Top of Tube		(in meters)	
		$L_1 = \lambda/4$			
		$L_2 = 3\lambda/4$			
		$L_3 = 5\lambda/4$			
				$\Sigma =$	
				Avg. $\lambda =$	

Name: _____

Table 2

F	T	L		λ (in meters)	
Frequency of Tuning Fork		Length from Top of Tube			
		$L_1 = \lambda/4$			
		$L_2 = 3\lambda/4$			
		$L_3 = 5\lambda/4$			
				$\Sigma =$	
				Avg. $\lambda =$	

Table 3

F	T	L		λ (in meters)	
Frequency of Tuning Fork		Length from Top of Tube			
		$L_1 = \lambda/4$			
		$L_2 = 3\lambda/4$			
		$L_3 = 5\lambda/4$			
				$\Sigma =$	
				Avg. $\lambda =$	

Analysis:

Knowing that

$$v = f \lambda = f / T$$

The speed of sound can be determined by making a graph, plotting f versus T , with f on the ordinate (y axis) and T on the abscissa (x axis). For each tuning fork you used, plot that frequency and the corresponding average wavelength calculated in your tables. After plotting these three points on the graph, find the best line to fit the data. The slope of the line is the velocity of sound.

Compare what you discovered with the known velocity of sound in air of 343 m/s.