Physics 1107 - Introductory General Physics I

Physics Laboratory Manual

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Section One - Introduction to the Physics Laboratory

Introduction to the Physics 1107 Lab

Objectives

Laboratory work is an integral part of the Physics 1107 and 1207 courses. The lab component of the course has been designed with a number of objectives in mind:

To develop

- fundamental skills in making measurements;
- awareness of the precision and accuracy of various types of measurement;
- the ability to record data in a clear, well-organized fashion;
- skills in data analysis;
- the ability to present results in a clear, concise report.

Requirements of the Students

1. Each student is expected to complete all experiments during a semester. Missing an experiment will result in a grade of 0 for that lab. If there is a legitimate reason for missing an experiment, the lab instructor should be notified as soon as possible, preferably before the lab date. Reasons include documented medical illness, court appearances, etc. **There are no make up labs.**

2. An attempt will be made to coordinate the time during the semester at which each experiment is performed with the presentation of the pertinent material in the classroom. However, this will not be possible in all cases. Consequently, the theory appropriate to each experiment is given in some detail in the outline provided. In order to be adequately prepared for each experiment, it is expected that prior to coming to the lab you will study the appropriate outline carefully and read the relevant sections in your textbook.

3. A 'pre-lab' quiz will be due before each lab. This quiz will be available for 24 hours on Blackboard during a pre-set day in each week, which will be before your lab day, and will be due at 11:59 PM on that day. You will have 15 minutes to complete this quiz once you open it and you will only have one attempt.

4. Each experiment is intended to take about one hour (or less). The rest of each lab period is to be spent analyzing the data obtained and performing the required calculations. Each student is expected to submit a report on each experiment. In addition, there may be questions based on the experiments on tests and the final exam. There will not be a laboratory exam.

5. Each student is required to have a folder in which to keep completed reports. **<u>The folder and its contents are not to leave the laboratory</u>**. A student may consult his/her binder when the lab is open (at the convenience of staff). Reports and quizzes that go missing from the laboratory may not be given credit in the student's final laboratory grade, i.e. the missing report or quiz will be counted as having a mark of zero.

6. Please note the following items with respect to the laboratory grading system.

    a. Lab reports are due at the end of each lab period.

    b. All submitted lab reports will be given appropriate weights in the tabulation of the laboratory grade.

    c. Half of the submitted lab reports will be randomly chosen for marking and the final grade will be based on the average of the marked lab reports. **Any labs that you miss will count as a zero and will be included in the average.** However, the lowest lab mark will be dropped. For example: There are six total labs and student A performs all of them, receiving marks of 70%, 80%, and 90% on the three marked reports. Student A will receive a final lab grade of 85% (because the 70% mark is dropped). Student B missed a lab, but received the same 70%, 80%, and 90% marks on the three marked reports. Student B would receive a final lab grade of 80% (because the lab grade of 0 for the missed lab was dropped).

    d. With the lab instructor's permission extra time may be given to finish a Report. Reports submitted within two days after the due date indicated by your instructor will suffer a grading penalty. It is approximately 10 % per day. No report that is more than two days late will be accepted.

    e. Your marks in the laboratory will contribute a maximum of 20% toward the final grade for the course.

7. In the case where a student is on the borderline of a grade division, a factor in determining the final grade may be the subjective evaluation of:

    a. the overall quality of the student's lab record (the folder contents)

    b. the student's performance in the lab (preparation, lab technique) and

    c. the student's participation in classes and labs.

8. You will be working in groups of 2 or 3. Partners will be randomly assigned each week and each student must complete their own lab report. You are encouraged to talk to each other and help each other out as this actually aids in learning the material. Labs are not a test of knowledge but a chance to develop and practice skills. This being said the final work you hand in must be your own, direct copying of parts of another person's lab report will be considered cheating and may result in a grade of 0 for that lab.

9. No visitors are permitted in the laboratory during the lab session.

10. No eating or drinking is permitted in the laboratory during experiments where contamination may occur.

The Lab Report

To start off your work on each lab, first you need to understand the big picture of that lab, i.e. what is it that you as the experimenter are tasked to determine. Read the entire experiment manual and ask yourself what questions the lab is trying to answer. This should not be confused with the method you are using to answer the question. For example, say we were doing a lab where we measure the period of a pendulum at different lengths in order to determine the local acceleration due to gravity g. There are several questions we could be trying to answer.

1. What is the local acceleration due to gravity?
2. Is the period of a pendulum proportional to the square root of its length?

Notice the method we are using is not mentioned in either question, in other words, the question is NOT "How do we find/calculate the acceleration due to gravity?".

Once we have these questions, we can devise an experiment to answer them, perform it and write up our results. Answering these questions is the reason we perform the experiment, and you will be referring to them several times in your write up and in your Pre-Lab Quiz.

The purpose of a lab report is to communicate to others what you have done in the lab: what you have measured, how you have measured it, and your interpretation of the measurements. This communication is aided if all reports follow the same general format, a traditional format that has evolved over the years. This gives the reader the option of reading the whole report or of going directly to some particular part of it.

Most of the reports will be submitted on sheets provided to you at the beginning of the lab session. The sheet will give you space to record your observations and data with the associated uncertainties, answer some questions, and summarize the results in a conclusion. Your submitted work must be clear and legible. Although you do not need to list the apparatus or method given in the lab manual, you must provide explanations and context for everything that you submit (i.e., write a few sentences to state what is it that you are calculating, what a diagram shows, or how you measured or obtained data).

If you continue in science, you will be writing and organizing your own experiments, but the format of your report will probably be similar. The following is the list of the required sections in your lab report:

Header:

At the top of the lab you should start with the title of the lab, your name, student number and the date.

Objective:

The objective is a single paragraph at the beginning of the lab report informing the reader as to the purpose of the lab. You should take the central questions you are trying to answer in the lab, determined previously for your Pre-Lab Quiz, and form them into a simple introduction for the reader. You should mention the method you will use to answer these questions but don't go into detail. Using the pendulum example discussed previously a good objective statement may be:

> *The objective of this lab is to use a simple pendulum to determine the local acceleration due to gravity in New Westminster BC, and to verify the relationship between the length and period of said pendulum.*

Data:

The Data section is a record of the actual values observed. A sample data table is shown below for an experiment in which acceleration is determined from measurements of distance and time. In this sample, the first column is for identification of the data, the second and third columns are data values. Tables should be numbered in the order that they appear and should have descriptive titles

Table #1: Distance-time measurements for the acceleration of a rolling cart

Run #	Distance, d (cm) ± 0.2	Time, t (s) ± 0.1
1	25.6	2.3
2	41.7	2.9
3	…	…

Calculations:

The Calculations section shows a sample set of all the calculations involved, in full detail. If you are repeating the same calculation a number of times on different sets of collected data, you should show one set of sample calculations for a particular data run. Be sure to clearly identify the run from which the data is being taken. The results of the calculations may be included with your data table, or you may make a new table for multiple calculation results. When possible, each partner must show calculations for a different data run so that their calculations are not identical.

For example, another column may be added to Table #1 above to show the calculated value of the Period Squared since we needed that for a plot. Even though the answers appear before the calculations section, a sample calculation for one of the periods must be shown in the Calculations section, each lab partner showing a different period calculation in their lab report.

Many experiments require the preparation of graphs to analyze. These graphs **must be** computer drawn. See the Graphing section for the requirements.

Discussion:

The Discussion is where you discuss the results of your experiment, taking your findings and putting them in their proper scientific context. In a research paper this tends to be the most important part of a report as it is where you describe the significance of your findings. In student labs this tends to be where you actually show you understand physics involved in the experiment and are not just mindlessly following the procedure.

It takes a long time and a lot of practice to learn how to write a good discussion. At the beginning of the course we will give you some guide questions to answer. These are the kind of questions a practicing scientist may think about when writing their discussion. Simply answer these questions to the best of your ability making sure to talk about the physics involved. Never give yes or no answers, always explain yourself. As the course progresses the questions may become more open ended and may eventually be removed, requiring you to come up with your own discussion using previous ones for inspiration.

The type of things you put in a discussion are as follows

- A comparison of your experimental results with the expected results

- Weather your results support or contradict the theory and why.
- Major sources of error (assumptions) should be identified and assessed as to the effect each source would have on the results.
- If possible suggest ways in which such errors might be reduced or avoided.
- Interesting observations and what they might mean, what physics do they reveal.

Conclusion:

Conclusion is a brief statement of what your experiment results showed and should closely reflect the objective stated at the beginning of the report. If the objective specified that a specific value, such as the acceleration of a falling object, was to be determined, give the value you determined. If a general principle, such as conservation of energy, was being tested, state whether your results support/contradict the principle.

For the sample objective given above an appropriate conclusion may be:

> *In this experiment we used a simple pendulum to determine the local acceleration due to gravity in New Westminster BC. The value of g was determined to be 9.78±0.3 m/s*^{2} *which agrees with the accepted value of 9.8 m/s*^{2}*. In addition, we verified that the period of the pendulum changes in proportion to the square root of its length.*

Measurement, Uncertainty, and Significant Figures

When any measurement is made in the lab, the precision of the measurement is limited and therefore some uncertainty must be associated with the measurement. This is done by recording your best estimate value with a reasonable number of significant figures (which includes all the known digits and the first estimated digits) and indicating the amount of uncertainty (or error) in the estimated digit.

Uncertainty may be shown in one of two ways: absolute or relative (percent). The absolute uncertainty has the same dimension as the measured quantity (e.g. length or time,) and is generally written with only one significant figure as any digits in the measurement beyond the estimated digit are meaningless.
For example, 0.02 cm in 124.36 ± 0.02 cm has only one significant figure, and is the <u>length</u> that shows the confidence (accuracy) in the last digit of 124.36 cm.

On the other hand, the relative (percent) uncertainty is unitless and makes it possible to add errors of different types of quantities that might be present in a calculation. For example, without percent uncertainty, one can not add errors of length and time while calculating velocity.

(Note: uncertainty (error) in the result of a calculation is the result of accumulation of the uncertainties (errors) of the data that were used in the calculation. See “propagation of uncertainties” section for more details.)

Here are some guidelines regarding determination of uncertainty of a measurement:

1. For example, suppose you are measuring the length of some well-defined object with a metre stick. You judged that the length is somewhere between 25.5 and 25.6 centimetres. There is some uncertainty as to the "true" length. A guide is to record the measurement as the average of the two limits, 25.55 cm and to indicate the absolute uncertainty as one half of the smallest scale division, 0.5 mm or 0.05 cm. It would then be recorded as 25.55 ± 0.05 cm. (Four significant figures with an uncertainty of 5 in the last digit.)

2. The guideline above is sometimes too optimistic. The estimated uncertainty must not only take into consideration the measuring instrument but also the nature of the measurement. If the object measured has edges that are not sharply defined, then you may judge that the length is somewhere between 25.4 and 25.6 and, therefore, a reasonable recording of the length might be 25.5 ± 0.1 cm. (Three significant figures with an uncertainty of 1 in the last digit.)

3. If measurements can be repeated under identical conditions to confirm results or check for possible variations, you should do so. In cases like this, the average value will have an uncertainty estimated from the variation in results. For example, if multiple trials of a timed experiment show results varying between a minimum of 7.13 s and a maximum of 7.32 s, the average time would be recorded as 7.2 ± 0.1 s. Note that the absolute uncertainty of ±0.1 s is equal to half of the difference between the minimum and maximum values. Another experimenter, who has better eye-hand coordination, may find results between 7.18 s and 7.24 s, giving an average of 7.21 ± 0.03 s. This type of uncertainty is known as "random uncertainty."

4. Measurements that are taken off a digital display (e.g. on a digital measurement device such as a stopwatch or a voltmeter,) are treated based on the stability of the displayed figures. If the display shows a stable reading that does not fluctuate, a guide is to record the displayed measurement with an uncertainty of ±1 in the smallest digit. If, however the displayed figures fluctuate as measurement is taken, then the average value and its uncertainty will be determined as explained in previous paragraph.

5. When using scientific notation with uncertainties you should keep both the measured value and its uncertainty to the same power. For example, you may have a measurement (or calculation) that gives $4.72 \times 10^5 \pm 3 \times 10^3$ m. The preferred way to display this number is $(4.72 \pm 0.03) \times 10^5$ m.

It is impossible to establish fixed rules for estimating the size of an uncertainty in our lab. One can only generalize that the uncertainty must be reasonable, chosen so that it is large enough to ensure that the true value of the measured quantity lies within the interval indicated but, at the same time, small enough to reflect what you think is the accuracy of the actual measurement.

Significant Figures

The use of an appropriate number of significant figures (or significant digits) in recorded data is a way of indicating precision. The greater the precision of the measurement, the larger the number of significant figures one is justified in using. For example, in length measurements the value 25.55 has four significant figures whereas 25.5 has only three significant figures. In each of these values, the last digit reflects an estimation of the part of the experimenter. Generally, digits that are known with certainty, and the first estimated digit, are called significant figures.

The number of significant figures is not related to the location of the decimal point. Furthermore, zeros that are merely used to indicate the location of the decimal point are not significant. For example, 1706, 170.6, 17.06 and 0.001706 all have four significant figures.

When a value is expressed as 1540, it is not clear as to whether or not the zero is significant. Scientific notation can be used to make this clear. To clearly indicate that it (the ending zero) is significant, the value should be expressed as 1.540×10^3. Expressing it as 1.54×10^3 indicates that the zero was not significant.

When combining measured values by addition, subtraction, multiplication or division, attention must be paid to the number of digits involved. The following rule will assist.

