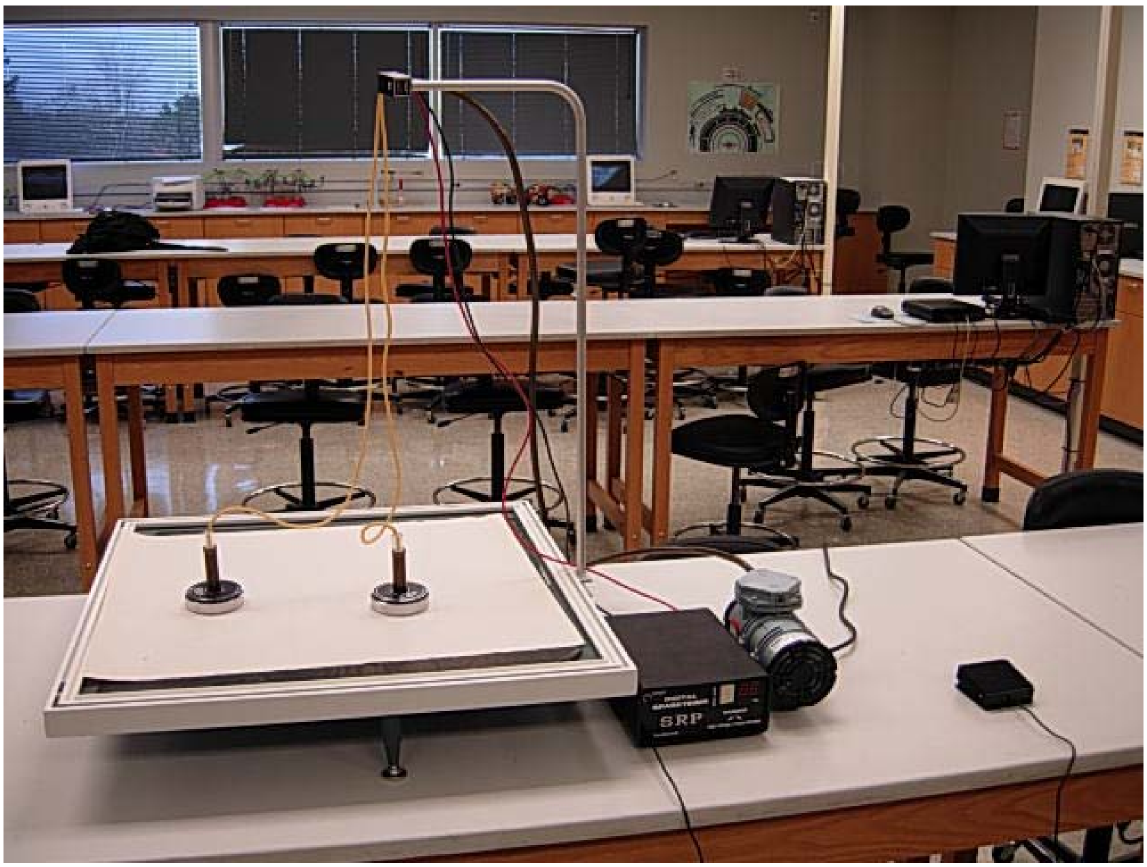
Physics 2111 Laboratory Manual



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The following is a list of experiments prepared for Physics 2111, General Physics Laboratory I which are performed in room 307 of the E. E. O'Banion Science Building. Along with most of the experiments are suggested pre-lab activities that are meant to accompany each lab. The purpose of the pre-lab is to get students thinking ahead to the subsequent experiment, so as to arrive better prepared on the day of the experiment. A set of 10 experiments is used in the "standard list" of experiments, but the individual instructor may switch one or two of them for another on the list. Many of these labs involve use of PASCO computer interface equipment which works with the Dells that are stationed in the lab. For the activities that include a computer assisted component, the computerized version is presented along with the traditional version, giving the class a choice of whether or not to use the computer interface equipment for that particular lab. Help for using the computers and the computer-interfaced equipment is located in a separate manual in room 305. At the end of this laboratory manual are suggested "capstone" exercises to be done in place of the traditional laboratory final exam.

Introduction (to this Document and the Labs)

Introduction

This laboratory manual has descriptions of the laboratories which you will be doing this semester. It also explains some of the concepts required to be understood in order to successfully complete this course and provides examples from everyday life illustrating the concepts. This laboratory manual is required reading material for this course.

The student will be learning to apply the scientific method. Science is the study of the interrelationships of natural phenomena and of their origins. The scientific method is a paradigm that uses logic, common sense, and experience in the interpretation of observations. The underlying basis of the scientific method is understanding through repeatable experiments. No theory is held to be tenable unless the results it predicts are in accord with experimental results.

A major problem is: how does one quantify data so that experiments can adequately be compared? Physicists try to apply a rigorous method of error analysis, and then compare results with respect to the inherent experimental errors. If two experiments produce results that are the same to within experimental error, then we say that the experiments have validated each other.

Error propagation

It is up to your instructor whether error analysis will be included in your lab assignments. It is recommended for the University Physics Laboratories (Calculus-based, for Physics and Engineering majors), but not necessarily recommended for the General Physics Laboratories (Algebra-based, for non Physics and non Engineering-majors). Since this is a manual for the General Physics Laboratory, the discussion on error analysis will be limited to the percent difference calculation (one may refer to the Physics 2511 Lab Manual for a more complete write up of error analysis).

In physics we often do experiments where we wish to calculate a value that has a functional dependence on some measurable quantities, for example:

$$y = f(x, z)$$

or

$$y = f(x_1, x_2, \ldots, x_n)$$

In some cases, we wish to determine how close our experimental value is compared to the published result. This is usually performed by finding the percent difference between the experimental value and the theoretical value. The percent difference is given by:

$$\%diff = \left| \frac{(\text{exp}erimental - theoretical)}{theoretical} \right| \times 100\%$$

NOTE: Technically the term "percent difference" refers to the difference between a measured or experimentally determined value and a theoretical or reference value.

“Percent error” is the difference between two measurements of the same value made by two different methods.

In general, errors in measurement can readily be obtained in the following ways:

1. If only one measurement was taken, use ½ the smallest scale division of the measuring device.
2. If multiple measurements were taken:
   - use standard deviation function on your calculator.
   - or use the standard deviation formula:

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

Experimental Errors

Experimental errors arise for many sources and can be grouped in three categories:

- **personal:** from personal bias or carelessness in reading an instrument (e.g., parallax), in recording observations, or in mathematical calculations.

- **systematic:** associated with particular measurement techniques
  - improper calibration of measuring instrument
  - human reaction time
  - is the “same” error each time. This means that the error can be corrected if the experimenter is clever enough to discover the error.

- **random error:** unknown and unpredictable variations
  - fluctuations in temperature or line voltage
  - mechanical vibrations of the experimental setup
  - unbiased estimates of measurement readings
  - is a “different” error each time. This means that the error cannot be corrected by the experimenter after the data has been collected.

Accuracy: how close to the true value is the result
Precision: how much spread is in the data
- the more precise a group of measurements, the closer together they are
- high precision does not necessarily imply high accuracy

Significant Digits

It is important that measurements, results from calculations, etc. be expressed with the appropriate amount of digits. A real-life example concerns the average weight of the football players on PV’s football team. If someone expressed this value as 305.234353556 lbs., that would not make much sense. If it were expressed as 305 lbs, that would make more sense, since typical scales found in bathrooms and gymnasia measure to the nearest pound. Similarly, when you present your results for a given experiment, the figures should contain no more digits than necessary. A useful rule to remember when presenting your results is the “weakest link” rule: your results are only as accurate as your least accurate measurement. If you are able to only make one or more measurements to the nearest tenth of a unit, and the rest to the nearest hundredth of a unit, the result / answer should be expressed to the nearest tenth. In summary, the rules for significant digits are as follows:

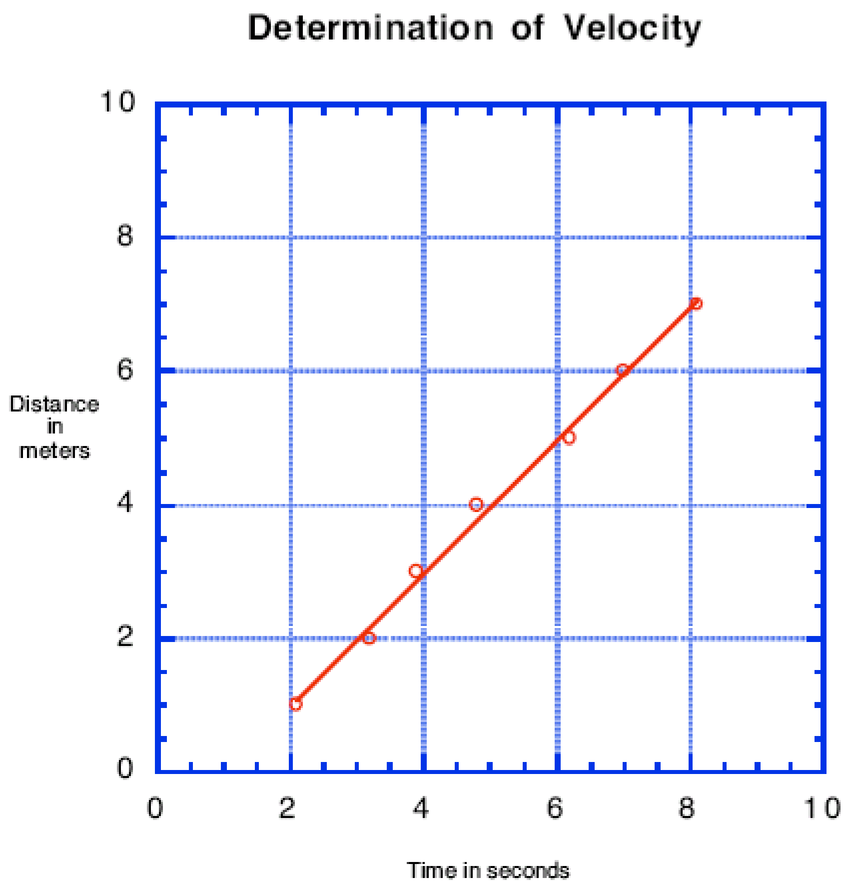
- exact factors have no error (e.g., e, π)
- all measured numbers have some error or uncertainty
    - this error must be calculated or estimated and recorded with every final expression in a laboratory report
    - the degree of error depends on the quality and fineness of the scale of the measuring device
- use all of the significant figures on a measuring device. For example, if a measuring device is accurate to 3 significant digits, use all of the digits in your answer. If the measured value is 2.30 kg, then the zero is a significant digit and so should be recorded in your laboratory report notes.
- keep only a reasonable number of significant digits
    - e.g., 136.467 + 12.3 = 148.8 units
    - e.g., 2.3456 ± 0.4345634523 units → 2.3 ± 0.4 units
    - NOTE: hand-held calculators give answers that generally have a false amount of precision.

Round these values correctly; again as a rule, the final answer should have no more significant digits than the data from which it was derived.

Graphing Techniques

The following graph is an example as to how you are to turn in a graph. Graphs are either to be done on a computer or on quadrille-lined paper, for example, engineering paper. Note that the graph has the following attributes:

1. Each axis has an informative title that contains the units of measurement.
2. There is a graph title.
3. The axes are computed such that the data nearly covers the complete graph.
4. There is a “best fit” straight line that most nearly goes through all of the data points.
5. The graph is clearly linear because the data “looks” straight, and is a good linear fit because all of the data points are near the best-fit straight line.
6. Since the data is linear it can be parameterized with the following equation: $x = x_o + vt$
7. This equation is similar to the standard equation of a straight line: $y = a + bx$ where *a* is the y-intercept and *b* is the slope.



The data for this graph contains a possible example of systematic error. Either all of the times are one second too large or the distances one meter too small as the best fit straight line does not extrapolate through the point {0, 0} as is expected if the measurement was started at zero.

Laboratory Report Format

The finer details of the Laboratory Report Format may vary from instructor to instructor, but each will use a format similar to that described below. In some cases, a blank template will be handed out for the each group to fill in; in others, the group may be asked to write their report, following the below format, on a computer or by hand on paper. The students will then hand in written or typed reports, either individually or as a group. If you type the report, but do not have access to a proper equation writer, then it is better to leave blank spaces and fill in the equations by hand. For example: $\surd x + 2$ is not the same as $\sqrt{x+2}$, nor is $x2$ an acceptable substitute for x^2. Ambiguous equations are much worse than hand-written equations. Students are expected to use the format for the laboratory report found on the following page.

Group Number: Date:

Group Members:

Purpose: What is to be done in this experiment?

Equipment: Apparatus used to perform the experiment.

Theory: The calculation equations used along with meaning of the symbols and units used. Equations can be neatly hand written.

Data: Raw data in tables should be placed in this section. Sample calculations should be shown. Error calculations should be shown.

Results and Discussion: Include a discussion of some of the sources of experimental error or uncertainty. If appropriate, should also include a comparison of various experimental errors. For example: We found that our value of the density, within one standard deviation, has a range of 2.68 to 2.78 $\times 10^3$ kg /m^3. The quoted value of the density for aluminum falls within this range, and no other material densities fall within this range, so our cylinder appears to be made of aluminum.

Conclusion: Short but comprehensive. Was the object of the experiment met?
For example: The density of the cylinder was found to be $(2.73 \pm 0.05) \times 10^3$ kg /m^3. We selected aluminum as the material composing our cylinder because the density of aluminum, 2.70 $\times 10^3$ kg /m^3, is within the experimental error of our calculated density.

Safety Reminder

It will be necessary to follow procedures to ensure safety in each lab. Most laboratory exercises do not present any significant danger, but some will require certain safety measures to be followed. The general recommendation is to follow all safety instructions, including those posted on the wall of the room you are in; if additional special safety guidelines are needed, they will be printed for each lab needing them.

Each student, student assistant, and instructor that uses the lab is required to receive a safety briefing before beginning laboratory exercises. More details on laboratory safety for Physics II laboratories is provided in the next chapter of this Laboratory Manual.

0. Safety Protocol for the Physics I Laboratory Environment

Safety in the laboratory is very important. The experiments performed in the laboratory are designed to be as safe as possible, but caution is always advised concerning the use of the equipment. When you arrive at the start of each class meeting, it is very important that you do not touch or turn on the laboratory equipment until it has been explained by the professor and permission has been granted to get started. The equipment for the labs are set up for you in advance, so resist the urge to play with the equipment when you arrive, as you may hurt yourself or others, or damage the equipment.