Addition or Subtraction

The number of **decimal places** in the result should be the same as the quantity in the calculation that has the fewest number of decimal places.

a) $145.23 + 22.\underline{6} = 167.83$ (number out of calculator)

$= 167.\underline{8}$ (correct number of sig. figs.)

b) $145.\underline{23} - 22.\underline{63} = 122.6$ (number out of calculator)

$= 122.\underline{60}$ (correct number of sig. figs.)

Note: The above examples show that calculators rarely show the correct number of significant figures. **Beware!**

c) $3.4211 \times 10^3 + 4.2 \times 10^2 = (3.4211 + 0.42) \times 10^3 = 3.84 \times 10^3$

Multiplication or Division

The number of **significant figures** in the result should be the same as the quantity in the calculation that has the fewest number of significant figures.

a) $3.27 \times \underline{1.2}$ = 3.924

= $\underline{3.9}$

b) $476.6 / \underline{3.82}$ = 124.76

= $\underline{125}$

Multiplication or Division by a Constant

Constants are treated as having an unlimited precision, or an infinite number of significant figures.

a) $2\ (\Delta D) = 2 \times 3.33 = 6.66$

b) ½ (12.8) = 6.40

Exercise 1: Note: the 2 and the ½ are constants

Calculation	**Value (out of calculator)**	**Final answer to correct number of significant figures**
24.56 + 0.0912 =		
½ (37.45) =		
5.23×2.435678 =		
2 (a) (ΔD) = $2 \times 3.45 \times 5.678$ =		
$(9.8)^2$ =		
$(16.2 \times 25.6) / 3.2$ =		

Propagation of Uncertainties

You may have noticed that the preceding significant figure rules made no mention of uncertainties. So, why did you bother estimating the uncertainties in your measurements? For two reasons:

Firstly, thinking about uncertainty while making a measurement helps to eliminate mistakes in recording the correct number of significant figures. For example, if a measurement appears to coincide with a major division on the measuring instrument, the tendency is to forget to record significant zeroes because the measurement is "exact". 19.00±0.05cm is reasonable but 19±0.05cm shows a mismatch in the decimal places of the measurement and its uncertainty.

Secondly, significant figure rules are only an approximate method for determining the precision of a calculated result. Therefore, **the following uncertainty calculation rules take precedence in calculating precision and significant figure rules will be the fallback method.** Graph slopes are one example where significant figures will be used in place of uncertainties.

When the value of a quantity or final result must be calculated with its uncertainty based on the measured data, the uncertainty associated with this calculated quantity or result must be evaluated in terms of the uncertainties associated with the measured data. For example, if a velocity is determined by dividing a measured distance by a measured time interval, the velocity has an uncertainty that is calculated from the uncertainties in the measurement of the length and time.

The following rules with examples will assist you in the computing of uncertainties associated with calculated quantities in the lab.

Addition and Subtraction

The absolute uncertainty in the result is the sum of individual absolute uncertainties. The uncertainty is in the same units as the measured value.

$(10.5 \pm 0.1 \text{ cm}) + (6.1 \pm 0.2 \text{ cm}) = 16.6 \pm 0.3 \text{ cm}$

$(10.5 \pm 0.1 \text{ cm}) - (6.15 \pm 0.02 \text{ cm}) = 4.35 \pm 0.12 \text{ cm} = 4.4 \pm 0.1 \text{ cm}$

Multiplying or Dividing

The percent uncertainty in the result is the sum of the individual percent uncertainties.

$(4.5 \pm 0.2) \times (1.9 \pm 0.1) = (4.5 \pm 4.4\%) \times (1.9 \pm 5.3\%)$

$= 8.55 \pm 9.7\%$

$= 8.55 \pm 0.829$

$= 8.6 \pm 0.8$

Note*:* $\%\ \text{uncertainty} = \frac{\text{Absolute uncertainty}}{\text{Value}} \times 100\%$

Powers

The percent uncertainty in the n^{th} power is n times the original percent uncertainty:

$(5.3 \pm 0.2)^2 = (5.3 \pm 3.77\%)^2$

$= 28.09 \pm (2 \times 3.77\%)$

$= 28.09 \pm 7.54\% = 28.09 \pm 2.12$

$= 28 \pm 2$

Roots

The percent uncertainty in the n^{th} root is 1/n times the original percent uncertainty:

$\sqrt{25 \pm 5} = \sqrt{25 \pm 20\%}$

$= (25 \pm 20\%)^{\frac{1}{2}}$

$= 5 \pm \left(\frac{1}{2} \times 20\%\right)$

$= 5 \pm 10\%$

$= 5.0 \pm 0.5$

Multiplication by a Constant

The absolute uncertainty in the result is equal to the constant times the original absolute uncertainty. The percent uncertainty remains the same.

$3 \times (2.2 \pm 0.1) = 6.6 \pm 0.3$

$4 \times (5.2 \pm 5\%) = 20.8 \pm 5\% = 21 \pm 1$

Division by a Constant

The absolute uncertainty in the result is equal to the original absolute uncertainty divided by the constant. The percent uncertainty remains the same.

$(6.6 \pm 0.5) \div 3 = 2.2 \pm 0.167$

$= 2.2 \pm 0.2$

$(20.4 \pm 5\%) \div 4 = 5.1 \pm 5\%$

$= 5.1 \pm 0.255$

$= 5.1 \pm 0.3$

Exercise 2: Remember, the absolute uncertainty is written to only one significant figure. The value and uncertainty must have the same number of decimal places.

Calculation	**Value (out of calculator)**	**Final answer to correct number of figures.**
$(24.5 \pm 0.2) + (3.9 \pm 0.2) =$	$\pm$	$\pm$
$\frac{1}{2}(37.4 \pm 0.3) =$	$\pm$	$\pm$
$(5.23 \pm 0.03) \times (2.43568 \pm 0.00005) =$	$\pm$	$\pm$
$\sqrt{36 \pm 6} =$	$\pm$	$\pm$
$\dfrac{4.3 \pm 0.4}{8.6 \pm 0.6} =$	$\pm$	$\pm$
$(24.5 \pm 0.2) - (3.9 \pm 0.2) =$	$\pm$	$\pm$
$2\, a\, \Delta D = 2 \times (3.45 \pm 0.05) \times (5.6 \pm 0.2) =$	$\pm$	$\pm$
$(9.8 \pm 0.3)^2$	$\pm$	$\pm$

Comparing Values

Often you will want to compare your measured value to an expected value and judge whether they agree or not. One way to do this is to determine if the difference between the two values is possibly zero. We will cover three methods for doing this: one using uncertainty, one using significant figures, and one using a given percentage limit.

Absolute Discrepancy with Uncertainties

Let's see this by an example. If you have determined the acceleration due to gravity to be 9.3 ± 0.6 m/s^2 and the expected value is 9.81 m/s^2, then the difference between the two is 0.5 ± 0.6 m/s^2 after considering all the rules. As zero is a possibility in this range, the two values are in agreement. In other words, the expected result lies within the range of values associated with the experimental result, [8.7, 9.9] m/s^2.

Absolute Discrepancy with Significant Figures

If the uncertainty in the result has not been calculated, then we will assume the values are probably in agreement if the difference has one significant figure. Using this method, 9.3 m/s^2 probably agrees with 9.81 m/s^2, where their difference is 0.5 m/s^2 and has one significant figure. However, 9.69 m/s^2 probably does not agree with 9.81 m/s^2 because their difference, 0.12 m/s^2, has two significant figures.

Percentage Difference

Occasionally, you will perform an experiment without uncertainties and the significant figures are unknown or unreliable. This sometimes occurs when a computer program (a data acquisition software) is used and no precision estimate is given. In cases like this, when you are asked to compare two values to see if they agree, the lab manual may provide an uncertainty, usually as a percentage. You then calculate the percentage difference between the two values and compare it to the given uncertainty. The percentage difference calculation is shown below.

$$\%\text{ difference} = \frac{|a-b|}{\frac{(a+b)}{2}} \times 100\%$$

For example, if the experiment says assume 5% uncertainty and your calculated acceleration due to gravity is 9.5 m/s^2. Then the result agrees with the expected 9.81 m/s^2 because their percentage difference, 3%, is less than 5%.

Exercise 3: If the two values are 6.5 and 7.0, what is the percentage difference between them? Answer: __________

Do these numbers agree if the limits of experimental uncertainty are $\pm$ 5%? Answer:__________

Exercise 4: Find the percentage difference between the two values in each row, and decide if they agree within the limits of experimental uncertainty, or not.

Experimental Determined Values	Percentage Difference	Experimental limits	Same or different?
825 and 925		10%	
7.8 and 7.6		5%	
11 and 13		10%	
513 and 499		3%	

Average Values

Measurements are usually repeated several times, to confirm results or to check for possible variations. If several measurements are made under identical conditions, an average value can be found, and subsequent calculations can be done using the average value. The more measurements you make, the more reliable your average value will be. However, if conditions change in any way between the measurements, an average value will not be valid, and separate calculations must be done for each measured value.

Knowing when and where to use average values is something that comes with experience. The best guide is the test of identical conditions. If you are in doubt about whether or not to average, ask your instructor.

Graphing

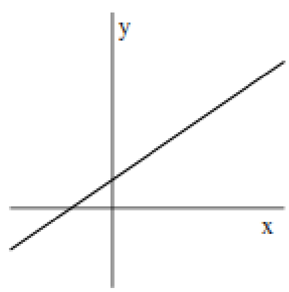
A graph is an effective way of displaying the measurements and the results of an experiment. It enables one to visualize the relationship between two quantities studied, for example, velocity and time. It also permits one to verify the mathematical relations that exist between two quantities. If the resulting "curve" is a straight line the relationship is linear, if the "curve" is a parabola then the relationship is a parabolic one, etc.

You will prepare your graphs on computer using either Excel or Google Sheets. The how-to instructions for these are given on the next few pages. **Hand-drawn graphs are not accepted.**

Curves and Straight Lines

The "curve" drawn through the points on a graph is always referred to as a "curve", even if it happens to be a straight line.

Linear Graphs



Linear: $y = mx + b$

If a graph of two generic quantities, y and x, exhibits a straight line, the algebraic equation relating the variables is often given as y = mx + b. The relationship is called "linear" or "directly proportional" and two pieces of information are necessary: the slope, m, and the y-intercept, b.

The y-intercept is the y-value at the intersection of the y-axis and the graphed line. Or, in other words, the y-value when the x-value is zero. It is easily read from the graph.

The slope of the line is the proportionality constant and is found by taking the rise (vertical change) over the run (horizontal change) or, in symbols, $\Delta y/\Delta x$. As such, it requires reading the location of two points on the line and calculating the ratio of the differences.

There are several important things to notice about the slope of a linear graph. No matter which two points on the graph are used to calculate Δx and Δy, the ratio of the two will be the same. In other words, the slope of a straight line is a constant and is a property of the line, not of where you are on the line. Also note that the slope value has units attached to it, determined from the units of your graph axes.

Determining the True Equation:

The generic mathematical equation for a straight line, $y = mx + b$, is easy to remember but it is just a starting point, as it is not often that the quantities being measured use the variables y and x. The “true” equation will have the same form but use non-generic variables.

For example, if a graph of velocity vs time shows a linear relationship, the slope is $\Delta v/\Delta t$, which is the definition of acceleration, a, and the y-intercept is the initial velocity, v_0.

Putting this information together results in the equation:

$$v = at + v_0$$

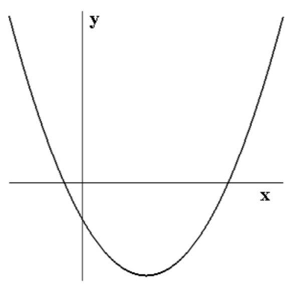
Note that sometimes you will have to identify linear equations with their terms in a different order. For example, the above equation is usually written:

$$v = v_0 + at$$

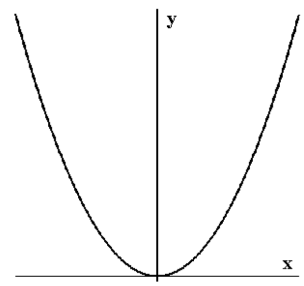
Which does not change the fact that a is the slope and v_0 is the y-intercept.

Non-Linear Graphs

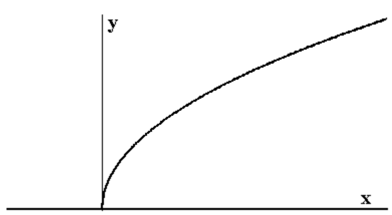
Data does not always fall conveniently along a straight line and you may see many types of non-linear graphs in this physics course. Here are some equations and their associated graphs.



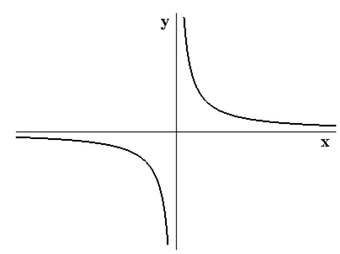
Quadratic: $y = ax^2 + bx + c$



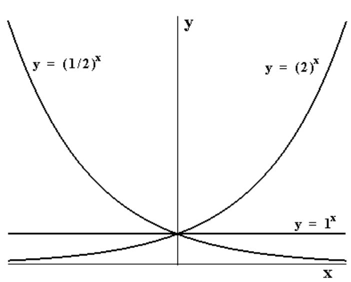
Parabolic: $y = ax^2$



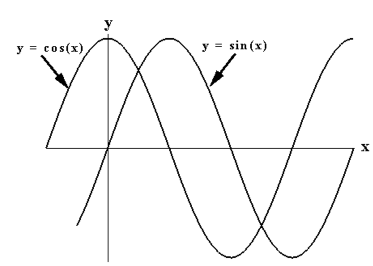
Square Root: $y = x^{1/2}$



Inverse: $y = {}^{1}/_{x}$



Exponential: $y = a^x$



Sine and Cosine: y = sin x and y = cos x

If theory leads us to expect a non-linear relationship or experiment results in a non-linear relationship, there are techniques we can use to plot the data in a linear form for easier analysis. For example, if after plotting *y* as a function of *x* the resulting graph looks parabolic, the x values can be squared and a new graph plotted with y as a function of x^2. If the relationship truly is parabolic, the new graph will be linear with a slope of *a*.

Properly Drawn Graphs

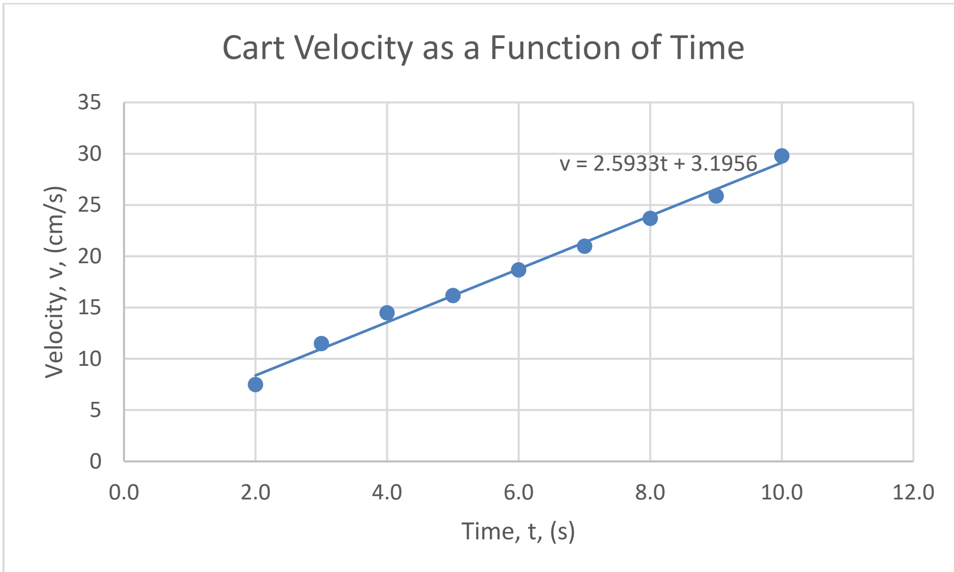
For Excel-drawn graphs:

A summary of the features of a properly drawn graph is given below and illustrated on the accompanying graph.

Note: The online version of *Excel* has limited functionality. Most importantly, it cannot create trendlines. If you use *Excel,* it should be the software-based version. If you want to use an online program, use *Google Sheets*.

1. Enter your data in two columns of a spreadsheet with the variable names in the first row as column headers. Excel will treat the column on the left as x (horizontal) and the column on the right as y (vertical), so plan accordingly.
2. Highlight the data cells (including the variable names) and insert a scatter chart.
3. Enable Axis Titles and Trendline in the Chart Elements. Note that the default trendline will not be the one you want. You will correct this in a later step.
4. Edit the title of your graph. As with hand-drawn graphs, the more descriptive the title is, the better. At a minimum, the title should tell, in words, what is being measured and include more than just the two variables. For example: Velocity of a Rolling Ball as a function of Time is much more helpful than v vs t.
5. Edit the axis titles to contain the full names of the quantities, their mathematical symbols, and their units.
6. Decide what type of relationship best represents the trend shown by your plotted points and, under more trend line options, have Excel draw the appropriate trend line and show its equation.
7. Edit the equation that appears on the chart to show the true variables, e.g.: $\underline{y} = 2.5933\underline{x} + 3.1956 \rightarrow \underline{v} = 2.5933\underline{t} + 3.1956$.
8. If you have several columns of data, e.g. for different trials of the same experiment, use different symbols for each data set or different colours if you have access to a colour printer.
9. If you are writing your report in Word, you can copy and paste the graph

into your Word document. Otherwise, first save your graph as an **image** file and then either insert it into your Word document, or upload it separately along with your PDF report file.



Excel Graph Expectations

For Google Sheets-drawn graphs:

A summary of the features of a properly drawn graph is given below and illustrated on the accompanying graph.

1. Start a new spreadsheet in Google Sheets and enter your data in two columns with the variable names in the first row as column headers. Google Sheets will treat the column on the left as x (horizontal) and the column on the right as y (vertical), so plan accordingly.

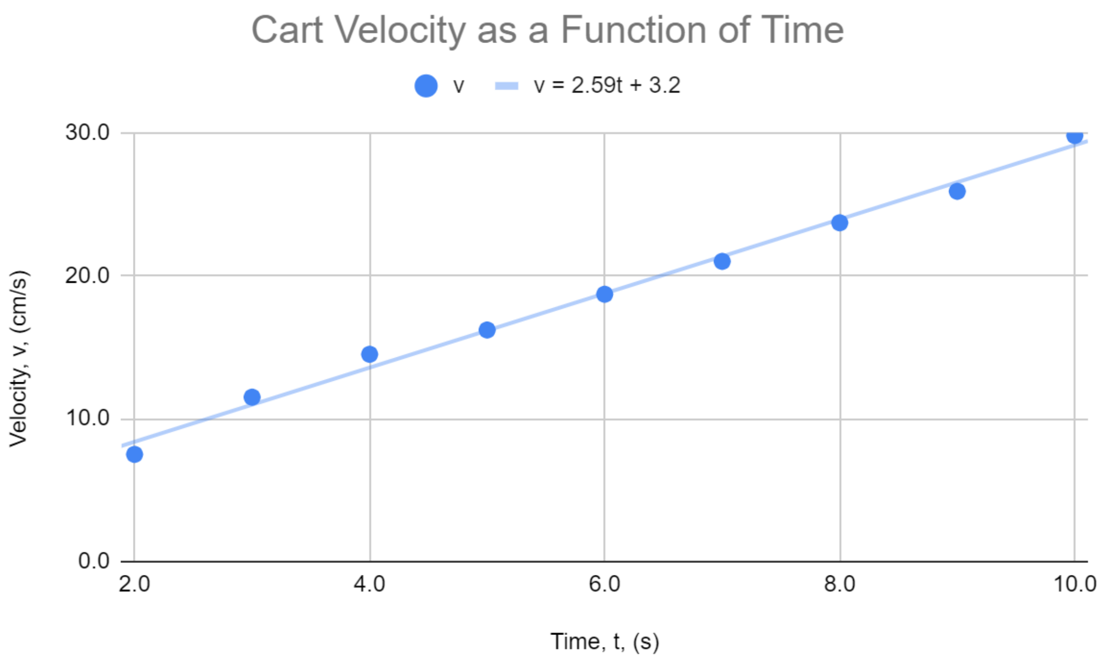
2. Highlight the data cells (including the variable names) and insert a chart. If Sheets does not default to a scatter chart, change the chart type.

3. Go to the Customise section of the Chart editor and edit the chart and axis titles of your graph. Sheets should also open the appropriate section automatically if you click on the chart item you want to edit. As with hand-drawn graphs, the more descriptive the title is, the better. At a minimum, the title should tell, in words, what is being measured and include more than just the two variables. For example: Velocity of a Rolling Ball as a function of Time is much more helpful than v vs t. The axis titles must contain the full names of the quantities, their mathematical symbols, and their units.

4. Decide what type of relationship best represents the trend shown by your plotted points and, in the Customise Series section of the Chart editor, activate the appropriate Trend line and show its equation with the Label option. The displayed equation is unlikely to have the "true" variables, so, make note of the calculated coefficients and intercepts and then change the Label to custom and type in the true equation as the Customised label, e.g.: $\underline{y} = 2.59\underline{x} + 3.2 \rightarrow \underline{v} = 2.59\underline{t} + 3.2$.

5. If you have several columns of data to be displayed on the same graph, e.g. for different trials of the same experiment, use different symbols for each data set or different colours if you have access to a colour printer.

6. If you are writing your report in Word, you can copy and paste the graph into your Word document. Otherwise, first save your graph as an **image** file and then either insert it into your Word document, or upload it separately along with your PDF report file.



Google Sheets Graph Expectations

Summary

As we have seen, a graph provides both a visual representation of your data and a means of deriving the algebraic relationship between variables or a numerical value of a physical quantity. Graphing techniques are very important in the lab portion of this course and you will have many opportunities to use them.

Section Two - Physics 1107 Experiments

Labs in the courses may occur in an order different from that presented in the lab manual. Always check your lab schedule

Graphing Straight Line Motion

Objective

The objective of this experiment is to examine a case of one-dimensional motion along an inclined plane. Specifically:

- to determine the relationships between position, velocity, and acceleration with time.
- to determine the type of motion (uniform velocity or uniform acceleration).
- to determine the mean (average) acceleration.

Introduction

This experiment uses a ramp and a low-friction glider. If you give the glider a gentle push up the ramp, it will move upward, slow down, stop, and then roll back down, speeding up as it goes back down the ramp. A graph of its velocity versus time would show these changes. Is there a mathematical pattern to the changes in velocity? What is the accompanying pattern to the position versus time graph? What would the acceleration versus time graph look like? Is the acceleration constant?

In this experiment, you will use the Vernier Motion Detector to collect position, velocity, and acceleration data for a glider moving up and down a ramp. Analysis of the graphs of this motion will answer these questions.

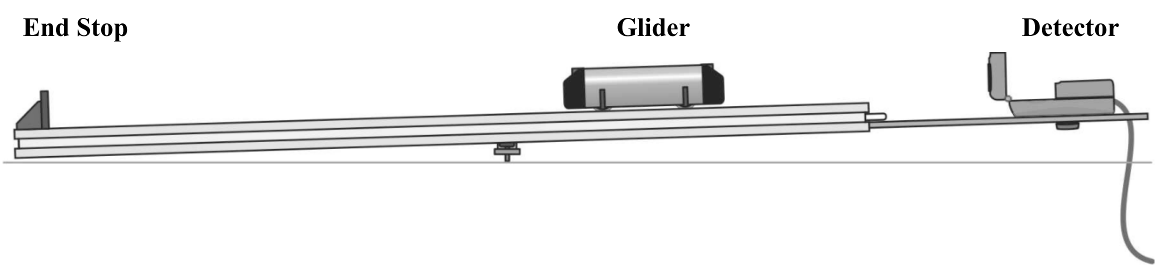


Figure 1

Apparatus

Linear Air track with a glider, blower unit, elevating block. Vernier Motion Detector, Vernier computer interface.

Procedure

1. Connect the Vernier Motion Detector to the computer interface. If the Motion Detector has a switch, set it to Track (Cart). 

2. Confirm that your ramp, glider and Motion Detector bracket are assembled as shown in Figure 1. Adjust the head of the detector so that it is pointing straight down the track.

3. If your motion detector is already connected to the computer, click on the Logger Lite icon on the desktop.

4. Place the glider on the track near the bottom end stop. Click ***Collect*** to begin data collection. You will notice a clicking sound from the Motion Detector. Wait about a second, then briefly push the glider up the ramp, letting it roll freely up nearly to the top, and then back down. Let the glider hit the bottom stop. Data collection will stop automatically.

5. Examine the position versus time graph. Repeat Step 4 if your position versus time graph does not show an area of smoothly changing position. Check with your instructor if you are not sure whether you need to repeat data collection.

Analysis

Note: **DO NOT** delete your graphs from the computer until the laboratory experiment is complete. You will need them for the second part of the lab.

Part 1. Finding the relationships and the type of motion

Print the three motion graphs. Use landscape mode to get large graphs.

To navigate between the graphs, click on the label of the vertical axis (either "position", "velocity", or "acceleration") to see the graphs menu. The graphs you have recorded are fairly complex and it is important to identify different regions of each graph. Notice that negative velocity is when it is moving towards the detector and positive velocity is when it is moving away from the detector. The zero point in position is set to be the initial position of the glider at the bottom of the track.

Note about readings from the graphs: No uncertainty in readings is required, however, you must record them with a reasonable number of significant figures that is consistent with the precision shown in the graphs.

Answer the following questions. Record your answers directly on the printed graphs.

a) Identify the region on the graphs, i.e. the time interval when the glider was being pushed by your hand.
   - Mark and label this region on all three graphs as **HAND**.
   - Record this time interval in seconds in a Table.
b) Identify the region on the graphs when the glider was moving freely up the ramp:
   - Mark and label this region on all three graphs as **FREE UP**.
   - Record this time interval in seconds in the same Table.
c) Identify the region on the graphs when the glider was moving freely down the ramp:
   - Mark and label this region on all three graphs as **FREE DOWN**.
   - Record this time interval in seconds in the same Table.
d) Determine the position, velocity, and acceleration at two specific points: when the glider had its maximum speed just as the glider was released, and when the glider was at the highest point on the ramp.
   - Mark and label both of these spots on all three graphs. Use the notation **V-MAX** for maximum speed and **P-MAX** for highest position.
   - Record your answers in Table 2.

Part 2. Determining acceleration

The motion of an object in constant acceleration motion is modeled by

$$\Delta x = v_0 t + \tfrac{1}{2} a t^2$$

where *x* is the position, v_0 is the initial velocity, *t* is time, and *a* is the acceleration. The velocity of the object changes according to

$$v = v_0 + at$$

which is a linear function of time with the acceleration being the slope of the graph and the initial velocity being the y – intercept.

a) Open the velocity versus time graph. To fit a line to this data, click and drag the mouse across the free moving region of the motion. From the “Analyze” menu choose “Linear Fit” button. Record the equation of the line generated by the Logger Lite. Also record the values for the slope and the y-intercept and state what each one represents.

b) Open the acceleration versus time graph. The graph of acceleration versus time should appear to be more or less constant during the freely moving portion.