While the experiments done in Physics I (classical mechanics) are generally safe, it is always important to be cautious when using equipment, especially if you are unfamiliar with the equipment. If you have any questions about the safety of a procedure or of the equipment, ask your instructor before handling the equipment. Some specific exercises in the laboratory do pose minor safety risks (e.g. the projectile motion lab and the centripetal force lab), and guidelines related to these are presented with the write up for these particular labs. In fact, each laboratory write-up contains a section on safety that should be read and followed carefully. Other hazards may come from broken glass or thermometers; in the event of such, these should be cleaned up by the laboratory assistant or the instructor.

Safety is also important for the equipment as it tends to be expensive and oftentimes delicate. The equipment is tested and set up prior to the laboratory period, but if you have any doubts about the functionality of the equipment or the way that it is set up, it is important to ask the instructor prior to conducting the experiment. If a piece of equipment is broken during an experiment, promptly notify your instructor or laboratory assistant who will remove the broken apparatus to a designated place and replace it with functioning equipment. ***Do not*** try to fix the equipment yourself.

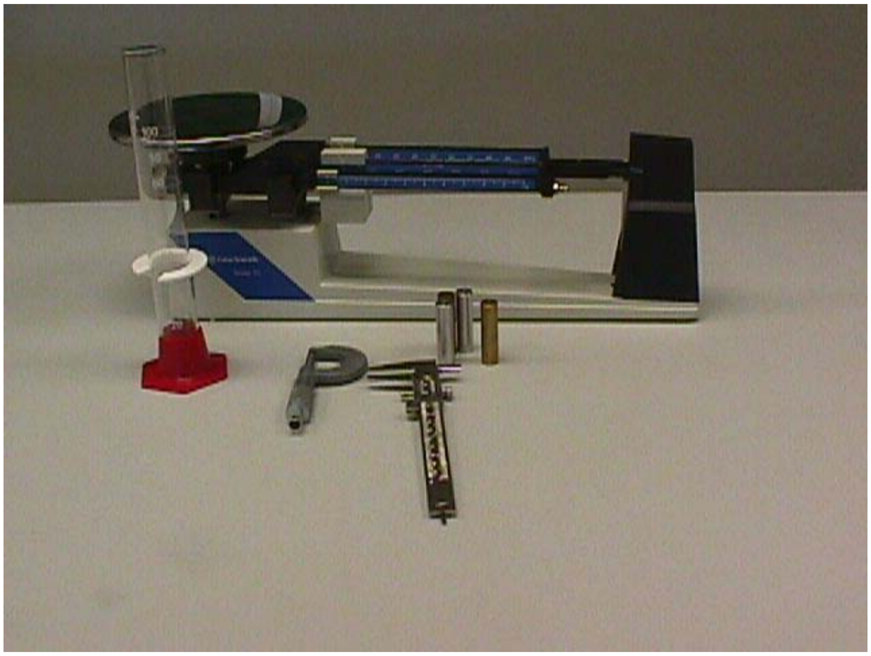
All Laboratory Students, Assistants, Faculty, and Staff must abide by the following safety rules when using the Physics Laboratory. This list may be modified as deemed appropriate for specific situations.

- Follow directions carefully when using any laboratory apparatus to prevent personal injury and damage to the apparatus.
- The instructions on all warning signs must be read and obeyed.
- Wear safety goggles for laboratory activities such as projectile motion, centripetal force, and other labs that involve rapid motion or acceleration of any kind. The goggles are provided by the department and each person in the lab must wear them.
- Long hair and loose items of jewelry or clothing MUST be secured during work with rotating machinery.
- Each student MUST know the use and location of all first aid and emergency equipment in the laboratories and storage areas.

- Each student must know the emergency telephone numbers to summon the fire fighters, police, emergency medical service or other emergency response services.
- Each student must be familiar with all elements of fire safety: alarm, evacuation and assembly, fire containment and suppression, rescue and facilities evaluation.
- NEVER aim or fire a projectile motion device at a person.
- When using the Air Tracks:
    1. Do not let air track carts run away from the user.
    2. Catch the cart before it crashes into the bumper or travels off from the table.
    3. Do not let the cart hit the motion sensor.
- Keep hands clear of any fan blades, moving parts, or projectile launchers (other than to pull the trigger).
- Laboratory walkways and exits must remain clear at all times.
- Glassware breakage and malfunctioning instrument or equipment should be reported to the Teaching Assistant or Laboratory Specialist. It is best to allow the Teaching Assistant or Laboratory Specialist to clean up any broken glass.
- All accidents and injuries MUST be reported to the Laboratory Specialist or Faculty teaching affected lab section. An Accident Report MUST be completed as soon as possible after the event by the Laboratory Specialist.
- No tools, supplies, or other equipment may be tossed from one person to another; carefully hand the item to the recipient.
- Casual visitors to the laboratory are to be discouraged and MUST have permission from the Teaching Assistant, Faculty Instructor of the section in question, or Laboratory Specialist to enter. All visitors and invited guests MUST adhere to all laboratory safety rules. Adherence is the responsibility of the person visited.
- No open-toed shoes are allowed in the laboratory (lab assistants and professor included), as weights or other objects may accidentally drop on people’s feet; ordinary footware provides a measure of protection from such instances.
- Location of PPE (Personal Protection Equipment):
    - Safety goggles are staged in the back in the drawer marked “goggles”
    - A first aid kit is available near the sink at the front of the lab

In addition, the laboratory manuals contain elements of the above as they pertain to each particular experiment.

1. Introduction to Measurement / Calculation of Density



Purpose

The purpose of this experiment is to introduce the student to the laboratory environment. This is done in several ways: with an introduction to the Excel spreadsheet and use of this program to learn how to draw graphs; with an exercise to learn how to use Vernier calipers and a micrometer; and a short experiment that uses the former to calculate the density of four cylinders, comparing these values of density to a standard list to identify the material that makes up each cylinder.

Introduction

Physics is the foundation of science and describes how things work. To approach the study of the universe in the most effective way, scientists utilize the scientific method, which is a paradigm that guides how inquiry is carried out. The process starts with a hypothesis or educated guess on how something works. That hypothesis is tested through observation, experimentation, calculations, and simulations. If the hypothesis passes the tests, then it is elevated to a theory or model. The theory continues to undergo testing as new evidence appears or as our ability to collect new data increases.

Theory

The Instructor will introduce the Excel spreadsheet utility in class, as well as demonstrate the use of the Vernier calipers and the micrometer. The students will have a chance to practice with these in the lab.

Density is defined as the mass of a substance divided by its volume.

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

The volume of a cylinder can be expressed as:

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

where: V = volume
r = radius
d = diameter
l = length
π = pi, the ratio of the circumference of a circle to its diameter (=$\frac{22}{7}$).

Substitute the expression for volume into the expression for density to obtain a formula in terms of the measurable quantities.

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

Equipment

Equipment Needed	**Qtty.**
Computer with Excel spreadsheet software	1
Lab balance	1
Vernier Caliper	1
Micrometer	1
Cylinders of four different types of metal	1 each

Procedure

1. The Introduction (to this Document and the Labs) section of this manual contains a thorough introduction of graphing techniques to be used in class. We will start with a simple exercise using the Excel spreadsheet to graph a set of points and to draw a best-fit line through these points. Note that your Instructor may have a different exercise in mind; this one is presented as a recommended activity. One can also do this exercise in the graphing utility of *DataStudio* to get a feel for how that program works.
    a. Copy the following points into the Excel spreadsheet (likely default name “Book1”). This book will ultimately be saved as an xls file to be included with your lab report.

x	y
0.5	2.5
1.0	2.7
1.2	3.7
2.0	6.5
2.5	6.7

    b. Having done that, click on the Chart Wizard button in the toolbar. A box entitled “Chart Wizard - Step 1 of 4 – Chart Type” should appear. Click on “XY Scatter” under “Chart Type”, then click the “Next” button
    c. Click on the “Series” tab, then the add button. Three editable boxes should appear at right, along with a thumbnail-type image of a graph in the upper

part of the box. Under "Name", put "Graphing Exercise", then in the "X values:" box, click on the icon button found at the right end of the box.

d. The Chart Wizard box should be minimized now, at which point you can go to the points and select which ones will be included as x-values. Click and hold on the first data point x-value and continue to hold as you slide the pointer (now appearing as a "+" sign) down to include all of the x-values. The selected boxes containing the values should be highlighted with a box defined by a moving dashed perimeter
e. When the points are selected, click the button icon on the minimized Chart Wizard box to maximize it, then repeat for the y values
f. Click on "Next" and add the chart title ("Graphing Exercise", if it is not already visible), and x and y values (under the "Titles" tab, name them "x" and "y", respectively). You can also click on the other tabs and edit your graph accordingly (it is recommended that under the "Legend" tab that you deselect the "Show legend" box, this will make the plot area of the graph larger since less area has to be devoted to the legend box)
g. Select whether you want the graph to show up as a new sheet or as an object within the current sheet, and click on "Finish"
h. Finally, with the graph complete, select the graph itself by clicking once on it (near the edge to select the graph and not just the interior), go to the "Chart" button at the top and single-click on it to generate a drop-down menu. Select "Add Trend line" from the list
i. A box will appear entitled "Add Trend line". Select "Linear" as the chart type. Click on the Options tab and select "Display equation on chart" and also enter "0.5" for each of the two boxes under "Forecast". Having done that, write the equation of the line in your report. Also include the R^r value (an index of goodness of fit) in your report.
j. Save your file as group-x-phys2111-P0y.xls (the *x* is your group number, and the *y* is the last digit of the course section number).

2. Next we will work with measurement and density. Measure the dimensions of the four cylinders. Use the Vernier calipers to take at least three measurements of each dimension (that is, each member of your group should measure each dimension) and then use the average of each dimension for your length and diameter values.
3. Use the balance to find the mass of the cylinder. What units did you measure the objects in?
4. Use the equation for density to calculate the density of each cylinder from the measurements that you have taken. Remember to convert the units of measurement to SI units for calculation.
5. Identify each cylinder using the density you calculated and the table on the next page. Using the reference density ("theoretical") and the actual density ("experimental") of each cylinder, calculate the % difference of each.

$$\%diff = \left| \frac{(experimental - theoretical)}{theoretical} \right| \times 100\%$$

State your answer with respect to error using the correct number of significant digits. Of what type of matter is each cylinder composed? That is, do your calculated values of density match to within experimental error (less than 5%) the densities in the following table (below)?

Aluminum	2.70×10^3 kg / m^3	= 2.70 g/cm^3
Chromium	7.19×10^3 kg / m^3	= 7.19 g/cm^3
Copper	8.93×10^3 kg / m^3	= 8.93 g/cm^3
Iron	7.86×10^3 kg / m^3	= 7.86 g/cm^3
Steel	7.82×10^3 kg / m^3	= 7.82 g/cm^3
Stainless Steel	7.70×10^3 kg / m^3	= 7.70 g/cm^3
Brass	8.40×10^3 kg / m^3	= 8.40 g/cm^3
Nickel	8.75×10^3 kg / m^3	= 8.75 g/cm^3

6. Use of the micrometer. (For this section write all measured values in micrometers or µm.)
   - What is the smallest scale division?
   - What is the inherent error of measurement using a micrometer?
   - Measure the thickness of one page in a book, as T_1.
   - Measure the thickness of 100 pages in the same book, as T_2.
   - Is $T_2/100 = T_1$?
   - How much error do you expect?
   - Why should this ratio hold? Why might it not?
   - (Optional) For additional practice with the micrometer, measure several additional small items. Each individual should measure the same object, then compare the measurements to see how close (or how far apart) the measurements are. The spread in several measurements is a reflection of the standard deviation of the sample of measurements.

Addendum: Making Column Graphs in Excel (Courtesy of Bob Aikenhead and Albert Bartlett). Directions for the two extra steps (beyond those needed to make an ordinary line graph) are given in all CAPS.

1) Highlight both data columns with or without the titles.
2) Click the Chart Wizard; this brings up "Chart Wizard, Step 1 of 4"
3) Choose Chart Type XY(Scatter) and any Chart Sub-Type.
4) Click Next
5) The next window is "Chart Wizard, Step 2 of 4"
6) CLICK THE "SERIES" TAB   The x and y data ranges now appear in the small windows in the lower right, "X Values" and "Y Values."
7) Click Next and the new window is "Chart Wizard Step 3 of 4"
8) Enter the titles and other data as called for on the tabs.
9) Click Next and the new window is "Chart Wizard Step 4 of 4"
10) Choose the place for the chart

11) Click Finish and you now have the XY (Scatter) graph in the Chart Sub Type that you chose in Step 3.
12) RIGHT CLICK IN THE CHART AREA and the "Chart Type" window drops down with the "X Y (Scatter)" choice highlighted.
13) CLICK "COLUMN" to highlight the "Column" choice
14) CLICK OK and you have your column graph ready to finish in the normal way.

2. Vectors on a Force Table

Purpose

The purpose of this lab is to experimentally understand vector operations.

Introduction and Theory

A vector is a mathematical object used to represent quantities, which have two (or more) independent dimensions, such as magnitude and direction. The rules of scalar arithmetic and algebra do not apply to vectors. Today we will examine the rules of algebraic vector addition. There are three methods that can be used: graphical, analytical, and experimental.

In two dimensions a vector can be defined by one of the following orthogonal representations, Cartesian or polar coordinates:

$$\boldsymbol{A} = \boldsymbol{A_x}\hat{\boldsymbol{\imath}} + \boldsymbol{A_y}\hat{\boldsymbol{\jmath}} \text{ or } \boldsymbol{A} = \{\boldsymbol{A}, \theta_{\boldsymbol{A}}\}$$

Where $\hat{\imath}$, $\hat{\jmath}$ are unit vectors along the *x* and *y*-axes of a Cartesian coordinate system respectively. In polar coordinates, ***A*** is the magnitude of the vector (its length) and θ_A is the angle to the vector as measured counter-clockwise from the positive *x*-axis of a Cartesian coordinate system. Bold characters are vector quantities and non-bold characters are scalar quantities. The projections of the vector ***A*** upon the Cartesian axis are: (i.e., polar to Cartesian transformation)

$$\boldsymbol{A}_x = \boldsymbol{A}\cdot\hat{\boldsymbol{\imath}} = \boldsymbol{A}\cos\theta_A,\ \boldsymbol{A}_y = \boldsymbol{A}\cdot\hat{\jmath} = \boldsymbol{A}\sin\theta_A$$

To transform from the Cartesian representation to the polar representation:

$$A = \sqrt{A_x^2 + A_y^2}, \quad \theta_A = \tan^{-1}\left(\frac{A_y}{A_x}\right)$$

The angle is measured counter-clockwise from the positive x-axis (which is defined to be at zero degrees). A second vector can be defined as:

$$\boldsymbol{B} = \boldsymbol{B_x}\hat{\boldsymbol{\imath}} + B_y\hat{\jmath}$$

The sum of the two vectors is:

$$\boldsymbol{R} = \{\boldsymbol{R}, \theta_R\} = \boldsymbol{A} + \boldsymbol{B} = (\boldsymbol{A}_x + \boldsymbol{B}_x)\hat{\boldsymbol{\imath}} + (\boldsymbol{A}_y + \boldsymbol{B}_y)\hat{\boldsymbol{\jmath}}$$

To investigate the nature of vector addition experimentally we will use a force table to add two vectors by measuring the net effect of the forces when the system is at equilibrium. Newton's Second Law gives the following equation for forces acting on a point when the acceleration of the point is zero:

$$\sum_{i=1}^{n} F_i = ma = 0$$

We are adding:

$$\boldsymbol{R} = \boldsymbol{A} + \boldsymbol{B}$$

which, when Newton's second law is applied, yields:

$$\boldsymbol{A} + \boldsymbol{B} - \boldsymbol{R} = \boldsymbol{0}$$

This means that in order to achieve equilibrium on the force table, the resultant vector must be placed in its complementary position.

Equipment

Equipment Needed	**Qtty.**
Force Table with 4 pulleys	1
Four Weight hangers	1
Set of slotted weights (masses) Including (at least) 3 of 50g and 3 of 100 g	1
String and ring assembly that usually comes with the force table	1
Protractor	1
Ruler	1
Bubble Level	1
3 Sheets of Cartesian graph paper	3

Procedure

1. Given: ***A*** has an angle of 30° and a mass of 200 grams
   B has an angle of 120° and a mass of 200 grams

- Change this information into the polar representation of a vector. It is necessary to convert the units to kilograms and then express this as a force vector, that is, in units of Newtons (Check with your instructor if you don't know how).
- Find their vector sum by experimental, graphical, and analytical methods. Express the experimental result in polar coordinates. Express the graphical result in rectangular coordinates. Express the analytical result first in the basis vector representation then convert it to the polar representation.
- Refer to the experimental hints below.

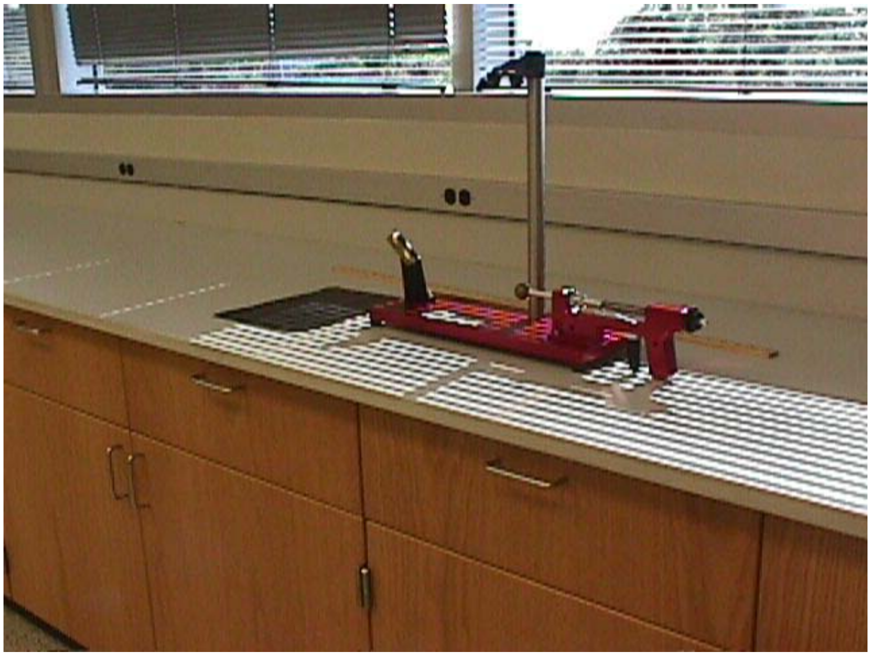
2. Compare the results from each of the three methods of part one. Which method do you think gives the more accurate results? Why?
3. For the experimental results of part 1 show that: $\sum F_i = 0$
4. Draw a picture of the force table top with all vectors used in part 1 labeled correctly.
5. What are some physical sources of experimental error?
6. Your instructor may give additional situations to work with experimentally on the force table. One possible exercise involves finding the resultant of three masses at three different angles.

Experimental hints:

1. Put 200 grams on ***A*** and ***B*** and then add masses to the negative of the resultant and vary the angle of the resultant until the circle is balanced in the middle of the force table. Don't forget to include the mass of the weight hanger. When this occurs a state of equilibrium exists and the sum of the vectors should be zero.
2. Calculate the force on each vector in SI units. You will need to convert measured values in grams to kg, and then remember that A is a force vector and so must be in Newtons ($A = mg$). Values should be stated using 3 significant figures

3. 1D and 2D Motion: Free-Fall and Projectile Motion

(Adapted from Jerry Wilson, *Physics Laboratory Experiments*, 4th Ed., pp. 101-105, © 1994 Houghton Mifflin Company)



Purpose

The purpose of this lab is to (1) determine the value for g, the acceleration due to gravity and (2) determine the muzzle velocity of a projectile fired from a spring-loaded gun.

Safety reminder

Follow all directions for using the equipment. It is required that safety glasses be worn when doing all the procedures. When using the pendulum, be careful not to injure your hand when cocking the gun, and keep your fingers away from the projectile end of the gun.

Background and Theory

A free-falling object is an object which is falling under the sole influence of gravity. Any object which is being acted upon only by the force of gravity is said to be in a state of free fall. There are two important motion characteristics which are true of free-falling objects:

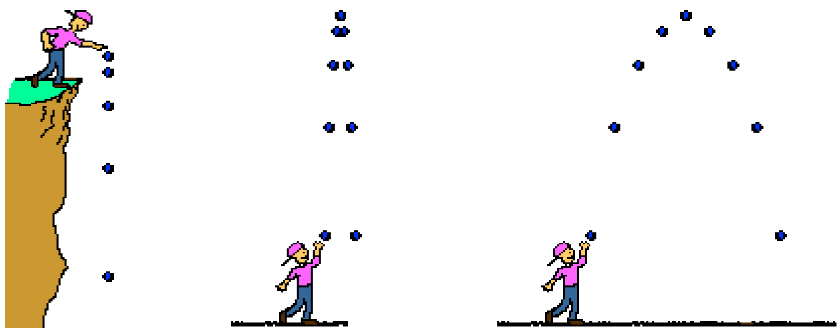
- Free-falling objects do not encounter air resistance.
- All free-falling objects (on Earth) accelerate downwards at a rate of 9.8 m/s^2

Examples of objects in free fall include skydivers, an object dropped from the top of a cliff, an apple falling from a tree etc. (www.howstuffworks.com)

A projectile is any object which once projected or dropped continues in motion by its own inertia (the property of matter by which it retains its velocity so long as it is not acted upon by an external force) and is influenced only by the downward force of gravity. By definition, a projectile has only one force acting upon it - the force of gravity. There are a variety of examples of projectiles. An object dropped from rest is a projectile. An object which is thrown vertically upward is also a projectile. And an object which is thrown upward at an angle to the horizontal is also a projectile.

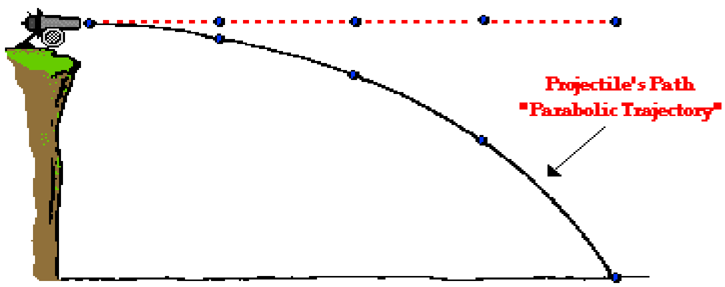
Projectile motion is simply the motion of an object in a plane (two dimensions) under the influence of gravity. The trajectory describes an arc. The equations of motion describe the components of such motion and are useful to analyze projectile motion. In textbook problems, the initial velocity of an object is typically given, and the subsequent motion is described with equations of motion. The method used in this lab will be to determine the initial velocity of a projectile from range-fall measurements. If a projectile is launched horizontally with an initial velocity of magnitude $v_{ox} = v_o$ from a height of y, then the projectile will travel a horizontal distance x (the range of the projectile) while falling the vertical distance y. You can apply this knowledge to all kind of sports such as football, basketball, baseball, and more.

Types of Projectiles



(www.howstuffworks.com)

Some of the examples pertaining to the projectile motion which include the general motion of the objects moving through air in two dimensions near the earth surface are golf ball, thrown or batted baseball, kicked football, speeding bullet and athletics doing a long or high jump.



(www.howstuffworks.com)

Consider a cannonball shot horizontally from a very high cliff at a high speed as shown in the above picture. Gravity will act downwards upon the cannonball to affect its vertical motion. Gravity causes a vertical acceleration. The ball will drop vertically below. Gravity is the downward force upon a projectile which influences its vertical motion and causes the parabolic trajectory which is characteristic of projectiles.

The initial vertical velocity is v_{oy} = 0, and the acceleration in the –*y* direction has a magnitude of $a_y = g$ (acceleration due to gravity—usually taken as negative but taken positive for convenience for this experiment). There is no horizontal component of acceleration (a_x = 0); the components of motion are described by

$$x = v_{\circ}t \quad \text{and} \quad y = \frac{1}{2}gt^2$$

Eliminating t from these equations, then solving for v_o, we have (neglecting air resistance):

$$v_{\circ} = \sqrt{\frac{gx^2}{2y}} = x\left(\frac{g}{2y}\right)^{1/2}$$

By measuring the range x and the distance of the fall y, one can calculate the initial velocity of the projectile.

Near Earth's surface, the acceleration of gravity is g = 9.81 m/s^2. Before we proceed with the range-fall measurements g will be determined from a simple free-fall experiment. If an object starts at rest then released at t = 0, the distance it falls will be

$$y = \frac{1}{2}gt^2$$

If we can assume air resistance is negligible. Thus, if we determine the time it takes an object to fall a distance y is t, then

$$g = \frac{2y}{t^2}$$

Equipment

Equipment Needed	**Qtty.**
Free-fall apparatus	1
Support rod and base	1
Metal ball	1
Projectile launcher	1
Projectile ball	1
Sheets of plain (and carbon) paper	several
Meter stick	1
Masking tape	---

Procedure

Part 1: Free-Fall

1. Practice securing the ball in the apparatus. See that the pad is placed below the ball so as to properly record the time to fall.
2. Measure the height from the pad to the bottom of the suspended ball and record it.
3. Zero the timer, drop the ball, and record the time to fall. Repeat for at least five trials.

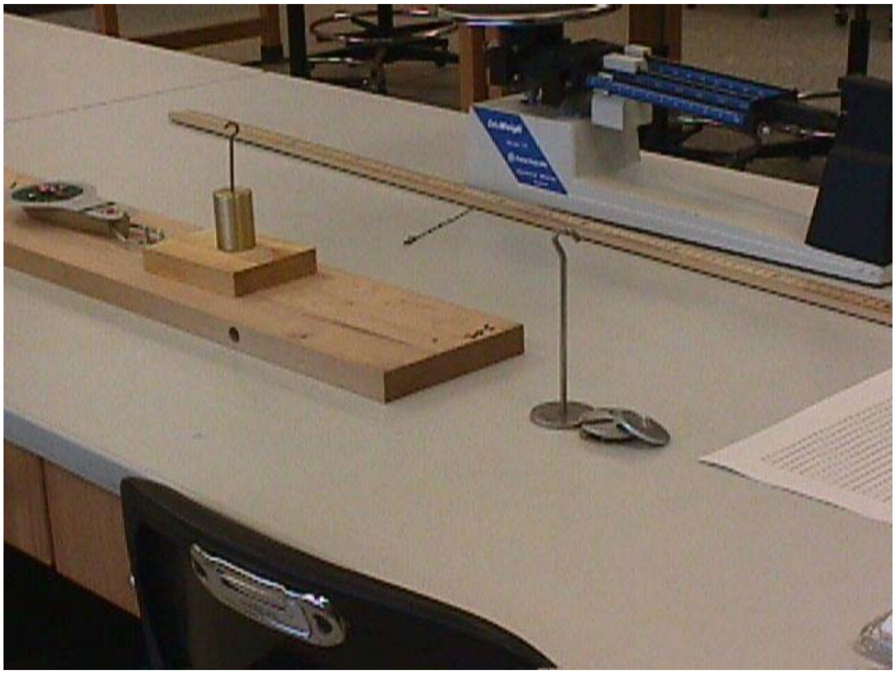
Part 2: Projectile Motion

1. Do a few tests of the apparatus to understand how it works. Making sure the pendulum is removed or restrained in the upper catch mechanism, position the apparatus near one edge of the laboratory table.
2. Position the projectile launcher near one edge of the laboratory table. Take a few practice shots to find the approximate range.
3. Place a sheet of paper where the ball hit the floor, and tape it there (or weigh it down) so it will not move. On top of this, place a sheet of carbon paper, which, when the ball strikes the paper, will leave a small mark on the paper allowing you to measure the range of the projectile. This measurement is taken from the position on the floor directly below where the ball leaves the gun (this location can be determined by putting the ball on the gun without loading the spring) to the centers of the marks on the paper on the floor.
4. Take as many trials as needed to be assured of a good determination of the range. Make sure the gun is fired from the same position each time. Measure the range *x* of each trial and record your measurements. Ignoring obvious outliers, find the average range as well as the standard deviation.
5. Measure the height *y* of the ball from the floor and record that in the data table. The height *y* is measured from the bottom of the ball (as it rests on the gun) to the floor.
6. Using a stopwatch, measure the time of flight of the ball, from the moment it is shot to the moment it hits the floor. Do this five times and take the average.
7. Using the equation below, calculate the magnitude of the initial velocity of the ball ($g = 9.80\ \text{m/s}^2 = 980\ \text{cm/s}^2$).

$$v_{x_o} = x\sqrt{\frac{g}{2y}}$$

To Consider: (a) what effect does the force of gravity have on the horizontal velocity of the projectile? Explain. (b) What effect does air resistance have on the range of the projectile? (c) If two identical metal balls, such as the ones used in class, were to be released at the same time, one simply dropped and the second shot horizontally from a projectile launcher, which would reach the ground first? Or would they both reach the ground at the same time? Why or why not? HINT: Compare the times you recorded for the free-fall ball and the projectile motion ball.