Click and drag the mouse across the free-moving portion of the motion. From the "Analyze" menu choose "Statistics". Record the data for the mean (average) acceleration during this.

c) The above two steps provide two results for the acceleration of the glider. How closely do the two values of acceleration compare? Calculate the percent difference.

Discussion

Based on your three graphs during the FREE UP and FREE DOWN time intervals, determine the type of motion (uniform velocity or uniform acceleration). Explain.

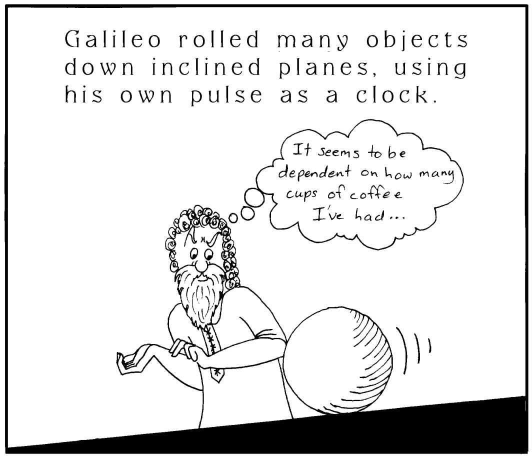
Do the two methods of determining the acceleration agree within the limits of experimental uncertainty? The limits of experimental uncertainty for this lab are + 5%. (This number is based on manufacture's specifications.) If they don't agree, explain what could be the reason.

Discuss the possible reasons why your graphs do not exactly satisfy the constant acceleration case for straight line motion.

Conclusion

Refer to the objective.

Accelerated Motion



Objective

The aim of this experiment is to examine a case of one-dimensional motion (a glider moving along an inclined plane)

- to determine if the data indicates constant acceleration,
- to determine the value of the acceleration,
- to determine whether or not the acceleration is mass dependent

Introduction

You will be repeating an experiment first performed by Galileo Galilei in 1608. This famous Italian scientist was the first to accurately describe motion in a straight line.

The motion of an object travelling in a straight line can be described by the following set of equations:

$$v_{av} = \frac{\Delta x}{t} \tag{1}$$

$$v = \frac{\Delta x}{\Delta t} \qquad as\ \Delta t\ approaches\ zero \tag{2}$$

$$a_{av} = \frac{\Delta v}{\Delta t} = \frac{v - v_o}{t - t_o} \tag{3}$$

The motion of an object travelling in a straight line at **constant** acceleration can be described by the following set of equations:

$$\Delta x = v_{av} t \tag{4}$$

$$v_{av} = \frac{v_o + v}{2} \tag{5}$$

$$v = v_o + at \tag{6}$$

$$v^2 = v_o^2 + 2a\Delta x \tag{7}$$

$$\Delta x = v_o t + \frac{1}{2} a t^2 \tag{8}$$

where Δx is the displacement of the object, v is the instantaneous velocity at time, t, v_0 is the initial velocity, and a is the acceleration of the object. (NOTE: We have assumed that t_i = 0, so t is the total time of travel.)

It can also be shown that for constant acceleration motion $v_{av} = \frac{1}{2} at$. This means it is expected that the average velocity, v_{av}, in constant acceleration motion to be a linear function of the time of travel, t. You will use this idea to determine if the glider's motion on an inclined air track is constant acceleration motion.

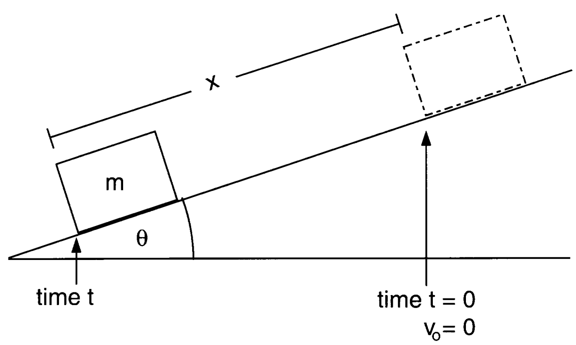


Figure 1: Object moving down inclined plane

In this experiment, a mass, m, will be released from rest on an inclined plane as in Figure 1 and will accelerate down the incline.

If the friction experienced by the object is negligibly small, then the acceleration is due solely to the component of the object's weight along the incline and depends only on the angle of inclination.

The apparatus used in this experiment consists of an air track (see Figure 2), glider, and timer. During operation, air is blown into the interior of the track from the exhaust of a blower unit; the air emerges from the numerous small holes on the sides of the track and buoys the glider upward from the surface of the track; the glider is, therefore, able to move on a cushion of air and experiences little friction as it moves.

The track will be inclined at a specified angle and the time taken for the glider to undergo various displacements along the track will be measured. The data will be analyzed to investigate the degree to which uniform acceleration has occurred.

Apparatus

Linear air track, blower unit, timer, glider, elevating block.

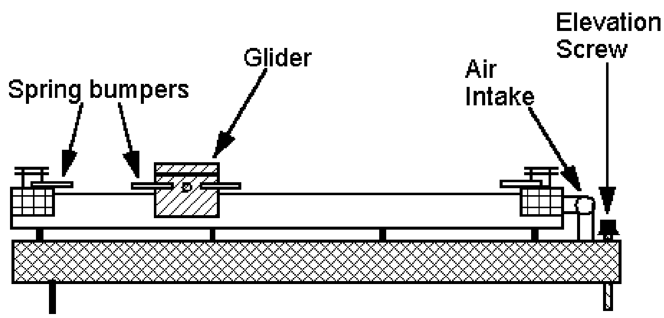


Figure 2: Linear Air Track

Procedure

1. Level the track such that the glider either remains stationary at the mid-point or moves slowly back and forth a short distance about this point.

   Note: Once the track has been levelled, avoid leaning on the table, and do not change the position of the track on the table

2. Incline the track by placing an elevating block under the foot of the elevation screw. (see figure 2)

3. Draw (sketch) a labelled diagram of the setup.

4. Measure and record the time of travel for 7 different displacements with the shortest being 15 cm and the longest being the maximum length possible on the track:

   a. Place the glider at the top of the incline and release it when you are ready for timing. Perform 2 trials for each displacement, and clearly record your data in a table.

b. Record the displacement values with uncertainty. Show a sample calculation for one of your displacements based on the carts initial and final positions.

c. Record the timing values as they are shown on the stopwatch, without uncertainty. You will determine the uncertainties of the timings in a later step.

5. Do you think the acceleration of the glider is mass dependent? In other words, do you think that gliders with different masses would have different travel times for the same displacement? Examine your prediction by repeating the timing for the longest displacement, but with a mass of 40 grams added to the glider. Perform 2 trials and record the results.

Analysis (you must include one sample calculation for each type of calculation.)

1. For each displacement, calculate and record the average travel time and its uncertainty.
2. For each displacement, calculate and record the average velocity and its uncertainty.
3. Drive the equation $v_{av} = \frac{1}{2}at$ from the given formulas in the introduction section. This equation reveals the relationship between v_{av} and time, t.
4. Plot a graph of average velocity versus average time.
   a. Include point (0 s, 0 cm/s) as one of the data points on your plot. This point corresponds to when and where the cart starts its motion.
   b. Before going further, examine if the trend in data-points plotted on your graph appears to match the expected relationship between average velocity and time? You should make comments about this in discussion section.
   c. Use Excel (or any other computer plotting program that you used) to fit the correct mathematical relationship to your data. Include the equation of the best fit line on your graph.
5. Using your fit in Step 4.c, determine the acceleration of the glider. This is your experimental result for the acceleration. Show your reasoning.

Discussions

1. Based on your graph, describe how the average velocity of the glider varies with time. Is this what you expected? Why?
2. Based on your results, was the acceleration of the glider mass dependent? Discuss your reasoning.
3. Comment on the major sources of error.

Conclusions

For information on how to write a conclusion refer back to the section of the lab manual on writing reports (page 10).

Projectile Motion

Objective

The objectives of this experiment are to investigate the motion of a projectile:

a. to determine the type of motion it undergoes,

b. to determine the initial velocity of a projectile, and

c. to use the theory of projectile motion in a practical application.

Theory

Projectiles have been objects of intense study throughout history primarily because of military concerns. People wanted to be able to throw things (rocks, spears, etc.) as far as possible while still being accurate.

In his *Dialogue Concerning Two New Sciences*. Galileo Galilei was the first person to provide an accurate description of projectile motion: A projectile follows a parabolic arc during its flight. This occurs because the accelerations in the horizontal and vertical directions are different.

Although the projectile is moving in two directions at once, the time of flight is common to both. Therefore, the time of flight for a horizontal launch, calculated from an analysis of the vertical direction, can be used to find the initial velocity in the horizontal direction.

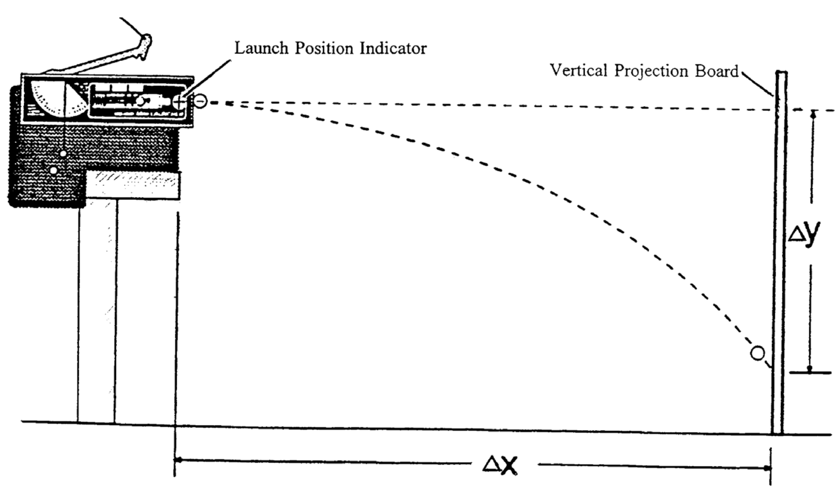


Figure 1

Vertical Motion

The projectile will undergo a vertical displacement, Δy (see figure 1), during the time of flight, t, and if we launch the projectile horizontally there will be no initial velocity in the vertical direction. Ignoring air resistance, the acceleration will only be due to gravity, g, and the one-dimensional uniformly accelerated motion equation, $\Delta y = v_{0y}t + \frac{1}{2}a_y t^2$, can be simplified to:

$$\Delta y = \tfrac{1}{2}\mathrm{g}t^2$$

Rearranging for the time of flight gives the expression:

$$t = \sqrt{\frac{2\Delta y}{g}}$$

Horizontal Motion

The horizontal displacement undergone during this time is called the range of the projectile, Δx. (again see figure 1) If we again ignore air resistance, there is no acceleration in the horizontal direction and the one-dimensional uniformly accelerated motion equation, $\Delta x = v_{0x}t + \frac{1}{2}a_x t^2$, can be simplified to:

$$\Delta x = v_{0x}t$$

Projection at an Angle

But not all projectiles have an initial velocity that is horizontal. If the ball is launched at an angle, θ, above the horizontal, then the time of flight obtained from the vertical motion is given by the sum of the time going up and the time going down, which, assuming the initial velocity is the same as for the horizontal launch, can be shown to be

$$t = \frac{v_o \sin\theta}{g} + \sqrt{\frac{(v_o \sin\theta)^2}{g^2} + \frac{2\Delta y}{g}}$$

where $v_0 \sin\theta$ is the vertical component of the initial velocity. (Note: enter absolute values for Δy and g in the above equation.)

The predicted range for the angled launch would then be

$$\Delta x = (v_o \cos\theta)\, t$$

where $v_0 \cos\theta$ is the horizontal component of the initial velocity.

Apparatus

Pasco Mini-launcher, push rod, steel ball, C-clamp, plumb-bob, vertical projection board, carbon paper, long strip of plain paper, 2 metre sticks, tape, safety goggles.

Note: The projectile (steel ball) emerges from the launcher at a hazardous velocity. DO NOT look into the barrel ("loaded" or "unloaded"), and DO NOT position yourself in the path of the projectile. Eye protection must be worn at all times.

Procedure

Part A: Path of a Horizontally Launched Projectile.

1. Clamp the Mini-launcher to the table so that the launch position is beyond the edge of the table.
2. Set the launcher to launch horizontally and tape a plain paper strip to the front of the vertical projection board.
3. With a moveable piece of carbon paper covering the paper at the height of the launcher, load the launcher till it “clicks” **once**.
4. Place the vertical projection board against the end of the launcher and pull the trigger. The mark left by the projectile is your y = 0 or launch point.
5. Locate the projection board so that the vertical surface is 20 cm from the launch position. Note: there is a diagram on the side of the launcher showing the projectile at launch position and it is the front edge of the projectile that hits the board.
6. Reload and launch the projectile at least twice.
7. Repeat with the board located 40, 60, 80 and 100 cm from the launcher to obtain coordinates for the points along the trajectory.
8. For each horizontal displacement note the mean point of impact (centre of the cluster of spots) of the ball on the paper, then measure and record the vertical displacement between this point and the launch point. Determine the uncertainty of the vertical displacements from the vertical spread in the points of impact.
9. Plot the trajectory of the projectile by graphing its vertical displacements versus the corresponding horizontal displacements. In addition to those measured points, include the initial displacement (launch point) to give a better representation of the trajectory of the projectile.

Discussion

Based on your results (graph), how do you describe the motion of the projectile in two dimensions, i.e. what is its type of motion? How do you know this? (You must refer to your results for reasoning.)

Would your graph look different if you used an object with a different mass? Why or why not?