4. Static and Kinetic Friction

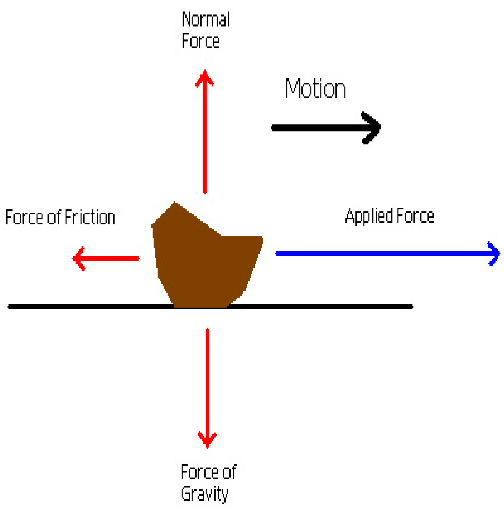


Purpose

The purpose of this lab is to calculate the static and kinetic coefficients of friction.

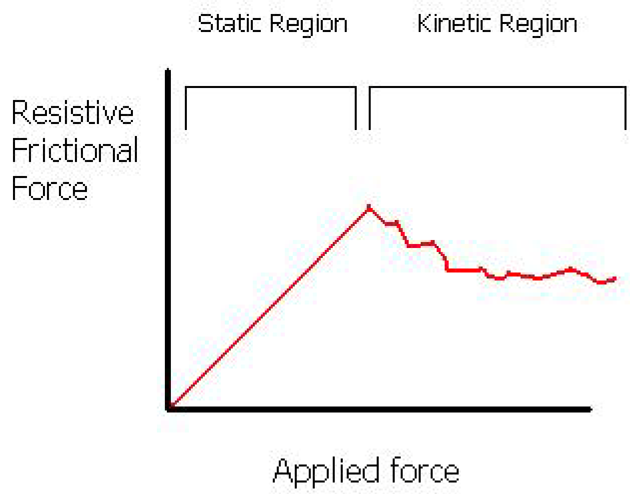
Background and Theory

Friction is a key concept when attempting to understand the details of car accidents. Friction can be defined as the resistance to motion between contacting surfaces. In some cases the magnitude of the frictional force is proportional to the magnitude of the normal force. That is, this relationship can be parameterized as:



$$f = \mu N$$

where μ = the coefficient of friction. When a force is applied to a body, and no motion occurs, then the applied force is balanced by an opposite force called static friction. The maximum value of this force occurs just before the object starts to move. Once the body starts to move, then the resistance on the body is due to the force of kinetic friction. In general $f_s > f_k$ and so the object accelerates once it starts to move. The coefficient of kinetic friction can be measured by observing a body moving at constant speed. With our apparatus, it is not possible to measure a constant speed, but it is possible to obtain a close approximation of constant speed.



(pictures from howstuffworks.com)

Looking at the surfaces of all objects from a microscopic perspective reveals lots of tiny bumps and ridges. These microscopic peaks and valleys lodge against one another when the two objects slide past each other. This becomes an important consideration when driving in the winter with the presence of ice. Ice has a lower coefficient of friction which translates to a longer stopping distance. A higher coefficient of friction decreases your stopping distance. It is better for your tires to use static friction rather than kinetic friction to stop the vehicle. If the tires are rolling along so that the surface touching the ground is never sliding, then static friction is acting to slow the car. If the wheels are locked and sliding, then kinetic friction is acting to slow the car. In order to utilize static friction when you need to stop quickly, there are several options. One can attempt to apply just enough braking to stay within the static range of friction and not too much to cause the brakes to lock. This is the best way to stop, but it can be difficult to apply just enough pressure (and not too much) to stop in this manner.

One way to get around this challenge is to pump the brake, which has the effect of alternating the use of kinetic and static friction as the wheels lock and unlock. Antilock brakes or computer-controlled braking systems are more effective in making effective use of kinetic and static friction to safely stop the car. The best solution to all this is simply to drive slower.

As one rounds a curve, one experiences a slightly different set of forces, since the vehicle tends to “want” to continue straight ahead. This is explained by Newton’s first law of motion: an object will not change velocity without a force acting on it. In this case, by turning, one causes the car to change lateral velocity and move to the side by applying frictional forces from the tires. If the tires don’t have a coefficient of friction large enough to provide the force needed to move the car laterally (e.g. “bald” tires or an icy surface), then the car slides forward and possibly off the road. In ideal situations, the tires maintain static friction to enable the car to turn, but the maximum speed is limited so as to prevent the tires from slipping.

Equipment

Equipment Needed (Without Computer Assistance)	**Qtty**
Board with attached pulley or incline plane	1
Small wooden block with hook	1
Weight hanger and set of weights	1 set
Spring scale	1
String	1
Protractor (optional with incline plane exercises)	1
Lab balance	1
Table Clamp and support	1
Meter stick	1
Sheets of Cartesian graph paper	2

Equipment Needed (With Computer Assistance)	**Qtty**
Force Sensor (for the Static Friction Component)	1
Small wooden block with hook	1
Weight hanger and set of weights	1 set
Spring scale	1
String	1
Lab Balance	1
Table Clamp and Support	1
Meter stick	1
Photo gate / Pulley system	1

Procedure

Without the Assistance of the Computer

1. Use the apparatus to take five trials with increasing weight on the wooden block.
2. Measure the mass required to start the block moving. Make a table of these masses along with the masses on the cart. Calculate the force of static friction and the normal force for each trial. Then plot f_s vs. N using either graph paper, engineering quadrille lined paper, or the printout of a computer graphics program. Find the value of the coefficient of static friction from the graph. Does the graph show that the static frictional force is proportional to the magnitude of the normal force?
3. Measure the mass required to provide just enough force to keep the block moving at a constant velocity. Make a table of these masses along with the masses on the cart. Calculate the force of kinetic friction and the normal force for each trial. Then plot f_k vs. N. (This data set can be plotted on the same graph as the last data set.) Find the value of the coefficient of kinetic friction from the graph. Does the graph show that the kinetic frictional force is proportional to the magnitude of the normal force?
4. Are the extrapolations to the y-intercept close enough to zero such that they can be considered to be zero? Explain what sources of systematic error could cause the y-intercept not to go through zero. Do these systematic errors change the value of the slope?

5. What is the physical reason that $f_s > f_k$?

- Write up your report using the standard format, which is: Purpose, Equipment, Theory, Data, Results and Discussion, and Conclusion.
- Your discussion should include some physical sources of error and an explanation as to how well the data fits the theoretical model.

Bonus: Why is it experimentally convenient to have the block move along the board with a uniform speed when determining the coefficient of kinetic friction?

With the Assistance of the Computer

(Adapted from *Physics Labs with Computers, Vol. 1*, PASCO, pp. 199-202)

There is an array of data that can be recorded. By changing the variables, one can study friction and how changing surface area, mass, texture, static, or kinetic situations affect what is measured. One can devote one to two lab periods and do all of the following, or the instructor may select which part(s) to do in a single lab period. Also note the availability of the electronic workbook for this lab…if instructed to do so, all of the instructions will be on the workbook and you will refer to it from this point on in this experiment.

1. Scenario I, Large Smooth Surface

a. Place the block with its largest smooth side on the horizontal surface
b. Put enough mass on the mass hanger so that the block will slide on the surface without needing an initial push. Measure and record the TOTAL hanging mass.
c. Pull the block back from the Photo gate / Pulley system until the hanging mass is almost up to the pulley. Hold the block in place while turning the pulley so that the photo gate's beam is not blocked (red LED on the photo gate is not lit).
d. Begin data recording, then release the block.
e. End data recording before the block hits the pulley—do not let the block hit the pulley. This data will appear as Run #1.
f. Repeat this procedure once more; the data will appear as Run #2.

2. Scenario II, Different Mass of Block

a. Double the mass of the block by placing a mass approximately equal to the mass of the block on top of the block.
b. Measure and record the total mass (*M*) of the block and additional mass
c. Double the hanging mass; measure and record the total hanging mass (*m*) in the Data Table.
d. Record one run of data to see how the different mass affects the coefficient of kinetic friction

3. Scenario III, Different Surface Area

a. Remove the additional mass from the block and from the mass hanger to return the block and mass hanger to their original state from Scenario I.
b. Place the block so that its smallest smooth side is on the horizontal surface.
c. Record the data and compare this run to that from Scenario I.

4. Scenario IV, Different Surface Material

a. Place the block so that its **largest rough side** is on the horizontal surface (or if all sides are the same roughness, use a rougher horizontal surface)
b. Put enough mass on the mass hanger so that the block will slide on the surface without needing an initial push. Measure and record the TOTAL hanging mass, including the mass of the hanger.
c. Record one run of data as before to see how the different material affects the coefficient of kinetic friction.
d. Place the block so that its **smallest rough side** is on the horizontal surface (or if all sides are the same roughness, use a rougher horizontal surface).
e. Record data using the same hanging mass you used for the largest rough side so you can compare this run to the data for the largest rough side.

5. Scenario V, Different Hanging Mass

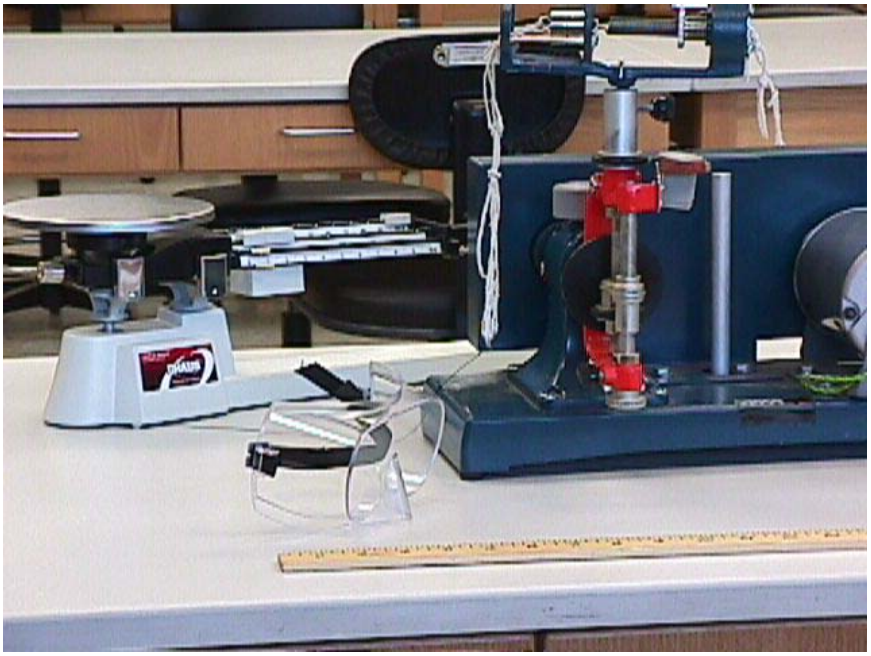
a. Return the block to the original orientation as in Scenario I (largest smooth side down).
b. Put an amount of mass on the hanger that is LARGER than the amount you used in Scenario I. Measure and record the total hanging mass.
c. Record data as in Scenario I (only one run is needed).
d. Repeat the process using two larger totals for the hanging mass. Be sure and record the total hanging mass for all three trials.

Determine the experimental acceleration for each of the data runs. To do so, click in the Graph display to make it active. Find the slope of the velocity versus time plot, the average acceleration of the block. To do this, select Run #1 from the Data Menu in the Graph display. If multiple data runs are showing, first select No Data from the data menu, then select Run #1. Click the Scale to Fit button to rescale the Graph axes to fit the data, then click the 'Fit' menu button and select Linear.

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

5. Centripetal Force

(Adapted from Jerry Wilson, *Physics Laboratory Experiments*, 4th Ed., pp. 115-124, © 1994 Houghton Mifflin Company)



Purpose

The purpose of this experiment is to investigate centripetal force and its role in keeping an object in uniform circular motion.

Background and Theory

An object moving in a circular path requires a centripetal force to keep it in the circular path. Centripetal simply means “center seeking” and describes the force directed toward the center of an orbit or circle traced out by the moving object. Two examples include the Earth revolving around the Sun and atomic electrons moving around the nucleus. In these cases, the centripetal force is supplied by gravitational and electrical interactions, respectively.

The difference between centripetal force and centrifugal tendency (also referred to a “force”, but is not a true force), a result of inertia rather than of force, can be explained with a familiar example. People ride roller coasters for the thrill of the experience, but that thrill has more to do with centripetal force than with speed. The acceleration and centripetal force generated on a roller coaster are high, conveying a sense of weightlessness.

Few parts of a roller coaster ride are straight and flat. The rest of the track is generally composed of dips and hills, banked turns, and in some cases, clothoid loops. (One of the capstone exercises involves a simulated roller coaster, other exercises involve the study of K'nex model roller coasters which nicely illustrate these features) The latter refers to a geometric shape called a clathoid, which looks like an upside-down tear drop. The shape has a much smaller radius at the top than at the bottom, a key factor in the operation of the coaster train through the loops. At one point in the past, roller-coaster designers tried perfectly circular loops, which allowed cars to enter them at speeds that were too high and involved too much force, resulting in rider injury. Eventually, it came to be recognized that the clathoid shape provides a safe, fun ride.