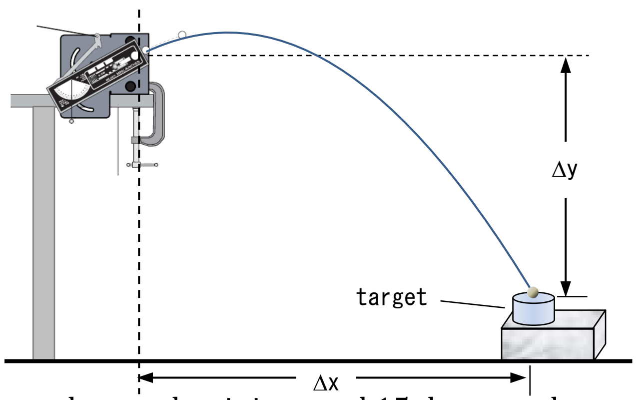
Part B: Determination of the Projectile's Initial speed.

In this part you will determine an experimental value for the initial speed of the projectile when it is launched.

Use the theory of projectile motion and the measurements of Δy and Δx that you made when the target board was located at 100 cm distance in the previous part, to calculate the time of flight and the initial speed of the projectile. Record this work clearly in your report.

Part C: Practical Application of Projectile Motion

In this part you will determine the horizontal position at which you must place the target provided by your lab instructor, so that the projectile hits the target after being launched.



1. Adjust the launcher so that it is aimed 15 degrees above the horizontal. Record this angle in your report.
2. Using your knowledge of the theory of projectile motion, the average initial speed determined in the previous part, and relevant measurements†, calculate the horizontal position you would like the target to be placed at. (No uncertainties required in this part's calculations; however, you must follow the significant rules in calculations.)

   († - You decide what to measure! Note: you must clearly state and record what you measured.)

3. Set up the target at the location that you calculated (predicted). **While your lab instructor is present** launch the projectile.

Discussion

Was your application of the theory successful? If not, discuss what seems to be the reason.

Discuss major sources of error.

Conclusions

Static Equilibrium

Objective

The objective of this experiment is to verify the first and second conditions for static equilibrium.

Theory and Introduction

Static means not moving. Therefore, an object in static equilibrium does not move or change.

If an object does not move, then it has a constant velocity of zero and its acceleration must also be zero. If the acceleration is zero, then according to Newton's Second Law, the net force must also be zero. Thus, the first condition of static equilibrium is that the net force on the object is zero.

A similar argument can be made for rotational motion. If the object does not rotate, then the net torque on the object must be zero. This is the second condition for static equilibrium.

Part 1: First Condition

In situations where all the forces on an object can be considered to be acting through one point, the forces are called concurrent. In this case, only the first condition needs to be satisfied because concurrent forces cannot cause a body to rotate.

One such situation is shown here. The forces act along a line.

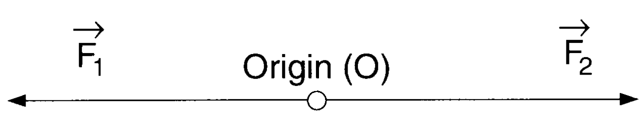


Figure 1: Two Concurrent Forces

For static equilibrium in Figure 1 we must have the following vector equation:

$$\vec{F}_1 + \vec{F}_2 = 0$$

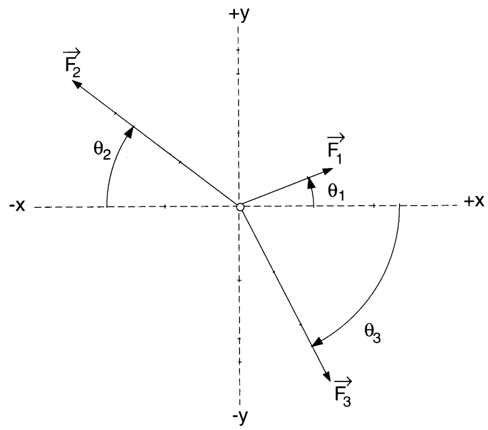


Figure 2: Three Concurrent Forces **(Angles measured relative to the nearest x axis)**

Another example is shown in Figure 2. Using a two-dimensional x - y grid, we have chosen the origin of the coordinate system to be the point where the forces are concurrent. The directions of the forces were then indicated relative to the **nearest** x direction, so that each angle to be used is less than 90°. Thus, the force and its two components form a right triangle with the force as the hypotenuse. Trigonometry can then be used to calculate the magnitude of the components. The signs of the components depend upon whether they point in the positive or negative direction of an axis.

To satisfy the first condition for equilibrium, the forces must sum to zero:

$$\sum F = F_1 + F_2 + F_3 = 0$$

And therefore, the components must also sum to zero:

$$\sum F_x = F_1 \cos\theta_1 - F_2 \cos\theta_2 + F_3 \cos\theta_3 = 0$$

$$\sum F_y = F_1 \sin\theta_1 + F_2 \sin\theta_2 - F_3 \sin\theta_3 = 0$$

Note that the x component of F_2 and the y component of F_3 are negative because F_2 and F_3 point in the negative x and y directions, respectively.

Alternately, the directions can be specified relative to the positive x-direction, as in Figure 3.

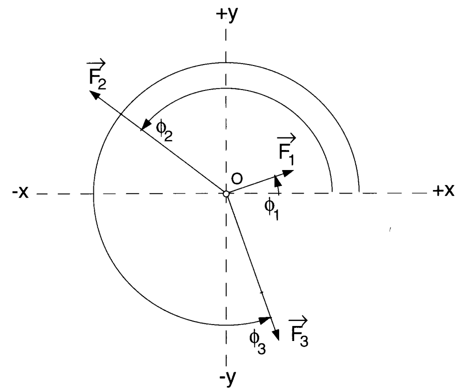


Figure 3: Three Concurrent Forces **(Angles measured relative to the +x axis)**

Then the signs of the components will be determined by the signs of the sine and cosine of the angle.

$$\sum F_x = F_1 \cos\phi_1 + F_2 \cos\phi_2 + F_3 \cos\phi_3 = 0$$

$$\sum F_y = F_1 \sin\phi_1 + F_2 \sin\phi_2 + F_3 \sin\phi_3 = 0$$

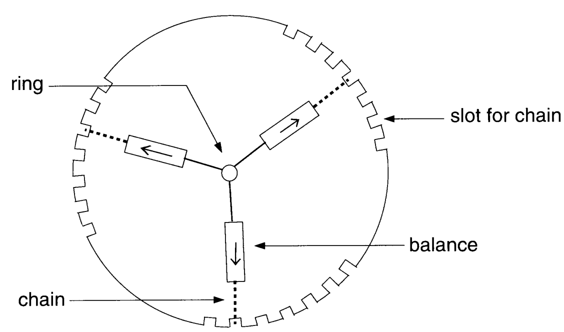


Figure 4: Force Board

The apparatus used in this experiment consists of a circular force board on which are arranged a metal ring and three spring balances calibrated in Newton's, the SI (metric) unit of force. The ring is the object on which the forces are acting and these forces are the tensions in the spring balances.

The magnitude of the force exerted by a spring balance on the ring can be varied by adjusting the length of chain between a fastening slot and the balance. The direction can be varied by changing the slot, and can be measured relative to a convenient axis by means of a protractor.

Apparatus

Force board, 3 spring balances attached to a ring, paper, ruler, and protractor

Procedure

Note: each lab partner will do this separately with different tension and the location of the balances

1. Place a piece of paper on the force board and arrange the three balances over it in a manner similar to that in Figure 4.

   Note: *Make sure that each balance has a value greater than 5.0 Newtons but less than 20.0 Newtons in each arrangement used.*

2. Record the force readings on all three balances and write the values on the paper beside the balances.

3. Record the directions of the forces by drawing with a sharp pencil along the edges of the balances. For convenience, add arrowheads to show the directions of the balances on the paper.

4. Remove the paper from the board. Extend the lines on the paper until they cross. They will not come to the same point because you traced along the edge of the balance, which is parallel to the actual force.

5. Draw an x axis on the paper and measure the directions of the forces relative to it. All angles are measured relative to an x-axis, either the nearest x-axis or the positive x-axis. It does not matter which one you choose, just be consistent. (See Figures 2 and 3 as examples.) You do not need to draw a y axis since you will not be measuring any angles relative to it. Record these angles and sketch your three forces on the x-y axes shown on the report sheet making sure to label each force and angle.

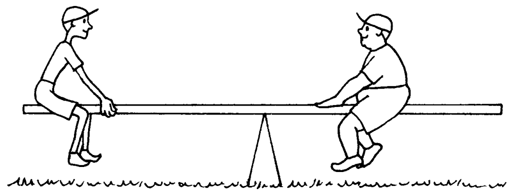
6. Using the angle made by each balance with the x axis, calculate and tabulate the x-components of the tensions, including their signs. Round the components to the nearest tenth of a Newton. For example, 1.2 or 0.8, not 0.95 N. Repeat this for the y-components.

7. Add the x and y components separately.

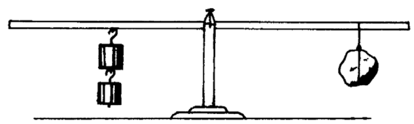
Discussion

Discuss your evidence pertaining to the first condition of static equilibrium and what you believe the most significant source of uncertainty in your lab is.

Part 2: Second Condition



A see-saw or teeter-totter is a simple mechanical device that rotates about a pivot. It is a type of lever.



Laboratories do not normally have see-saws. However, we do have some meter sticks, knife-edge clamps, and masses that will be used to discover how levers work.

A torque is caused by a force, *F*, being applied some distance, *l*, away from the pivot point, fulcrum, or axis of rotation. If the torque is unbalanced (net torque not zero), the body will rotate. Therefore, a body in static equilibrium must have a net torque of zero acting on it.

$$\begin{aligned}\sum \tau &= \tau_1 + \tau_2 \\ &= F_1 l_1 + F_2 l_2 = 0\end{aligned}$$

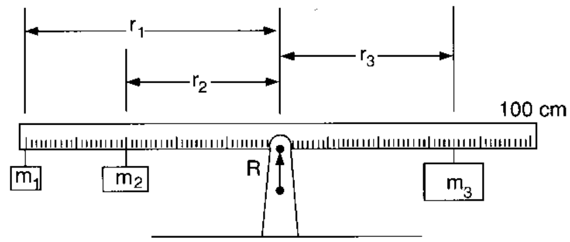
Rather than assign positive and negative signs to the torques, we can say that the torques in the clockwise direction must balance the torques in the counter clockwise direction.

$$F_1 l_1 = F_2 l_2$$

Apparatus

Meter stick, knife-edge lever clamp, balance point (fulcrum), 3 mass hangers (3 loops of string), hooked masses

Procedure



Note: As in the previous part each lab partner should do this separately with different mass positions on the balance. Try to make each of yours significantly different, don't just move all the masses a few cm.

1. Carefully balance a meter stick horizontally on a knife edge holder. Record the position of the fulcrum.

2. Hang four loops of thread from the meter stick ensuring there is at least one loop on each side of the fulcrum. You will suspend the masses from these "low-mass" hangers.

   Note: we are using one more mass than the figure above shows.

3. Hang (suspend) four masses of at least 50g each on each of the 4 low-mass hangers. Adjust the position of the masses until you find a position where they balance the metre stick. Let the apparatus settle. Nothing should be moving. Record the mass value and position of each mass on the meter stick.

Calculations

1. Calculate the distance from the fulcrum to each mass (the leaver arm)

2. Calculate the torque due to the force of gravity (weight) of each mass.

3. Calculate the total torque on the right and left side of the fulcrum.

Discussion

Discuss your evidence pertaining to the second condition of static equilibrium and what you believe the most significant source of uncertainty in your lab is.

Conclusion

Friction

Objective

The object of this experiment is to investigate friction between two plane surfaces in contact and, from the observations made, to determine the coefficients of static and kinetic friction between the surfaces.

Introduction

Whenever one solid object moves or tries to move along the surface of another solid object, each exerts a force of friction on the other. The friction is parallel to the surface which exerts it and opposite in direction to the motion or intended motion.

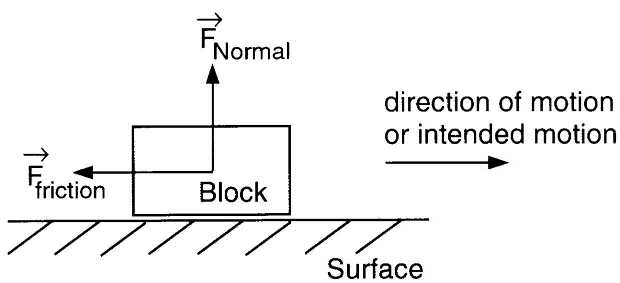


Figure 1

Figure 1 shows a block in contact with a surface. If the block moves along or tries to move along the surface, then the surface exerts two forces on the block: the normal force, $\vec{F}_N$, which is always perpendicular to the surface, and the friction force, $\vec{f}$, which is parallel to the surface. If the block is not moving but experiences a force (not shown in the diagram) which is directed to the right and which is not large enough to cause the block to move, then the friction force exerted by the surface to oppose this force is called the static friction force, $\vec{f}_s$. Obviously, static friction is a variable quantity since the friction increases so as to keep the block stationary when the applied force is increased. However, there is a maximum force of static friction, f_s^{max}, beyond which the block will start to slide. Once the block starts to move, the friction force, for most surfaces, rapidly decreases to a constant value known as the kinetic friction force, $\vec{f}_k$.

In general, the maximum static friction force and the kinetic friction force are proportional to the normal force for a wide range of values:

$$f_s^{\max} = \mu_s \; F_N$$

$$f_k = \mu_k \; F_N$$

μ_s and μ_k (the proportionality constants) are the coefficients of static and kinetic friction respectively and depend only upon the nature and condition of the surfaces in contact.