As the roller coaster moves into the loop, then up, over, and down, the riders constantly change position and speed. Going up the loop, the coaster slows due to a decrease in kinetic energy, or the energy that an object possesses by virtue of its motion. At the top of the loop, the coaster has potential energy, or energy possessed by virtue of height / position. At this point, the kinetic energy has dropped to zero. Once the coaster starts down the other side of the loop, kinetic energy (and the associated speed) increases rapidly once again.

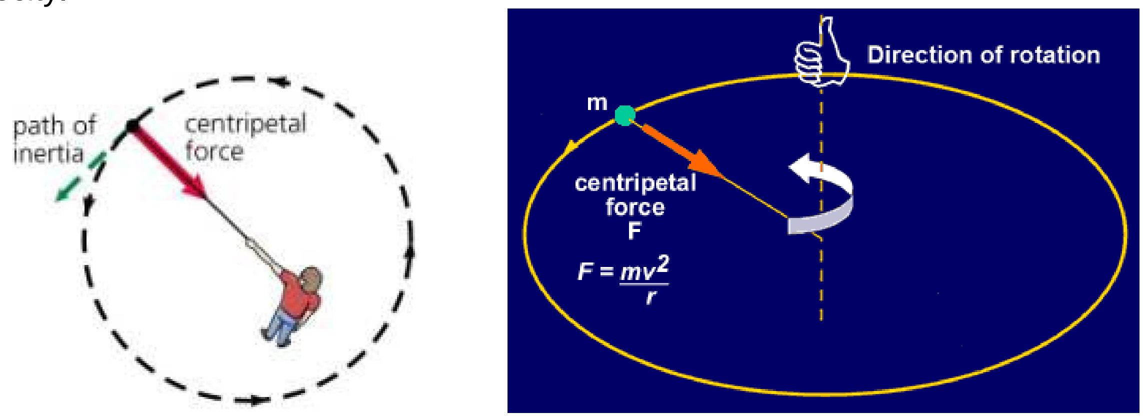
Centripetal force can be easily reproduced in the laboratory setting. One demonstration includes a person swinging a mass or a ball on a rope in a horizontal circle around one's head. The centripetal force supplied by the person and transmitted through the rope can be written as follows:

$$F_c = ma_c$$

or equivalently:

$$a_c = \frac{v^2}{r}$$

with a_c being the magnitude of the centripetal force vector directed toward the center of the circular path, r the radius of the circle defined by the path, and v the tangential velocity.



(www.howstuffworks.com)

The object in uniform circular motion moves with a constant speed, but not a constant velocity. Even though the magnitude of the velocity vector is constant, the direction is continuously changing, resulting from the centripetal acceleration, a_c. This acceleration results from the applied centripetal force, F_c and both are always directed toward the center of the object's circular path.

From Newton's second law, $F = ma$, the magnitude of the centripetal force is:

$$F_c = ma_c = \frac{mv^2}{r}$$

where m is the mass of the object. In terms of distance and time, the orbital speed, v is given by $v = 2\pi r/T$, where $2\pi r$ is the circumference of the circular orbit and T is the period.

The centripetal force can also be expressed in terms of the angular velocity, ω or frequency of rotation, f, by using the expressions $v = r\omega$ and $\omega = 2\pi f$:

$$F_c = \frac{mv^2}{r} = \frac{m(r\omega)^2}{r} = mr\omega^2$$

and

$$F_c = mr(2\pi f)^2 = 4\pi^2 mrf^2$$

where ω is in units of radians per second and f is in hertz (cycles per second). It is the usual convention in rotational motion to think of f as being in revolutions per second.

Equipment

Equipment Needed	**Qtty.**
Lab timer or stopwatch	1
Meter stick	1
Weight Hanger & Slotted weights	1
Strings	1
Laboratory balance	1
Centripetal Force Apparatus	1
Vernier caliper	1
Safety glasses	1

Procedure

In our Laboratory we have three types of Centripetal Motion Apparatus. Each device is operated by a motor, but is set up differently. One device has a variable speed motor, which can be adjusted by moving a rubber friction disk by means of a milled screw head. Your instructor will have prepared the device for use or will instruct you on how to do so. The second device has a small motor controlled by a control device that varies the rate of rotation. The third is a low form-digital readout device. Each apparatus will be treated in turn.

A. Large, variable speed Centripetal Force Apparatus

1. Before turning on the rotator, make certain that the force apparatus is locked securely in the rotor mount by means of the locking screw. Have your instructor check your setup at this point.
2. Put on the safety glasses and turn on the rotor. Adjust the speed of the rotor until the pointer rises and is opposite the head of the index screw. The instructor will provide more details on how to successfully achieve the correct speed in order to maintain the pointer horizontally at the critical speed. The pointer will be slightly erratic until a particular speed is reached, then it will "jump" and point horizontally toward the index screw. You will probably want to do a few trial runs to get the feel for how the setup works.
3. Practice engaging the counter and adjusting the rotor speed (Do not do this too forcefully or too lightly, as either the rotor will be slowed or the rotor may lose contact with the rotor gear). When you are ready to take measurements, record the number that is displayed on the counter. Start the counter and rotor and allow it to run over a 1-min. interval, timing the interval with a stopwatch. Once this is finished, take the final counter reading and stop the rotor. The difference between the two counts is the number of rotations in the time interval.
4. Repeat this four more times at 1-min intervals, but do not use the previous final counter reading for the next initial interval reading. Advance the counter to a new, arbitrary reading for each trial. Take the absolute value of the difference between the initial and final values (yes, some of the counters count down instead of up…) to find the number of rotations for each one-minute interval (they should all be similar). Compute the average value of these, and divide this value by 60 (1 min. = 60 s) to obtain the average rotation frequency in hertz (Hz).
5. Without altering the spring tension setting, remove the centripetal force apparatus from the rotator and suspend it from a support. Hang enough mass for the hanger to produce the same extension of the spring as when on the rotor (pointer aimed at the index screw position), and record this mass, *M'* to include the mass of the hanger. Also, record the mass of the cylinder *m* in the force apparatus (this value is stamped on the end of the cylinder).
6. Add the masses to find the total suspended mass, $M = M' + m$, and compute the direct measure of F_c = the weight of the total suspended mass = Mg. Before removing the weights from the support, use a Vernier caliper to measure the distance *r*, or the radius of the circular rotational path, and record. This is the distance between the axis of rotation and the center of mass of the cylinder.
7. Compute the centripetal force with the expression $F_c = mr(2\pi f)^2 = 4\pi^2 mrf^2$ and compare this value with that obtained from the amount of suspended mass required to produce the same extension of the spring—compare the two using the percent difference formula.
8. As an optional extension to this lab exercise, one may vary the tension of the spring and repeat the activity outlined above.

B. Manual Centripetal Force Apparatus

1. This device is originally a hand-operated apparatus, with a motor, taking the place of the hand to rotate this apparatus with a constant speed. A pulley mounted to the base of the apparatus is used to make direct measurement of the spring tension supplying the centripetal force for uniform circular motion of a particular radius indicated by the distance between the vertical pointer rod and the axis of rotation.
2. Determine the mass of the bob by removing it and weighing it on a laboratory balance. Reattach the bob to the string on the horizontal support arm and attach the spring as well.
3. Activate the motor to rotate the bob until its radius of rotation increases and stabilizes. Next, carefully adjust the position of the vertical pointer rod to line up vertically with the point on the end of the rotating bob and measure the distance (from the pointer tip and the center of the vertical rotor shaft). You will leave the pointer rod in this position for the rest of the experiment.
4. Measure the amount of time for the bob to make 25 rotations, with one student operating the lab timer and a second student counting off the rotations. Note: make sure you are comfortable with the procedure for rotating the bob and making the measurement before you record your measurements.
5. Repeat the counting-timing procedure four more times, and take the average time. Find the frequency by dividing 25 by the average time the apparatus took to make the 25 rotations (in seconds). Calculate the average speed of the bob, using the data and the formula $v = c/t = 2\pi r/T,$ where c is the circumference of the circular orbit and T is the average time per revolution. Then calculate the centripetal force using $F_c = \frac{mv^2}{r}$.
6. Attach a string to the bob opposite the spring and suspend a weight hanger over the pulley. Add weights to the hanger until the bob is directly over the pointer. Record the weight, *Mg*, including the mass of the weight hanger. This measured weight is a direct measure of the centripetal force supplied by the spring during rotation. Compare this value with the calculated value and compute the percent difference between the two.
7. One may vary the mass, radius or spring tension and compare the final results with that obtained in the procedure. One may also compare results obtained with the two different centripetal motion apparatus, while trying to make everything between the two as consistent as possible.

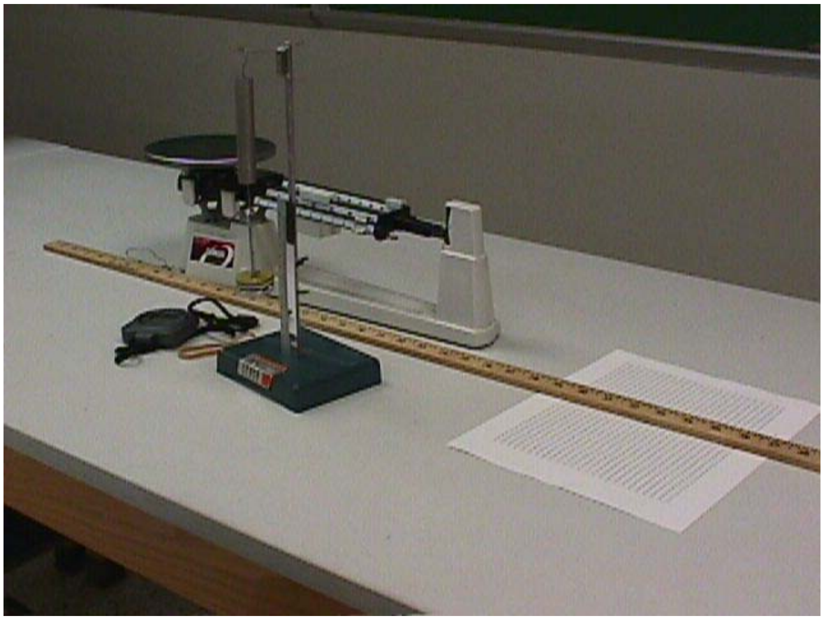
C. The CENCO Motor Driven Rotator with Digital Display

1. Before turning on the rotator, securely lock the rotator in the upright position, mount the spring-mass rotator assemble into the rotator and tighten the chuck. Be certain that that both the rotator and spring-mass assembly are secure.
2. Put on the safety glasses first, and then turn on the rotor. Set the display to read “rpm”. Adjust the speed of the rotor so that the pointer within the spring-mass assembly just rises to be opposite the head of the index screw. Record

the rotator speed required to achieve this with its uncertainty. You will probably want to do a few trial runs to get the feel for how the setup works.

3. Without altering the spring tension setting, remove the spring-mass assembly from the rotator and suspend it from a support. Hang enough mass for the hanger to produce the same extension of the spring as when on the rotor (pointer just rising to point at the index screw position), and record this mass, *M*, needed to achieve this. (Remember to include the mass of the hanger.) Also, record the mass of the cylinder *m* in the spring-mass assembly (this value is stamped on the end of the cylinder).
4. Before removing the weights from the support, use a Vernier caliper to measure the distance between the axis of rotation and the center of mass of the cylinder. This is the radius of the circular rotational path, *r*.
5. Compute the centripetal force with the expression $F_c = 4\pi^2 m f^2$ and compare this value with the force, $F_g = (m+M)g$, required to produce the same extension of the spring.
6. Vary the tension of the spring and repeat the activity outlined above.

6. Hooke's Law



Purpose

The purpose of this lab is to understand and calculate the spring constant for a spring.

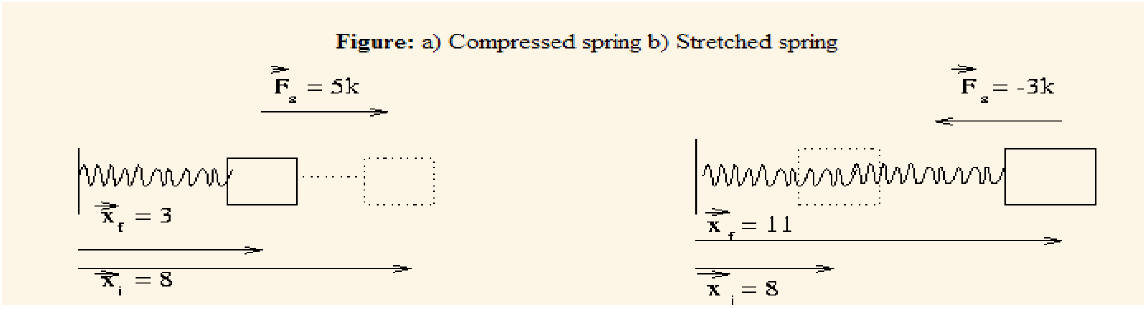
Introduction and Theory

Any material that tends to return to its original form or shape after being deformed is called an elastic material. The degree of elasticity is dependent on the internal properties of the deformed material. In many elastic materials the deformation is directly proportional to a restoring force that resists the deformation. This linear relationship is called *Hooke's Law* (generalized for three dimensions).

$$\boldsymbol{F} = -k\boldsymbol{x}$$

where $\boldsymbol{F} = m\boldsymbol{a}$ is the restoring force, m is the mass subject to the restoring force, $\boldsymbol{x}$ is the displacement from the equilibrium ($\boldsymbol{F}_{\text{net}} = 0$) position, and $\boldsymbol{k}$ is a constant vector.

Hooke's law states that the amount of deformation of an elastic object is proportional to the force applied to deform it. A rubber band behaves according to Hooke's law. When the rubber band is pulled on (force applied), the rubber band stretches and the force is proportional to the stretch of the rubber band. The greater the force, the more stretch. With less force, the rubber band does not stretch as much. After a person has applied a force to the rubber band by pulling it and starts to let it go, easing on the force applied, the stretch of the rubber band becomes less. Therefore, the force applied is proportional to the amount of deformation on the rubber band. Similarly a coil spring is another example, similar to the rubber band where Hooke's law is obeyed.



(www.howstuffworks.com)

For our purposes, we consider motion in one dimension, and Hooke's Law takes on the more familiar form

$$F = -kx$$

Today's experiment involves Hooke's Law for springs. However, Hooke's Law applies not only to springs, rubber bands and other obvious elastic materials. Hooke's Law governs pendulums, a ball oscillating about the bottom of a u-shaped valley, molecular vibrations, just to name a few examples. Indeed, Hooke's Law governs any conservative system (i.e., a system that conserves its mechanical energy) that undergoes a "small" displacement from its equilibrium position. According to Hooke's Law, when a system is displaced from its equilibrium position, the system will undergo a repetitive "to-and-fro" motion, i.e., oscillate, about its equilibrium position at a well-defined frequency or period of oscillation.

A system oscillating according to Hooke's Law is said to undergo *simple harmonic motion*. Hooke's Law represents the equation of motion for a simple harmonic oscillator.

$$\frac{\Delta^2 x}{\Delta t^2} = -\left(\frac{k}{m}\right)x$$

The solution of the equation of motion is that the mass oscillates in time and has the position

$$x = x_{\max}\cos(\omega t + \varphi)$$

where $x_{\max}$ is the amplitude, the angular frequency is $\omega = 2\pi f = \sqrt{k/m}$, where f is the frequency, and φ is the phase at $t = 0$. (It is usual to assume $x = x_{\max}$ at $t = 0$ so that $\varphi = 0$.) The period, T, of the oscillation is $2\pi/\omega = 1/f = 2\pi\sqrt{m/k}$.

Note that $v = \Delta x/\Delta t = -\omega x\sin(\omega t + \varphi)$, and the acceleration is $a = -\omega^2\cos(\omega t + \varphi)$. Note that $a = \Delta v/\Delta t$, and it follows that $\omega = \sqrt{k/m}$. At the maximum displacement from the equilibrium position, the speed of the object is zero, and the magnitude of its acceleration is a maximum (maximum magnitude of the restoring force). As the object passes its equilibrium position, its speed is a maximum and its acceleration is zero.

For today's experiment, we will suspend masses on a spring hung vertically. For a spring, the constant *k* is called he "spring constant" (be careful not to overextend the spring such as to cause permanent deformation, which changes the spring constant and may ruin the spring). The force of gravity will be used to find equilibrium positions for a spring. That position is given by

$$F = mg = -k(x - x_{\circ})$$

where x_o is the position of the spring when no mass is hung on it. A plot of *m* versus *x* yields a line with slope $-k/g$ and y-intercept kx_o/g. The spring constant *k* can then be determined from the slope. If one displaces the mass from its equilibrium position and releases it, the mass will oscillate with a period

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

A plot of T^2 versus *m* yields a line with slope $4\pi^2/k$.

Equipment

Equipment Needed (Without Computer Assistance)	Qtty.
Set of coil springs	1 set
Rubber band (optional)	1
Hooke's Law Apparatus (modified meter stick or the smaller metal apparatus shown in the image above)	1
Slotted Weights & Weight hanger	1
Lab timer / Stopwatch	1
Lab balance	1

Equipment Needed (With Computer Assistance)	Qtty.
Force Sensor	1 set
Motion Sensor	1
Balance	1
Base and Support Rod	1
Clamp, right-angle	1
Mass and Hanger Set	1
Meter stick	1
Spring, k ~2 to 4 N/m	1

Procedure

Without the Assistance of a Computer—note that one can use a spring of a certain k in place of the rubber band; one can also compare this with a second spring of different k.

1. Hang a spring on the meter stick/support and suspend a weight hanger on the spring. If the spring is too stiff, you may want to increase the mass on the hanger

for the first measurement so that the oscillation frequency is not too fast. (For the position *x* one can just read either the position of the bottom of the hanger along the meter stick or the position of the spring pointer. Note that we are interested in the slope of *m* vs. *x* or T^2 vs. *m*, and the zeroes of *m* and *x* only affect the intercepts and not the slope.)

2. Record the position *x*.
3. Displace the mass a reasonable amount (thereby compressing or stretching the spring) and release. Record the period of oscillation. (The reaction time δt is the same whether you measure the total time, Δt, for one period, 10 periods, 20 periods, or whatever number. So, the uncertainty of the period, $\delta T = \delta t$ divided by (number of oscillations) is reduced as a larger number of oscillations is used for timing, $T = \Delta t$ divided by (number of oscillations)
4. Add mass to the spring in a reasonable increment and repeat steps 2 and 3 until you a sufficient number of data points (say 5 or 6 trials).
5. Repeat steps 1—4 for Spring 2 (Or you can substitute a rubber band).

Table 1. Data for Springs (note…one table for each spring).

Measurement number	Mass (*m*)	Distance (*x*)	Period (T)	Period ^{2} (T^2)
Trial 1	•	•	•	•
Trial 2	•	•	•	•
• • Trial 6	• • •	• • •	• • •	• • •

With the Assistance of a Computer

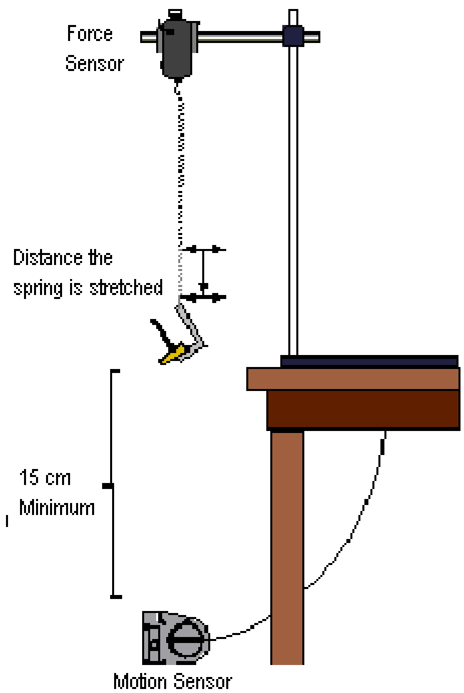
(Adapted from Pasco's *Physics Labs with Computers—Teacher's Guide,* Vol. I).

1. Set up the apparatus as shown in the diagram on the next page. The Force Sensor will have been calibrated for you. Suspend the spring from the Force Sensor's hook so that it hangs vertically.
2. Use the meter stick to measure the position of the bottom end of the spring (without any mass added to the spring). For reference, record this measurement as the spring's equilibrium position.
3. Press the tare button on Force Sensor to zero the Sensor. Start data recording. The program will begin Keyboard Sampling. Enter 0.000 in units of meters (m) because the spring is unstretched.
4. In *DataStudio* move the table display so you can see it clearly. Click on the Start button to start recording the data. The Start button changes to a Keep and a Stop button 

. The Force will appear in the first cell in the Table display. Click the Keep button to record the value of the force.
5. Add 20 grams to the end of the spring (be sure to include the mass of the spring) and measure the new position of the end of the spring. Enter the difference between the new position and the equilibrium position as the Δx, 'Stretch'

(meters) and record a Force value for this Stretch value by clicking on the 'Keep' button.

6. Add 10 grams to the spring (for a total of 30 grams additional mass) and measure the new position of the end of the spring, enter the stretch value and click 'Keep' to record the force value.
7. Continue to add mass in 10-gram increments until 70 grams have been added. Each time you add mass, measure and enter the new displacement value from equilibrium and click 'Keep' to record the force value.
8. End data recording by clicking on the Stop button. The data will show as Run #1.
9. Determine the slope of the Force vs. Stretch graph. Click the 'Scale to Fit' button, , to rescale the graph axes to fit the data. Next, click the Fit menu button, , and select Linear. Record the slope of the linear fit in your lab report.
10. Repeat the above steps for a spring of a different spring constant (stiffness).

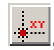


Optional Additional Computer Assisted Activity, the Period of Oscillation:

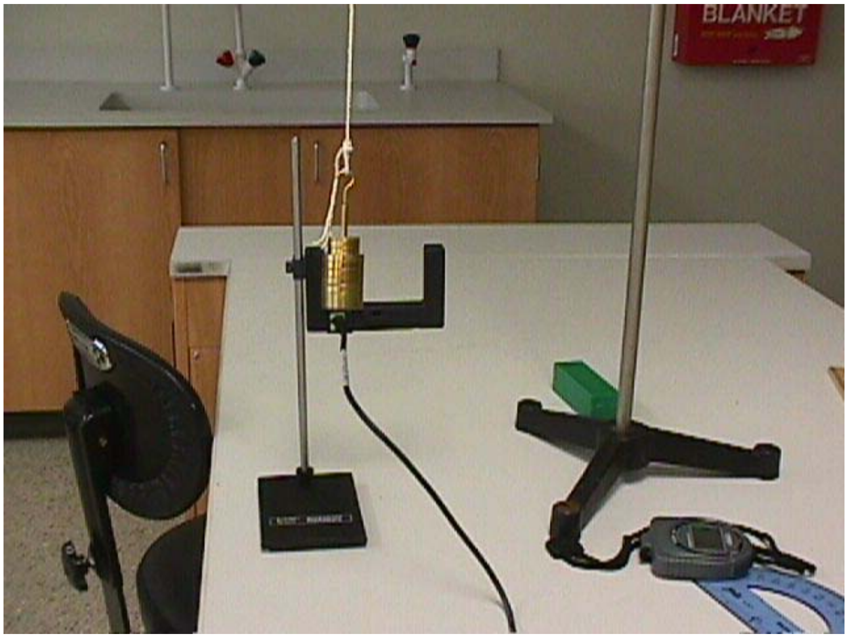
Repeat the experiment with the Motion Sensor as shown in the above illustration.

1. Remove the Force Sensor and replace the spring directly to the support rod.
2. Add 70 grams of mass to the weight hanger. Pull the mass down to stretch the spring about 20 cm (making sure it is still at least 15cm from the motion sensor), then release.
3. Begin recording data after the spring has oscillated a few times to allow any side-to-side motion to damp out. Record for about 10 seconds, then stop.
4. Make sure that the position curve resembles the plot of a sine function. If not, check the alignment between the Motion Sensor and the bottom of the mass

hanger at the end of the spring. You may need to increase the size of the reflecting surface by adding a 5-cm diameter circular paper disk to the bottom of the mass hanger, then repeating the trial run.

5. To analyze the data, first rescale the graph axes to fit the data, using the Scale to Fit button (), and find the average period of the oscillation of the mass. To find this period, click on the Smart Tool button, , and move the Smart Tool to the first peak in the plot of position versus time. Read the value of time at this position and record this value in you Lab Report. Move the Smart Tool to each consecutive peak and record the value of time shown for each peak.
6. Find the period of oscillation by calculating the difference between the times for each successive peak, then finding the average of these periods. Record your result in the Laboratory Report.

7. The Simple Pendulum

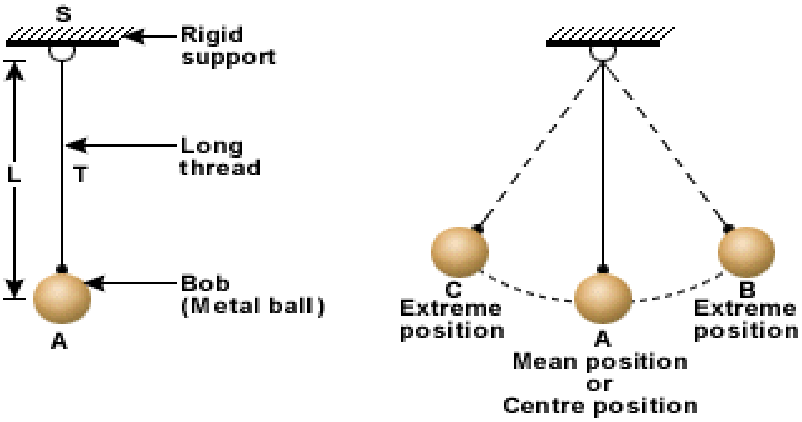


Purpose

The purpose of this experiment is to use the apparatus for a physical pendulum to determine the dependence of the period of the pendulum on its initial angle and its length.

Background and Theory

A pendulum is a mass (or the bob) on the end of a string of negligible mass, which, when initially displaced, will swing back and forth under the influence of gravity over its central (lowest) point.



(a) Simple pendulum (b) Motion of a simple pendulum

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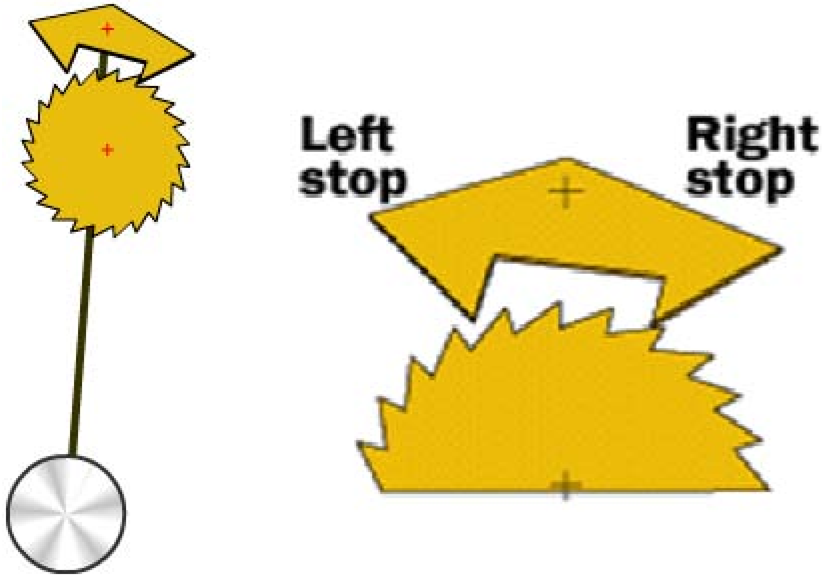
Oscillations of the pendulum: One complete to and fro motion is known as the oscillation of the pendulum. One oscillation is the motion taken for the bob to go from position B (initial position) to A (mean position) to C (the other extreme position) and back to B. Time period of the pendulum: The time taken for one oscillation by the pendulum is called the time period of the pendulum. Time period is also called period of the pendulum. This is denoted by T.

Pendulum used as a Clock:



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Simple pendulums are used to keep time in clocks. In an escapement (a device used to release just a bit of stored energy at regular intervals in even amounts to turn the gears of a clock in a precise manner) there is a gear with teeth of some specific shape. There is also a pendulum, and attached to the pendulum is a device to engage the teeth of the gear. The basic idea that is being demonstrated in the figure is that, for each swing of the pendulum back and forth, one tooth of the gear is allowed to "escape."