In this experiment the coefficients will be determined for an arborite glider on a wooden surface using two different methods, during which the glider is in mechanical equilibrium.

Critical Angle Method for μ_s

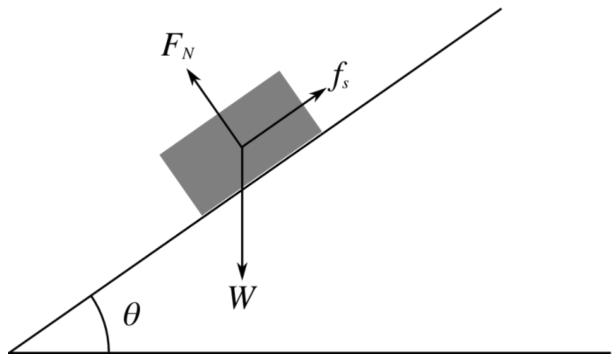


Figure 2

Figure 2 shows a block of weight W, resting on an inclined surface and experiencing the forces indicated. If the angle of inclination, θ, is increased from zero, the glider will just start to move down the surface when θ exceeds a critical value, θ_c. Using Newton's first law to solve the free-body diagram for the situation where the glider is just about to move will give the relationship to find the coefficient of static friction.

Constant Velocity Method for μ_k

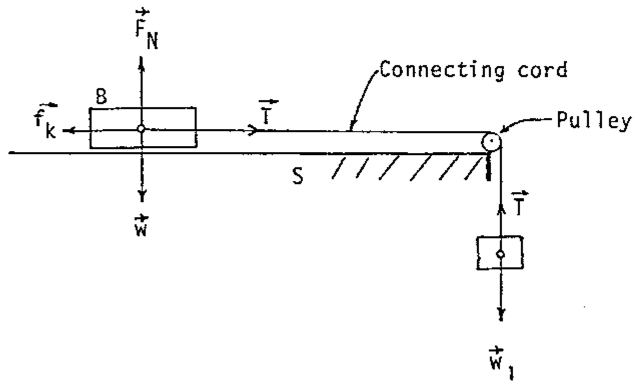
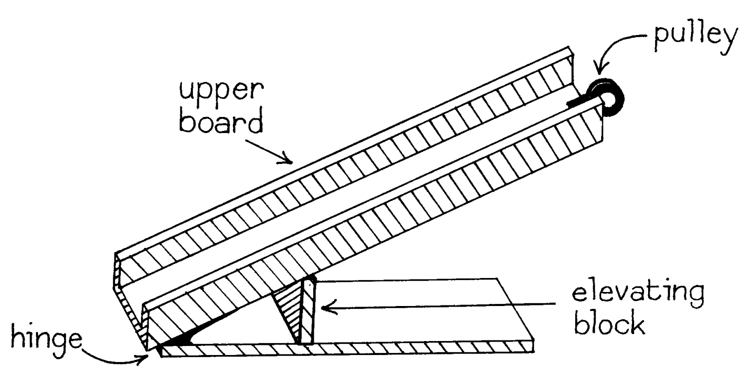


Figure 3

If the value of the hanging weight in Figure 3, w_1, is adjusted until the block slides along the horizontal surface at constant speed, Newton's first law and the free-body diagrams for the glider and suspended mass will yield a set of equations to find the coefficient of kinetic friction between the glider and the surface.

Apparatus

Friction board apparatus, arborite glider, protractor, set of slotted masses, mass hanger, pulley, drive cord, elevating block, triple-beam balance.



Procedure - Static Friction

1. Determine the coefficient of static friction for the arborite glider and wooden surface combination using the critical angle method as follows:

a. Place the glider on the **initially horizontal** upper board of the apparatus about one third the way along the board.

b. Place the elevating block on edge between the two boards at the end opposite the hinge joining the boards.

c. By gently sliding the block toward the hinge, increase the angle of inclination of the upper board until the glider just starts to move on its own. **Avoid jarring the table or the board during a trial.**

d. Identify the angle at which motion was just about to begin.

2. Repeat step 1 at least once and calculate an average value of the critical angle and then a value for the coefficient of static friction.
3. Repeat steps 1 and 2 with first a 100 gram slotted mass and then a 200 gram slotted mass added to the glider to check for a mass dependence.

Procedure - Kinetic Friction

Determine the coefficient of kinetic friction using the horizontal plane as follows:

1. Measure the mass of the glider.
2. Measure the mass of the hanger.
3. Add 200 grams to the glider and place it on the board.
4. Attach the pulley to the end of the board.
5. Attach the ends of the cord to the glider and mass hanger and then suspend the hanger over the pulley.
6. Add masses to the hanger until the glider appears to slide along the board at a **constant speed after being started with a push**. Determine **the range of mass** which appears to produce a constant speed for uncertainty purposes.
7. Calculate the average value of the added mass and its uncertainty.
8. Calculate the total glider mass and the total suspended mass and their uncertainties.
9. Calculate the forces of kinetic friction and normal force experienced by the glider. Show your work.
(You do not need to include uncertainty on the above calculations, but you should carry significant figures correctly through all your calculations.)

10. Repeat the above steps five times, successively increasing the mass added to the glider by 100 grams.
11. Plot a graph of friction force versus normal force and find the coefficient of kinetic friction from the slope of the resulting line.

Discussion

1. Do your results show a mass dependence for the coefficient of static friction? Explain
2. Do your results show a mass dependence for the coefficient of kinetic friction? Explain
3. Comment on major sources of error in each part.

Conclusion

Refer to the objective.

Orbital Motion and Centripetal Force

Objective

The objective of this experiment is to determine, from kinematic quantities, the centripetal force acting upon a body executing uniform circular motion.

Introduction

A body traveling in a circle at constant speed is accelerating and, therefore, according to Newton's First Law, there must be a resultant force. The resultant can be shown to be directed toward the centre of the motion at every point along the path and is termed the centripetal force, F_r.

Kinematics

The circular motion of an object in orbit about some axis can be described kinematically in terms of distance travelled, arc length S in Figure 1, tangential velocity, $\vec{v}_t$, and acceleration of the centre of mass of the object, $\vec{a}$. In general, the acceleration of the centre of mass at any point in the motion can be treated in terms of two vector components: the tangential acceleration, $\vec{a}_t$, which is associated with a change in the magnitude of the velocity and the centripetal acceleration, $\vec{a}_r$, which is associated with a change in the direction of the velocity.

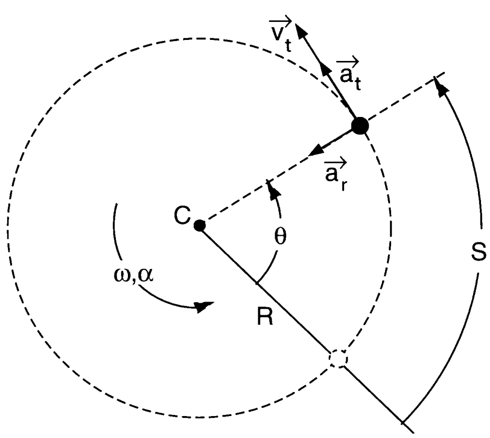


Figure 1

If the object executes uniform circular motion (motion at constant speed), then it can be shown that:

$$S = 2\pi Rn$$
$$v_t = \frac{S}{t}$$
$$a_t = 0$$
$$a_r = \frac{(v_t)^2}{R}$$

Where n is the number of revolutions, t is the time over which the revolutions take place, and R is the radius of the orbit.

Centripetal Force

The orbiting object in the experiment is a bob suspended from one end of a horizontal bar supported at the top of a vertical shaft (see Figure 2). The bob is also attached to the shaft by means of a coiled spring. Also located on the apparatus mounting board are a vertical reference indicator for radius measurements and a pulley by means of which masses can be attached to the bob. The bob is made to execute uniform circular motion by suitable rotation of the shaft by hand.

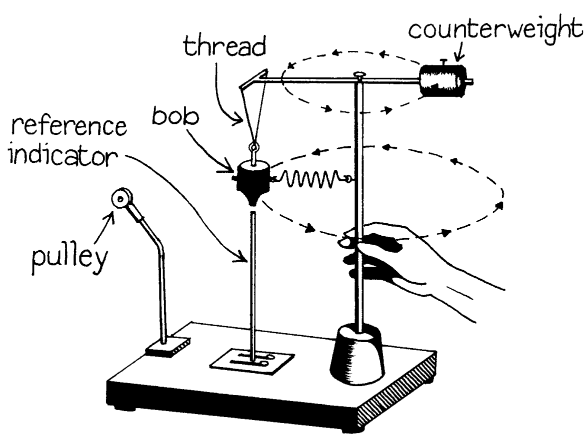


Figure 2

When the vertical shaft of the apparatus (Figure 2) is rotated, the bob will move outward away from it and the spring will be stretched. The tendency of the rotating bob to swing outward is opposed by the restoring force of the spring. When the constant speed of rotation is such that the bob is vertically below the point of suspension and the spring is horizontal, the restoring force of the spring will be directed toward the centre of the motion at every point along the circular path and, therefore, will constitute the resultant/centripetal force acting on the bob.

The centripetal force experienced by the bob can be found using Newton's Second Law:

$$F_r = ma_r$$

where m is the mass of the bob.

The magnitude of the centripetal force experienced during the rotation can also be determined, indirectly, by attaching masses, m_s, to the stationary bob by means of the pulley (See Figure 3).

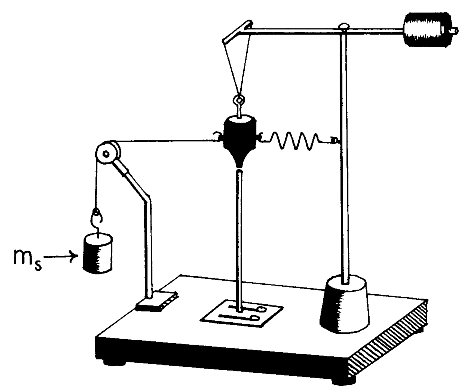


Figure 3

When the weight, F_s, of the masses so attached causes the spring to stretch to the same length as was caused by the rotating bob, then the value of this weight will be equal in magnitude to the centripetal force which was acting on the bob during rotation.

Apparatus

Hand-operated centripetal force apparatus, timer, ruler, set of masses, cord, triple-beam balance.

Procedure

1) Measure the mass of the bob.

2) Assemble the apparatus as in Figure 2, ensuring that the screws at the top of the vertical shaft and on the counterweight tighten against the flat portions of the horizontal bar. Position the reference indicator somewhere between the minimum and maximum radius of rotation, and with the spring detached from the bob, adjust the position of the horizontal bar and the length of the suspending thread such that, when the bob is hanging freely, the blunted point located on the bottom is situated exactly above the reference indicator and just clears it.

3) With the spring attached again to the bob, rotate the shaft (using your thumb and forefinger) at a constant speed and such that the point on the bottom of the bob passes directly over the reference indicator with the **spring horizontal** and the **thread vertical**. Time 20 revolutions while maintaining this speed.

4) Repeat step 3 once and calculate an average value for the time.

5) Calculate and tabulate values of the arc length traveled by the bob, the tangential speed of bob, the centripetal acceleration of the bob, and the centripetal force acting on the bob during rotation. Show these calculations and record the results in table 2.

6) Check your value obtained for the centripetal force by using the arrangement shown in Figure 3. (Assume ‘g’ at the location of the laboratory to be 9.81 m/s^2).

Discussion

Do your measured stretching forces verify your calculated centripetal forces?

Conclusions

Refer to the objective.

Conservation of Linear Momentum

Objective

The objective of this experiment is to study one-dimensional collisions on an air track to determine whether the linear momentum of the system is conserved during slightly less than ideal conditions and to determine the elasticity of a collision.

Introduction

When two objects collide, one of three possible types of collision will occur:

1. elastic – where the objects separate after the event and the kinetic energy of the system is conserved during the event
2. inelastic – where again the objects separate after the event but the kinetic energy is not conserved
3. perfectly inelastic – where the objects remain stuck together after the event and the kinetic energy of relative motion is entirely transformed into other types of energy

In an elastic collision the kinetic energy is transformed into elastic energy during the contact and then the elastic energy is transformed back into kinetic energy. This process occurs without any loss in the energy of the system.

In both types of inelastic collisions, the sum of the kinetic energies of the objects just after the collision is less than that before the collision. Part of the initial kinetic energy of the system is transformed into heat, sound, deformation, etc., during the collision.

In all three cases the total momentum of the system is conserved as long as there are no unbalanced forces acting on the system.

The linear momentum of an object, $\vec{p}$, is the product of its mass, m, and velocity, $\vec{v}$:

$$\vec{p} = m\vec{v}$$

For a completely inelastic collision between two objects of masses m_1 and m_2 with initial velocities of u_1 and u_2, the relation which applies is simply a statement of conservation of momentum:

$$(m_1 + m_2)v = m_1u_1 + m_2u_2$$

where v is the velocity of the combined pair after collision.