For example, if the pendulum is swinging toward the left and passes through the center position as shown in the figure on the right, then as the pendulum continues toward the left the left-hand stop attached to the pendulum will release its tooth. The gear will then advance one-half tooth's-width forward and hit the right-hand stop. In advancing forward and running into the stop, the gear will make a sound... "tick" or "tock" being the most common. That is where the ticking sound of a clock or watch comes from. The hour, minute and the second hands are tied to the gears. The hands rotate with the gears, thus showing the correct time.

The pendulum escapement continues this motion until all of the energy stored behind the gear is used up. Typically, this means that the clock spring has fully unwound and it is time to wind it before it stops oscillating.

The pendulum that we will use in this experiment consists of a small object, called a bob, attached to a string, which in turn is attached to a fixed point called the pivot point. The length of a pendulum is the distance from the pivot point to the center of mass of the pendulum. Since the mass of the string is much less than the mass of the bob, the length of the pendulum can be adequately approximated as the distance from the pivot point to the center of mass of the bob.

There are four fundamental physical properties of the pendulum:

- the length
- the mass
- the angle
- the period

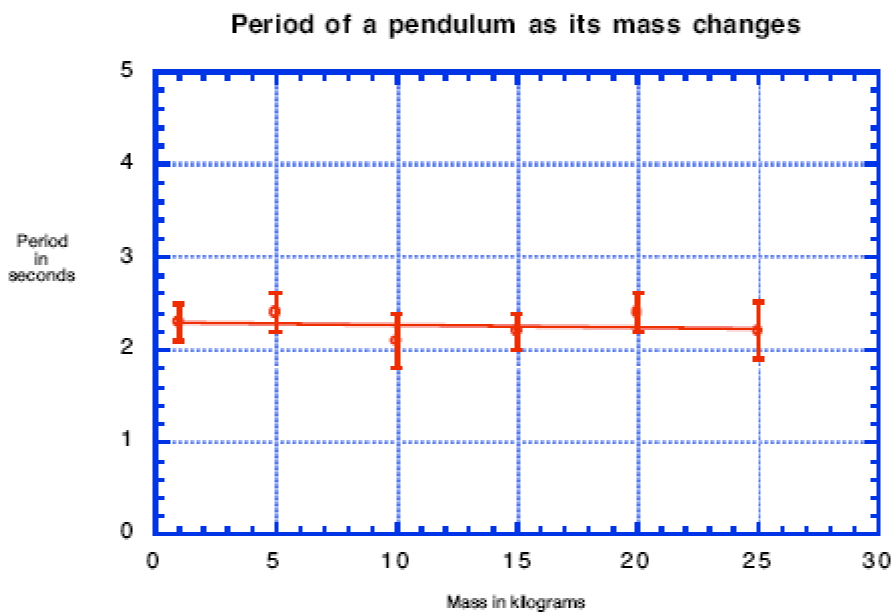
We will choose the period, that is, the time for the pendulum to go back and forth once, to be the dependent variable, and set the other physical properties to be the independent variables. If the instructor so chooses, we may also study the other properties of the pendulum as well. The period, T, of a pendulum is expressed mathematically as:

$$T = f(m, L, \theta)$$

The independent variables can strongly influence, weakly influence, or have no influence on the dependent variable. To scientifically determine the strength of the dependence, the independent variables are varied one at a time. If the varying of a physical quantity causes no variance of the dependent variable to within experimental error, then that measured physical quantity has no effect on the dependent variable. For example, if the mass of a physical pendulum is changed and the period is measured, then the data taken will produce a graph similar to the following graph (next page).

In the graph on the next page the vertical bars are called error bars. They are the one standard deviation errors in the averages for each data point. The observation that the best-fit line is horizontal and lies within all the error bars is sufficient evidence to enable one to state that the period of the pendulum is independent of its mass.

To determine the dependence of the period of the pendulum on its initial angle and its length requires two independent sets of measurements. In the first set keep the length constant while the angle is varied; in the second set keep the angle constant while the length is varied.



Equipment

Equipment Needed (Without Computer Assistance)	Qtty.
Pendulum Clamp and string (or Young's modulus / double rod support stand and string)	1
Rod and Base	1
Meter stick	1
Protractor	1
Hooked Masses or slotted masses with mass hanger, or hooked balls (5) or cylinders (5) to serve as Pendulum Bobs to serve as Pendulum Bob	1 set
Stopwatch or Lab Timer	1

Equipment Needed (With Computer Assistance)	Qtty.
Brass, Aluminum, Wood, and / or Plastic Pendulum	1
Photo gate	1
Balance	1
Base and Support Rod	1
String	1 m
Meter Stick	1

Procedure

The data sheet for this exercise will be provided by the instructor, who may either provide the sheet itself or give the format he wants you to follow when collecting, organizing, and presenting your data in the laboratory report.

Without the Assistance of the Computers

1. Attach a string to the pendulum clamp mounted on the provided stand. Ensure that you understand where the pivot point is.
2. Use the following set of angles (10°, 20°, 30°, 45°, and 60°) for timing the period. When timing the period, greater accuracy can be obtained by timing for ten periods and dividing the result by 10. Use one-half the smallest scale division of your measuring device to estimate the standard deviation in the period of the pendulum.
3. Make a graph of period versus angle, with the one standard deviation error bars displayed for the error in the period. Does your data show that the period has a dependence on angle? Why?
4. At an angle of 20 degrees, measure the period of the pendulum for five different lengths of the pendulum. Decrease the length of the pendulum by 10 cm for each trial. When timing the period, greater accuracy can be obtained by timing for ten periods and dividing the result by 10. Use one-half the smallest scale division of your measuring device to estimate the standard deviation in the period of the pendulum.
5. Make a graph of period versus length, with the one standard deviation error bars displayed for the period. Does your data show that the period has a dependence on length? Why? What sort of dependence?
6. Write a report, which includes: Purpose, Apparatus, Theory, Data (raw data in tables), Graphs, Discussion (sources of error), and Conclusion.

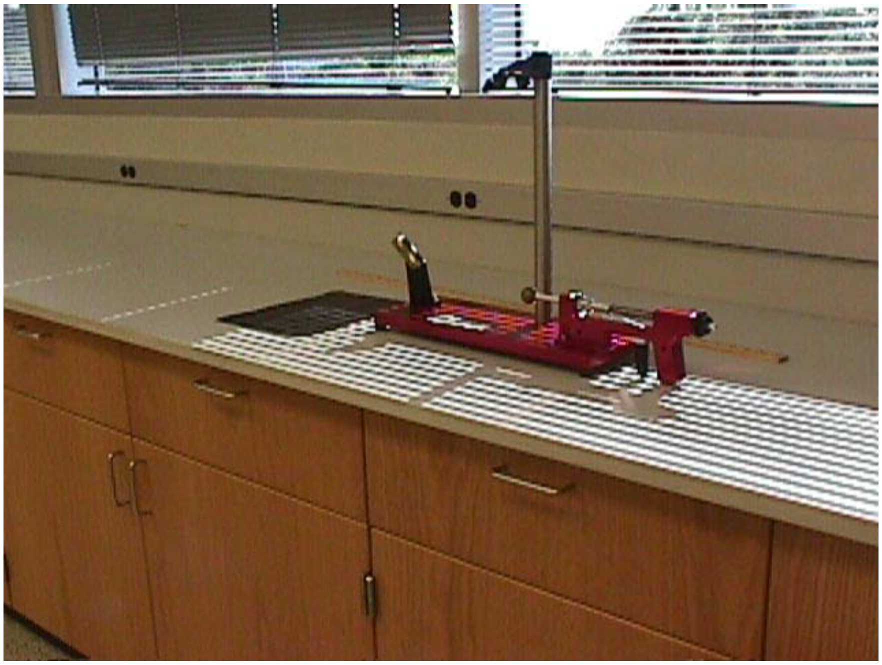
Bonus: Show that: $T \propto \sqrt{L}$ using a graphical method.

With the Assistance of the Computers

Please note that one can repeat the experiment both with and without the computers and compare the results. What are the advantages and disadvantages of each approach to the experiment? The following is the recommended for this lab.

1. Typically this step is completed during the setup process of the lab. If not, set up the timer so that the period measured after three successive blocks of the photo gate beam by the pendulum. To do this, click on the Timers button to activate the Timer Setup Window (ask for assistance from your instructor, lab assistant or laboratory specialist if you do not know how to do this).
2. Type ‘Pendulum Timer’ in the Label Box of the Timer Setup Window, then use the pick box to choose the Blocked option three times. When finished, click the Done button and the Pendulum Timer will appear in the data window.
3. Repeat Steps 2-6 in the first procedure (“Without the Assistance of the Computers”). Note that one can investigate the relationships between length and period, mass and period, and amplitude and period. In each case, the effects of air resistance are held constant, since the shape and size of the pendula are identical (not necessarily the case in the first set of procedures).

8. Conservation of Linear Momentum (Ballistic Pendulum or Air Table)



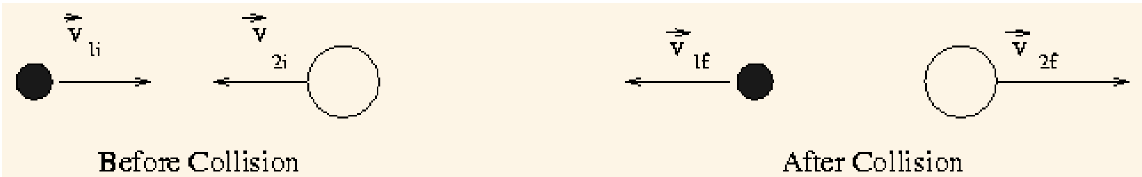
Purpose

The purpose of this lab is to calculate the initial velocity of a projectile using the principles of the conservation of linear momentum and the conservation of energy. An alternate objective is to verify experimentally that momentum is conserved in a collision

Introduction

Consider the following example: A fast moving car has more momentum than a slow moving car of the same mass, and a heavy truck has more momentum than a small car moving with the same speed. The more momentum an object contains, the harder it is to stop it, and greater effect it will have if it is brought to a sudden stop by impact or collision. A football player is more likely to be stunned if tackled by a heavy opponent running at top speed than by a lighter or slow moving tackler. A heavy, fast-moving truck can do more damage than a slow-moving motorcycle.

Collisions are a common occurrence in everyday life: a tennis racket or a baseball bat striking a ball, two billiard balls colliding, one railroad car striking another, a hammer hitting a nail, etc. (can you think of more examples?). When a collision occurs, the force usually jumps from zero at the moment of contact to a very large value within a very short time, and then abruptly returns to zero again.



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The total vector momentum of the system is conserved; it stays constant. Consider for example the collision of two balls. We assume the net external force on the system of two balls is zero- that is the only significant forces are those that each ball exerts on the other during the collision. The sum of the momentum is found to be the same before and after the collision. If m_1v_1 is the momentum of ball number 1 and m_2v_2 is the momentum of ball number 2, both measured before the collision, then the total momentum of the two balls before the collision is $m_1v_1+m_2v_2$. After the collision, the balls each have a different velocity and momentum. The total momentum after the collision will be $m_1v_1'+m_2v_2'$. In summary:

Momentum before = Momentum after

$$m_1v_1+m_2v_2 = m_1v_1'+m_2v_2'$$

No matter what the velocities and masses involved are, it is found that the total momentum before the collision is same as afterwards, whether the collision is head on or not, as long as no external force acts.

Theory

1D Collisions, Ballistic Pendulum

Note: One can combine this with the projectile motion part of experiment #3 and present both as a single lab entitled "Ballistic Pendulum". The concepts of conservation of energy can be represented mathematically by the following expressions:

$$\sum F_{ext} = \frac{\Delta p}{\Delta t} = 0 \qquad p_b = p_a \qquad \Delta E_k + \Delta E_p = 0$$

The second equation states that the momentum before a collision is equal to the momentum after a collision. The third equation describes the conservation of the total mechanical energy (kinetic and gravitational potential energy) of the system during an elastic collision. When a projectile collides with and sticks to another target, then the mass of the system after the collision is the sum of the mass of the projectile and the target before the collision. Since momentum is conserved in a collision, we have:

$mv_0 = MV$ where: m = mass of the particle
M = mass of the projectile plus pendulum

If the target is constrained to pivot on a rigid pendulum, then the potential energy at the top of the swing must be equal to the kinetic energy at the collision point. That is:

$$E_k(bottom) = E_p(top), \qquad E_k = \frac{1}{2}MV^2 \qquad E_p = Mgh$$

From the above equations the velocity of the projectile just before the collision can be found to be:

$$v_0 = \frac{M}{m}\sqrt{2gl(1-\cos\theta}$$

2D Collisions with Air Table

A consequence of Newton's third law is conservation of momentum. The momentum, **p**, of an object is defined as the product of an object's mass and its velocity:

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

and has units of kg·m/s in MKS units. Newton's third law states that

$$\mathbf{F}_{12} = -\mathbf{F}_{21}$$

i.e., that the force acting on object **1** by object **2** is equal in magnitude and opposite in direction as the force acting on object **2** by object **1**. In terms of momentum, Newton's second law states that (in the limit as $\Delta t \to 0$)

$$\mathbf{F} = m\mathbf{a} = m\frac{\Delta v}{\Delta t} = \mathbf{p}$$

The third law can be written

$$\Delta t\, \mathbf{p}_1 = -\Delta t\, \mathbf{p}_2$$

or

$$\Delta t\ (\mathbf{p}_1 + \mathbf{p}_2) = \Delta t\, \mathbf{p}_{\text{total}} = 0$$

Thus, for an isolated system, i.e., when no external forces are present, the total momentum of a system is constant:

$$\Delta t\, \mathbf{p}_{\text{total}} = \Delta t \sum_i \mathbf{p}_{\text{i}} = 0$$

and thus

$$\sum_i \mathrm{m_i}\mathbf{v}_{\text{i}} = \text{constant}$$

Applied to the collision of two objects, conservation of momentum states that

$$m_1\mathbf{v}_{1\text{o}} + m_2\mathbf{v}_{2\text{o}} = m_1\mathbf{v}_{1\text{f}} + m_2\mathbf{v}_{2\text{f}}$$

where $\mathbf{v}_{\text{io}}$ and $\mathbf{v}_{\text{if}}$ are the object's velocities before and after the collision, respectively.
The kinetic energy of an object is

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

In a collision, the total kinetic energy may or may not be conserved. A collision in which the total kinetic energy is conserved is an "elastic" collision. Otherwise, the collision is said to be "inelastic".