For a perfectly elastic collision, we must also consider that kinetic energy is conserved when deriving the relations which apply. Consider a perfectly elastic collision between masses m_1 and m_2, with initial velocities $\vec{u}_1$ and $\vec{u}_2$. Suppose that after the collision their velocities are $\vec{v}_1$and $\vec{v}_2$ respectively. The principle of conservation of momentum, in scalar form, yields:

$$m_1 v_1 + m_2 v_2 = m_1 u_1 + m_2 u_2$$

and conservation of kinetic energy yields:

$$\tfrac{1}{2} m_1 {v_1}^2 + \tfrac{1}{2} m_2 {v_2}^2 = \tfrac{1}{2} m_1 {u_1}^2 + \tfrac{1}{2} m_2 {u_2}^2$$

Rearranging these equations, we have:

$$m_1(v_1 - u_1) = m_2(v_2 - u_2)$$

and:

$$m_1({v_1}^2 - {u_1}^2) = m_2({v_2}^2 - {u_2}^2)$$

Taking the ratio of the two equations and rearranging gives the relative velocity equation for this type of collision:

$$v_2 - v_1 = u_1 - u_2$$

In other words, in a perfectly elastic one-dimensional collision, the relative velocity of separation of the objects after the collision equals the relative velocity of approach before the collision. The ratio of the relative velocities is commonly called the coefficient of restitution, e.

$$e = \frac{v_2 - v_1}{u_1 - u_2}$$

In this experiment, the colliding objects are gliders moving along an air track. The initial and final velocities of the gliders will be determined by measuring the times required by the gliders to travel particular distances before and after the collisions. It will be assumed that friction on the air track is negligible and, in each instance, the instantaneous velocity immediately before or after the collision has a magnitude equal to the respective average speed.

Apparatus

Linear air track, two timers, two gliders with spring bumpers, two gliders with Velcro™ couplers, blower and triple-beam balance.

Procedure

Note: Before starting this experiment, ensure that the track is level and clean and that the bottom surfaces of the gliders are clean and they move easily above the track surface when the blower is on. Avoid high-speed impacts between the gliders and the end bumpers of the track.

Perfectly Inelastic Collision

1. Measure the masses of the two gliders (A and B) equipped with Velcro™ couplers.
2. Examine the perfectly inelastic collision of these two gliders, one of which is initially stationary, as follows:
    a. Set one of the gliders in motion toward one of the end bumpers of the track while the second glider is placed motionless at the centre of the track.
    b. Start a timer when the glider rebounds from the end bumper.
    c. When the gliders collide, stop the first timer and start the second timer simultaneously.
    d. Stop the second timer when the now joined gliders encounter the other end bumper.

       Note: Try a couple of practice runs before taking readings. Also note that the time uncertainty cannot be obtained from repeated trials as you push the glider at a different speed each time. Use the time uncertainty supplied by your lab instructor.
    e. Calculate the velocity of the initially moving glider from the time and distance travelled before impact with the stationary glider. Calculate the velocity of the joined gliders after collision similarly.

       Note: We are assuming that the gliders experience a negligible amount of friction and, therefore, the velocities immediately before and after collision have magnitudes equal to the average speeds being calculated.

f. Calculate and compare the momentum of the system before and after the collision to determine whether the linear momentum of the system was conserved.

Discussion

1. Was the total linear momentum of the system conserved during collision? Explain. Was this outcome expected for this type of collision?

Inelastic/Elastic Collision

1. Examine the head-on collision of two initially moving gliders (C and D) as follows:

    a. Push the two gliders equipped with spring bumpers toward each other from opposite ends of the track. Start one of the timers when they collide and note the point at which this collision occurs. After this collision, the gliders will separate and move off toward opposite ends of the track where they will rebound from the end bumpers and then start toward each other again. When they collide the second time, stop the first timer and start the second timer simultaneously. Again, note the point where this collision occurs. Permit the gliders to collide a third time and when this third collision occurs, stop the second timer and note the point of impact.

        Note: The collision under examination is the second one. The other two are to obtain time and position values to calculate velocities. As previous, try a couple of practice runs before taking readings.

    b. Calculate the speed of each glider immediately before the second collision using the time and distance travelled between the first and second collisions and **make the speeds into velocities using an appropriate sign convention.** Do the same to calculate the velocities immediately after the second collision.

    c. Calculate the coefficient of restitution to determine the extent to which the collision has approximated the elastic situation.

Discussion

What did you expect the coefficient of restitution to be for the collision that you just investigated? Does your calculated coefficient of restitution agree with what you expected? Explain.

Conservation of Energy

Objective

The objectives of this experiment are to

- examine the energies involved in the motion of a mass on a spring;
- test the principle of conservation of energy.

Introduction

We can describe an oscillating mass in terms of its position, velocity, and acceleration as a function of time. We can also describe the system from an energy perspective. In this experiment, you will measure the position and velocity as a function of time for an oscillating mass and spring system, and from those data, plot the kinetic and potential energies of the system.

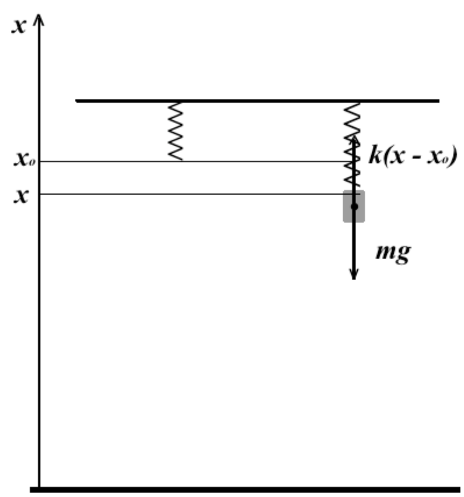


Figure 1.

Energy is present in three forms for the mass and spring system. The mass, *m*, with velocity, *v*, can have kinetic energy *KE*

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

The spring can hold elastic potential energy, PE_S. We calculate PE_S by using

$$PE_s = \frac{1}{2}k(x - x_o)^2$$

where k is the spring constant and $(x - x_o)$ is the extension or compression of the spring from the equilibrium position x_o.

The mass and spring system also has gravitational potential energy $PE_g = mgx$, where x is the height above the level where gravitational potential energy is chosen to be zero ("ground level").

If there are no other forces experienced by the system, then the principle of conservation of energy tells us that the total energy of the system E, which is the sum of gravitational potential energy, elastic potential energy, and kinetic energy, remains constant during the motion:

$$E = PE_g + PE_s + KE = \text{constant}$$

This statement we can test experimentally.

Figure 2.

Apparatus

Laptop, Vernier Motion Detector, ring stand and clamp/arm, 10-20 N/m spring, slotted mass hanger, slotted mass set.

Procedure

You do not need to include uncertainty on any of the following measurements (except for mass) or calculations, but you should make your measurements to a reasonable precision and carry significant figures correctly through all your calculations.

Part I - Determining the spring constant

To calculate the spring potential energy, it is necessary to measure the spring constant, k, as well as the equilibrium position of the spring. Hooke's law states that the spring force is proportional to its extension from equilibrium, or $F = -k(x_o - x)$, where x_o is the equilibrium (unstretched) position of the spring and x is the stretched position.

You can apply a known force to the spring, to be balanced in magnitude by the spring force, by hanging a range of weights from the spring. Once the weight comes to an equilibrium, the force of gravity will balance the spring force: $mg = k\,|x_o - x|$. Because this equation contains two unknowns, k and x_o, it is necessary to take the measurements for at least two different cases with differing masses m_1 and m_2. Note that in both of these cases you use a mass hanger to hang them, therefore m_1 and m_2 must include the mass of the hanger m_h. Then we can construct a system of two linear equations with two unknowns.

Applying Newton's second law to the stationary hanging mass yields:

$$\text{case1:}\quad m_1 g = k|x_o - x_1|$$

$$\text{case2:}\quad m_2 g = k|x_o - x_2|$$

(where m_1 and m_2 are added masses plus mass of the hanger m_h)

Using simple algebra solving for k and x_o, we obtain:

$$k = g\frac{m_2 - m_1}{x_1 - x_2} \qquad \text{and} \qquad x_o = \frac{m_2x_1 - m_1x_2}{m_2 - m_1}$$

1. Measure the mass of the mass hanger, m_h.
2. Mount the mass hanger and spring, as shown in Figure 2, in such a way that the hanger is about 40 cm above the detector. Securely fasten the hanger to the spring, and the spring to the rod, so the hanger cannot fall.
3. Add 100 g to the hanger.
4. Connect the Motion Detector to the computer interface with the Motion Detector sensitivity switch,  set to ***Cart***.
5. Position the Motion Detector directly below the hanging mass, taking care that no extraneous objects can send reflections back to the detector.
6. If your motion detector is already connected to the computer click on the Logger Lite icon on the desktop.
7. Make sure the mass is hanging motionless and click ***Collect*** to begin data collection. The motion detector will record the approximately constant position for the hanger and mass (m_1). Record this as your x_1.
8. Repeat the measurement with 300 g added on the hanger to obtain x_2.
9. Calculate the spring constant k and the equilibrium position x_o.

Part II - Energy in motion of a mass on a spring

1. Now with only 200 g added on the hanger, start the hanger oscillating in a vertical direction by lifting it a few centimeters (e.g. ~5 cm) and letting go. To minimize the swinging in the horizontal direction, delicately lift the mass by the top of the slotted mass hanger.
2. Click ***Collect*** to gather position and velocity data.
3. During the recording time the mass will move up and down several times. You will see the oscillations on the graph of position versus time. Choose one cycle (peak to peak) that is the smoothest (you may have to repeat the measurements to get a nice smooth curve). Highlight the desired region on the graph. Record the times, positions, and velocities for the cycle in Table 4.

Analysis

1. Calculate the gravitational potential, elastic potential, kinetic, and total energies for each of the moments.

   Note: You may find it easier (and much faster) to do these calculations using an excel spreadsheet. However, make sure you include this data in your table.

2. Make a graph of gravitational potential energy, elastic potential energy, kinetic energy, and total energy versus time on the same plot.

Discussion

From the shape of the total energy *vs*. time plot, what can you conclude about the conservation of mechanical energy in your mass and spring system? If the total energy varies, what could be the possible reasons? Comment on locations of maxima and minima of different energies throughout the cycle.

Conclusion

Moment of Inertia

Objective

The objective of this experiment is to examine the kinematics of rotational motion when a system is accelerating. Using the law of conservation of energy, the moment of inertia of a rotating system will be found and compared with the theoretical value.

Introduction

All systems that move have kinetic energy.

In linear (translational) motion, the resistance to being accelerated is called the inertial mass, *m*, and the magnitude of the motion is called the velocity, *v*. In rotational motion, the resistance to being rotationally accelerated is called the moment of inertia, *I* and the magnitude of the rotation is called the angular velocity, ω.

The kinetic energy equation has a similar form in both cases:

Translational	Rotational
$KE = \frac{1}{2}mv^2$	$KE_R = \frac{1}{2}I\omega^2$

The value for the moment of inertia depends on the distribution of the mass in the system. For a point mass, *m*, rotating at a distance, *r*, from the pivot point, then:

$$I_{point\ mass} = mr^2$$

For a system composed of a number of parts or particles, the moment of inertia is the sum of the individual moments of inertia. For a collection of n point masses it would be:

$$I = \sum_{i=1}^{n} m_i r_i^2$$

For other distributions, the moment of inertia can be determined using calculus. For example:

$$I_{sphere} = \frac{2}{5}mR^2 \qquad I_{disk} = \frac{1}{2}mR^2$$

Where R is the radius of the sphere or disk, respectively.

Determining the Moment of Inertia

In this lab, you will use a wheel as shown in Figure 1 that is suspended with two strings attached to its axle.

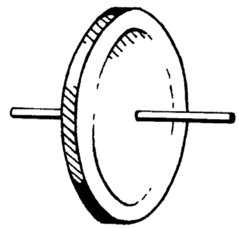


Figure 1: Rotating Wheel

The wheel will be released from rest and allowed to fall a distance, h. As the wheel falls, it converts gravitational potential energy into kinetic energy, both translational and rotational.

$$PE = KE + KE_R$$

where:

$$PE = mgh$$

Kinematics

The final velocities (translational and rotational) will be found using kinematics and just as the energy equation for rotational motion resembles the energy equation for translational motion, the translational kinematics quantities have rotational equivalents.

Translational	Rotational
$\Delta y = y - y_0$	$\Delta\theta = \theta - \theta_0$
$v_{average} = \frac{\Delta y}{t}$	$\omega_{average} = \frac{\Delta\theta}{t}$
$a = \frac{\Delta v}{t}$	$\alpha = \frac{\Delta\omega}{t}$

Assuming that the translational and rotational accelerations are constant, then:

$$v_{average} = \frac{v_f + v_0}{2}$$
$$\omega_{average} = \frac{\omega_f + \omega_0}{2}$$

Apparatus

Rotating wheel on stand, meter stick, timer, triple-beam balance with additional mass, ruler

Procedure

1. Secure the wheel so the axle is horizontal.
2. Measure the height of the axle, (note that this is the final height, y, since at this state the axel would be at the bottom of its descent.)
3. Wind the wheel up while counting the number of revolutions. Make sure the string winds smoothly and evenly along the shaft.
4. Measure the height of the axle again, (note that this is the initial height, y_0 , where the wheel starts its descent.)
5. Release the wheel and measure the time for the wheel to fall/rotate to the bottom.
6. Repeat using the same number of revolutions and change in height.
7. Measure the mass of the wheel.
8. Measure the **diameter** of the wheel.

Calculations

1. Calculate the average time of fall and its uncertainty.
2. For both the translational and rotational cases, calculate the displacements, average velocities, and final velocities of the wheel.
3. Calculate the initial potential energy of the wheel (note that $h=|\Delta y|$) and the final translational kinetic energy of the wheel and then, using conservation of energy, the final rotational kinetic energy of the wheel.
4. From this, find the experimental moment of inertia of the wheel.
5. Calculate a theoretical value for the moment of inertia of the wheel from the diameter and mass of the wheel, assuming it is a uniform disk.

Discussion

Compare your experimental and theoretical values and discuss.

Hooke's Law and Simple Harmonic Motion

Objective

The objective of this experiment is to investigate Hooke's Law and Simple Harmonic Motion with a spiral spring and, from the observations made, to determine the spring constant.

Introduction

Part 1: Hooke's Law

One statement of Hooke's Law is the following: the deformation experienced by an elastic body is directly proportional to the magnitude of the deforming force applied to that body. Therefore, if a spiral spring which obeys this law is stretched, the extension, x, produced is directly proportional to the applied force, F,

$$F = kx$$

where k (the proportionality constant) is termed the force constant of the spring or, simply, the spring constant.

For most tightly coiled springs, however (like the one used in this experiment), the equation has to be modified slightly to read

$$F = kx + F_o$$

where F_0 is the minimum force that must be applied to produce any extension, i.e. to just begin pulling the coils apart.

In this part of the experiment, masses will be attached to the free end of a spring suspended from a fixed support (see Figure 1) and the corresponding extension produced by the weight of each mass will be measured. The spring constant and minimum stretching force will then be determined graphically.

Part 2: Simple Harmonic Motion (SHM)

Simple harmonic motion is the simplest type of vibratory (oscillatory) motion. When an appropriate force is applied to an elastic body, the body is deformed. If the body obeys Hooke's Law, it will execute simple harmonic motion when this force is suddenly removed. Specifically, in this experiment, a mass will be attached to a spiral spring so as to stretch it to an equilibrium position; then the spring-mass system will be lifted slightly by hand and released. The system, when released, will oscillate up and down about the equilibrium position in simple harmonic motion.

The period of the motion of the mass-spring system, T, obeys the relation

$$T = 2\pi\sqrt{\frac{m_1}{k}}$$

where k is the spring constant and m_1 is the effective mass of the vibrating system. This effective mass includes the mass attached to the spring, m, and a certain amount of the actual mass of the spring, m_s',

$$m_1 = m + m_s'$$

Therefore, combining the above equations, we have:

$$T = 2\pi\sqrt{\frac{m + m_s'}{k}}$$

This relation can be rewritten in the form:

$$T^2 = \frac{4\pi^2}{k}m + \frac{4\pi^2}{k}m_s'$$

Showing that, if we plot T^2 versus m, a straight line should result.

In this part of the experiment, the period of the motion will be measured for various values of mass and the spring constant will again be found graphically.

Apparatus

Hooke's Law/SHM apparatus consisting of stand, mirrored scale, spring; set of slotted masses, mass hanger; timer, triple-beam balance.

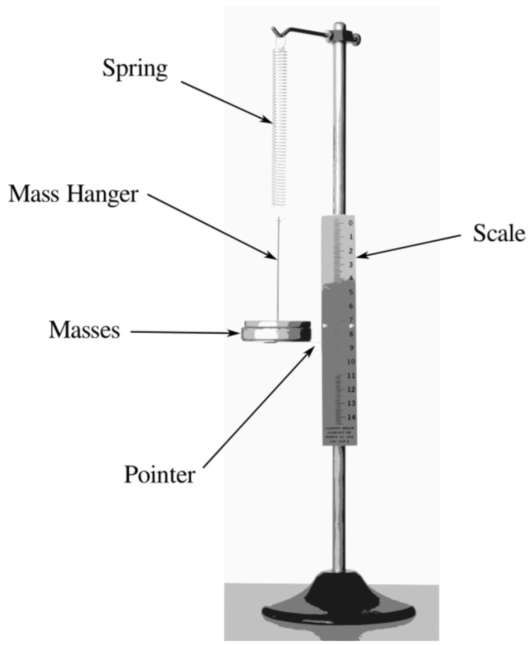


Figure 1

Procedure

Part 1: Hooke's Law

1. Measure the mass of the mass hanger.
2. Attach the mass hanger to the spring and set up as in Figure 1.
3. Adjust the height of the mirrored scale, located on the stand, in order that the bottom of the hanger (or the needle attached to the bottom of the hanger) coincides with the zero reading on the scale; to do this with some precision, align the hanger (or the needle) with its image in the mirrored surface of the scale.
4. Add 100 grams to the hanger and measure the extension of the spring. (Here again, take advantage of the mirrored surface of the scale to obtain the reading).
5. Repeat step 2 with masses of 200, 300, 400, 500, 600, and 700 grams added to the hanger.
6. Plot a graph of weight (weight of total mass suspended) versus extension and calculate the force constant of the spring from the slope of the resulting line and the minimum stretching force from the intercept on the weight axis.

Part 2: Simple Harmonic Motion

1. With 700 grams still on the mass hanger, lift the mass-spring system upwards about one centimetre and then release it so that a smooth up and down motion is produced.

2. Performing at least two trials, measure the time required for the system to execute 25 oscillations. From the average value of the time, calculate the period of this motion.

3. Repeat steps 1 and 2, with masses of 600, 500, 400, and 300 grams added to the hanger.

4. Plot a graph of period squared versus mass (including the mass of the hanger) and calculate the force constant of the spring from the slope of the resulting line.

Discussion

Does the spring constant you measured in Part 1 agree with the spring constant measured in Part 2? Assume that the experimental uncertainty is $\pm 5\%$ for each.

Conclusion

Refer to the objective.

Standing Waves on a String

Objective

The objectives of this experiment are to find the speed of a transverse wave on a string fixed at both ends and to examine the length dependence of the fundamental resonance frequency.

Introduction and Theory

When a transverse vibration is applied near one end of a string that is fixed at both ends, waves travel along the string and are reflected from the fixed ends. At certain frequencies of vibration, resonances occur and the wave appears to be standing still. (See your textbook for pictures.) These standing wave patterns are created by the interference of the traveling wave and the waves reflected from the fixed ends of the string. The resonance frequencies f_n can be predicted with the equation:

$$f_n = n\frac{v}{2L}$$

where: n is the harmonic number, v is the speed of the wave on the string, and L is the length of the vibrating string (See diagram)

The speed of the wave on the string is dependent on the tension in the string, F, and the linear density (mass per unit length) of the string, μ:

$$v = \sqrt{\frac{F}{\mu}}$$

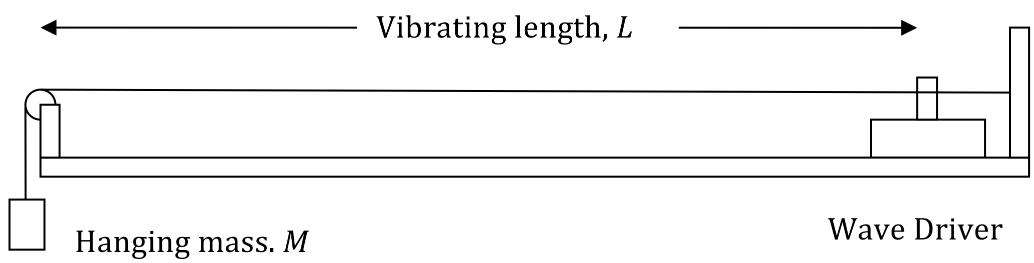
Stringed musical instruments are based on the above principles. However, playing music is much more than just creating a standing wave on a string as the resonances must be pleasing to the ear. Two concepts from music theory are the music intervals of an octave and a fifth. An octave is a doubling of frequency and a fifth is a frequency ratio of 3/2. Using the above equation, the ratio of the first and second harmonics is an octave and the ratio of the second and third harmonics is a fifth.

There are three ways that a stringed instrument can be tuned or played to create music. First, a string with a different linear density can be used. Second, the tension in the string can be changed. And finally, the length of the string can be changed. Usually, a combination of all three methods is used.

Part 1: The Speed of a Wave on a String

Apparatus

Function generator, wave driver, BNC to banana jack adaptor, c-clamp, string, pulley, masses, metre stick, triple beam balance, scissors



Data

1. Before tying any knots in your string, measure the mass, *m*, and length, *l*, of your string to find the linear density of the string.
2. Set up the apparatus as shown in the diagram. The string must be threaded through the small hole in the shaft of the wave driver and attached to the C clamp.
3. Attach a 100 g mass to the end of the string.
4. Connect the output of the function generator to the wave driver. Set the function generator to output a sine wave of maximum amplitude.
5. Find and measure the frequencies of the first 6 harmonics (Resonance frequencies f_1 through f_6).
6. Measure the length of the vibrating string, *L*.

Calculations

1. Graph the resonance frequencies as a function of the harmonic number and calculate the speed of the wave on the string from the slope of your graph and the length of the vibrating string.
2. Calculate a theoretical value for the speed of the wave from the tension and linear density of the string (mass per unit length).

Part 2: Length Dependence of the Fundamental Frequency

Apparatus

Same as part 1.

Data

1. Set the function generator to a musical fifth above the fundamental (n=1) frequency in part 1. Record this as the frequency for part 2.

2. Find the position of the wave driver that produces a fundamental resonance of the largest amplitude and measure the length of the vibrating string.

Calculations

1. Calculate a theoretical value for the length of the string using the equations given in the Introduction and Theory section and the definition of a musical fifth.

   Note: You do not have to calculate an uncertainty for the theoretical value because the uncertainty calculation rules require that the variables are independent. This is not the case here, since the length in part 2 is dependent on the length in part 1.

Discussion

Compare your experimental and theoretical values and discuss.

Conclusions

Refer to the objective.

Simple Pendulum

Objective

The objectives of this lab are:

- to investigate the motion of a simple pendulum to verify the theoretical relationship between its period and length.
- from the measurements taken, to calculate a value for g, the acceleration due to gravity, at the location of the laboratory.

Introduction (Theory)

A simple pendulum consists of a bob (of mass m) suspended by means of a light cord or thread (of length L) as in Figure 1.

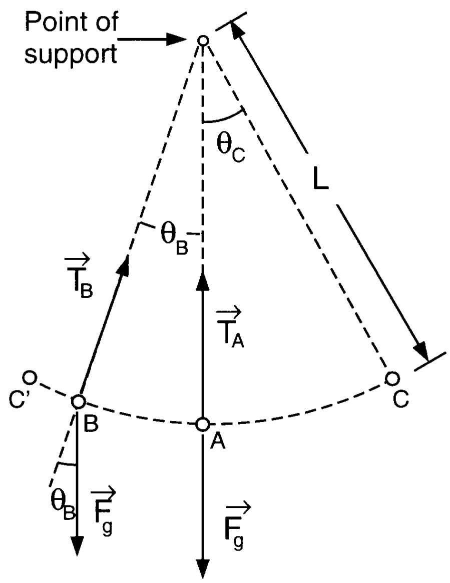


Figure 1

The pendulum length is measured from the point of suspension to the centre of the bob and the only restriction on the bob is that its radius be small in comparison to the length of the thread. Motion is initiated by displacing the bob and thread combination from the equilibrium position A to position C and then releasing it. After release, the bob will move back and forth along a circular arc about A. In the absence of friction, the motion would continue indefinitely with the bob always moving between the release point and a point at an equal displacement on the opposite side of equilibrium, C', and back to the release point. The time required for the pendulum to execute one complete oscillation, i.e., the time required for the pendulum to move from C to C' and return to C again, is called the period, T. The amplitude of the motion is the maximum displacement of the bob from the equilibrium position and can be described in terms of the angle, θ.

When the pendulum passes through its equilibrium position, the two forces acting on the bob (its weight, $\vec{F}_g$, and the tension in the thread, $\vec{T}_A$) are oppositely directed. However, when the bob is at some general point B, the weight of the bob may be resolved into two components: one directed perpendicular to the path (opposite in direction to the tension in the thread) and one directed tangentially to the path (trying to restore the pendulum to its equilibrium position). **For small amplitudes**, the relationship between the displacement and this 'restoring force' can be approximated as directly proportional and it can be shown that the relationship between the period and the pendulum length is described by the equation:

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

where g is the acceleration due to gravity.

Note that neither the mass of the bob nor the amplitude of the oscillation appears in this equation. However, this equation is only valid when the amplitude is small. For this lab, you can assume this equation is valid if the amplitude is less than 15°.

If you square both sides of the equation for the period, you get

$$T^2 = \frac{4\pi^2 L}{g}$$

which shows that a plot of the period squared, T^2 as a function of the length of the pendulum, L will be a straight line with a slope of $4\pi^2/g$.

Apparatus

Simple pendulum apparatus with a steel bob, timer.

Procedure and Calculations

1. Using the steel bob, adjust the pendulum length to be 20.0 cm. Evaluate an uncertainty for this length and record it.

2. Measure and record the time required for 20 **small** amplitude oscillations. Repeat the timing one more time.

3. Repeat steps 1 and 2 for the other pendulum lengths given by your lab instructor.

4. Show a sample calculation of the average time for 20 oscillations and its uncertainty for one of the pendulum lengths. Do the same calculations (but don't show them in your report) for the rest of the pendulum lengths and record the results in table 1.

5. Calculate the period and period squared for each length. Show one sample calculation of each. Record the results in table 2.

6. To examine the relationship between pendulum's period and length, plot a graph of period as a function of length with the data obtained. (What do you expect the graph to look like? Does it appear as you expected? Discuss these in Discussion section.)

7. To determine the acceleration due to gravity in the lab, plot a graph of period squared as a function of length. Fit your data to a straight line, as this was the expected relation between period squared and length (see the theory section.)

8. Use the slope of the T^2 vs L graph to determine the acceleration due to gravity in the lab. State your answer to the correct number of significant figures (based on the number of significant figures in the measured period squared and length.)

Discussion

1. Discuss the outcome of your graph of period vs length. Does it look as expected? Explain. (Does it verify the theoretical relationship.)
2. Discuss the outcome of your graph of period squared vs length. Does it look as expected? Explain.
3. Discuss the value you determined for g. Does it agree with the known expected value?
4. Discuss major sources of error.

Conclusions

Refer to the objectives.