Equipment (1D Motion with Ballistic Pendulum)

Equipment Needed	**Qtty.**
Ballistic Pendulum	1
Laboratory Balance	1
Meter Stick	1
Protractor	1

Equipment (2D Motion with Air Table)

Equipment Needed	**Qtty**
Air table	1
Pucks with air supply	2
Sheet of marking paper	1
Ruler	1
Protractor	1
Lab balance	1

Safety Reminder

Never aim or fire the projectile launcher at a person.

Procedure--1D Collisions

1. Do a few tests of the apparatus to understand how it works, then find the angle of displacement for five trials. Record these values.
2. Carefully remove the pendulum support and measure the physical length (pivot point to the center of mass) of the pendulum, the mass of the projectile, and the mass of the projectile **with** the pendulum. Record these values in a table to be included with your lab report.
3. Calculate the average angle.
4. Calculate the pre-collision velocity of the projectile.
5. Write up your report using the standard format, which is: Purpose, Equipment, Theory, Data, Results and Discussion, and Conclusion. Your discussion should include answers to the following:
   - Is the friction of the pendulum a random or systematic error?
   - Will this source of error cause your calculated velocity to be less than or greater than the actual velocity?
   - Remember to express your final answer with the error—using the correct number of significant digits and the correct SI units.

For two bonus points: Calculate the kinetic energy before and after the collision. Compare these two results. Is the collision between the ball and the pendulum elastic or inelastic?

Optional: A variation making use of the photo gate timers and the computer can be implemented. Place one photo gate such that the ball passes through the beam the instant it fires; place the other 10 cm down from the first and find the average velocity, in meters per second, of the ball as it leaves the projectile gun. Compare this average velocity with your calculated value. If they are different, why are they different? Find the percent difference between your theoretical / calculated ("reference") value and your measured ("measured") value with the following formula:

$$\%difference = \frac{|\,reference - measured\,|}{reference} \times 100\%$$

Procedure--2D Collisions

1. Each group, in turn, will produce a tracing of the positions of two pucks as they undergo a collision on the air table. Each puck leaves a trail of dots at a certain frequency. Record the mass of the pucks and the frequency.

2. Measure the velocities of the two pucks before and after the collision. Do this by measuring the distance a puck travels and divide by the elapsed time. Next, choose the pre-collision direction of one of the pucks as the x direction. Measure the angles the velocities make with respect to the x direction.

Data Analysis

1. Show that the total momentum is the same before and after the collision.

2. Determine the total kinetic energy before and after the collision. Is the collision elastic or inelastic? What percent of the initial kinetic energy remains after the collision?

9. Torque, Equilibrium and the Center of Gravity

(Adapted from Jerry Wilson, *Physics Laboratory Experiments*, 4th Ed., pp.151-155, © 1994 Houghton Mifflin Company)

Purpose

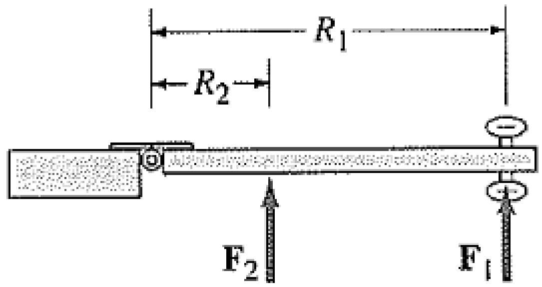
The purpose of this lab is to examine mechanical equilibrium and torque and how it applies to rigid bodies.

Introduction and Background

In many engineering applications, an important consideration is the conditions necessary for static and dynamic equilibrium. Several examples where this application is essential include beams in bridges and beam balances.

To make an object start rotating about an axis clearly requires a force. But the direction of this force and where it is applied are also important. For example consider an ordinary situation such as the door shown in the figure on the next page. If we apply a force F1 to the door as shown, we can see that the greater the magnitude F1 the more quickly the door opens. If we apply the same magnitude force at a point closer to the hinge say F2, we will find that the door will not open quickly. The angular acceleration of the door is proportional not only to the magnitude of the force, but is also to the perpendicular distance from the axis of rotation on the line along which the force acts. This distance is called the lever arm or moment arm, labeled as R1 and R2. If R1=3R2, then F2 must be three times as large as F1 to give the same angular acceleration.

Therefore Torque is defined as the product of the force's magnitude "*F*" and the perpendicular distance "*R*" from the axis of rotation, or *T= RF*.



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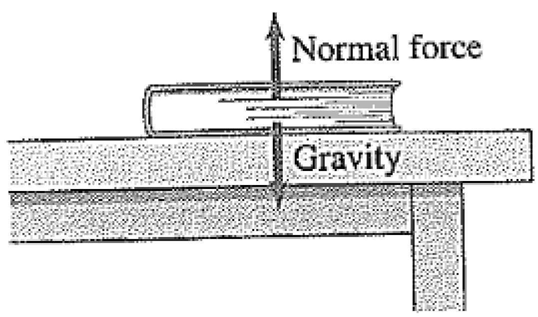
Objects within our experience have at least one force acting on them (gravity) and if they are at rest then there must be other forces acting on them as well so that the net force is zero. An object at rest on a table for example has two forces acting on it, the downward force of gravity and the normal force the table exerts upward on it. Since the net force is zero, the upward force exerted by the table must be equal in magnitude to the force of gravity acting downward. Such a body is said to be in equilibrium



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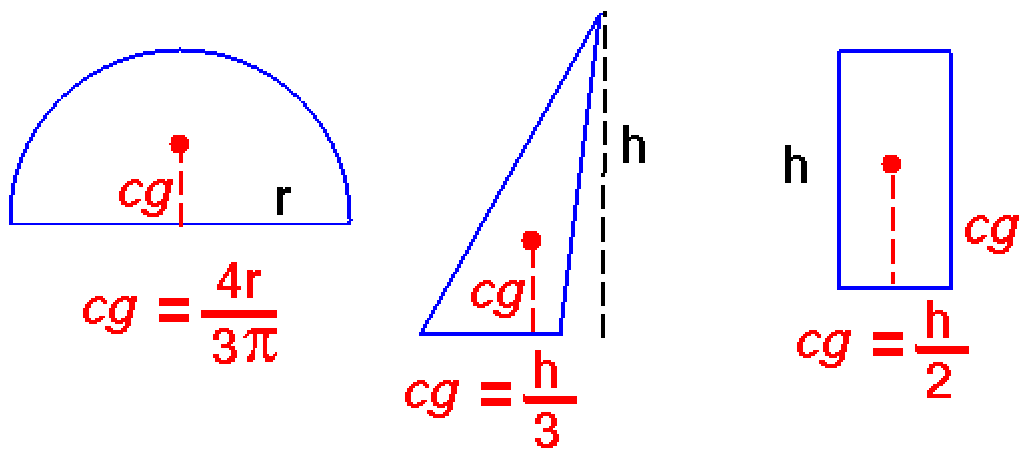
For an object to be in equilibrium it must not be accelerating, so the vector sum of all external forces acting on the body must be zero.

The center of gravity (CG) is the center of an object's weight distribution, where the force of gravity can be considered to act. It is the point in any object about which it is in perfect balance no matter how it is turned or rotated around that point.



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Theory

An object is said to be at rest, or in equilibrium, when the sum of the forces *F* and torques τ acting on a body are zero:

$$\sum F = 0$$
$$\sum \tau = 0$$

The first condition deals with translational equilibrium, that is, the body is not moving linearly or is moving with a constant linear velocity (such that a co-moving frame of reference sees the object “at rest”). The second deals with rotational equilibrium and either do not rotate (static case) or rotates with a uniform angular velocity (dynamic equilibrium case).

A torque or moment of force results from a force applied some distance from an axis of rotation. The magnitude of the torque is equal to the product of the force’s magnitude *F* and the perpendicular distance *r* from the axis of rotation to the force’s line of action. In short:

$$\tau = rF$$
$$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$$
$$\text{and } \tau = rF\sin\theta$$

with θ the angle between the **r** and **F** vectors.

This perpendicular distance *r* is called the lever arm or moment arm and has the units Newton-meter (N-m). Torques may be applied that result in counterclockwise- and clockwise motion. However, if these torques are balanced, such as no net motion occurs, the system is said to be in rotational static equilibrium. This condition is satisfied when:

$$\sum \tau = \sum \tau_{CC} + \sum \tau_{CW} = 0$$

where τ_{CC} and τ_{CW} are counterclockwise and clockwise torques, respectively.

The gravitational torques due to "individual" mass particles of rigid body define the center of gravity for a body. The center of gravity is the point of the body about which the sum of the gravitational torques about an axis through this point is zero. If one visualizes a rod of being made up of individual mass particles and the point of support is selected such that $\sum \tau = 0$, then

$$\sum \boldsymbol{\tau}_{\mathbf{cc}} = \sum \boldsymbol{\tau}_{\mathbf{cw}}$$

or

$$\sum_{CC} (m_i g) r_i = \sum_{CW} (m_i g) r_i$$

When the rod is in equilibrium, it is supported by a force equal its weight, and this support force is directed through the object's center of gravity. If the object's weight were concentrated at its center of gravity, so would be its mass, and we often refer to an object's center of mass instead of its center of gravity. These points are the same as long as the acceleration due to gravity *g* is constant (as in a uniform gravitational field). Note that *g* can be factored and divided out of the above *weight* equations, leaving *mass* equations.

Equipment

Equipment Needed	**Qtty.**
Meter stick	1
Support stand	1
Lab balance	1
String and knife – edge clamp or 4 knife-edge clamps (3 with wire hangers)	4
Hooked weights (1 of the 50g, 2 of the 100g, and 1 of the 200g,) or weight hangers and slotted weights to get desired masses	4 total
Unknown mass with hook (Optional)	1

Procedure

1. Determine the mass of the meter stick. Place a knife-edge clamp on the meter stick at the 50 cm line and place the meter stick on the support stand. Adjust the meter stick through the clamp until the meter stick is balanced on the stand. Tighten the clamp and record the distance of the balancing point x_o from the zero end of the meter stick.
2. *Case 1: two known masses*. With the meter stick on the support stand at x_o, suspend a mass m_1= 100 g at the 15-cm position on the stick. Suspend a second mass, m_2 = 200 g on the opposite side of the stick as m_1 and place it at the distance x_i needed to balance the meter stick. Record that measurement, $r_i = x_i - x_o$, which is simply the moment arm of the object. If you use the hanger clamps to suspend the masses, remember to include their masses in the determination of each torque. Compute the torques.

3. *Case 2*: *Three known masses*. Repeat the activities of #2, except use the following masses: m_1 = 100 g at the 30-cm position and m_2 = 200 g at the 70-cm position. Suspend m_3 = 50 g and adjust the moment arm of this mass to balance out the meter stick.
4. *Case 3: Unknown mass*. With the meter stick on the support stand at x_o, suspend the unknown mass (m_1) near one end of the meter stick (e.g. near the 10-cm mark). Suspend from the other end an appropriate known counter mass m_2 (e.g. 200 g) and adjust its position until the meter stick is in balance. Record the value of the known mass and the moment arms. Compute the value of the unknown mass by the method of moments and compare with the measured value by calculating the percent error.
5. *Case 4*: *Instructor's choice (optional).* Your instructor may have a particular case for you to investigate, and if so, the conditions will be given.

10. Rotational Inertia of a Disk and Ring (With the PASCO Rotary Motion Sensor)

(Adapted from the *Instruction Manual and Experiment Guide for the PASCO Scientific Model CI-6538 Rotary Motion Sensor*, pp. 15-20)

Purpose

The purpose of this experiment is to find the rotational inertia of a ring and a disk experimentally and verify that these values correspond to the calculated theoretical values.

Background and Theory

Rotational inertia is defined as an object's resistance to rotation. Rotational inertia of an object depends on the mass of the object, shape of the object, and the distribution of mass throughout the object. The higher the rotational inertia of an object, the resistance to being spun. The more mass in an object, the more inertia it has, the less it responds to being pushed. The outside parts of a rigid spinning object move faster than inside parts near the axis.

For example consider swinging a baseball bat either from the handle end or barrel end. A baseball bat is easier to swing when swung from the barrel end than the handle end because the rotational inertia in the barrel end is lesser compared to the rotational inertia in the handle end. A light push on a ping-pong ball sets it in motion, because it has a small inertia, while a light push on a bowling ball or a football has little noticeable effect because each has more inertia. Spinning a coin is a lot easier than spinning a lead block or a piece of rock because lead block or rock has a lot more mass which means a lot more inertia compared to a coin. The rotational inertia of a pulley is higher near the edge than near the axis.

The rotation inertia, I, of a ring about its center of mass is given by:

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

where M is the mass of the ring, R_1 is the inner radius of the ring, and R_2 is the outer radius of the ring. The rotational inertia of a disk about its center of mass is given by:

$$I = \frac{1}{2}MR^2$$

where M is the mass of the disk and R is the radius of the disk. To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since $\tau = I\alpha$,

$$I = \frac{\tau}{\alpha}$$

where α is the angular acceleration, which is equal to a/r (a = acceleration), and τ is the torque caused by the weight hanging from the thread that is wrapped around the base of the apparatus. Rearranging to solve for torque:

$$\tau = rT$$

where r is the radius of the pulley about which the thread is wound, and T is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass m gives

$$\sum F = mg - T = ma$$

Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the angular acceleration is measured, the torque and the linear acceleration can be obtained from the calculation of the torque.

Equipment

Equipment Needed	**Qtty.**
Mini-Rotational Accessory	1
Base and Support Rod	1
Paper clips (for masses < 1 g)	Several
Rotary Motion Sensor	1
Mass and Hanger Set	1
Triple Beam Balance	1
Vernier Calipers	1

Procedure

1. This should already be set up for you upon arrival but if not, the setup is done as follows: mount the Rotary Motion Sensor (RMS) to the support rod and connect it to the *Science Workshop 750 Interface*. Mount the clamp-on Super Pulley to the sensor. Tie one end of the string to the mass hanger and the other to one of the levels of the 3-step spool on the RMS.
2. Drape the string over the Super Pulley such that the string is in the groove of the pulley and the mass hanger hangs freely. NOTE: the clamp-on super pulley must be adjusted at a slight angle so the thread runs in a line tangent to the point where it leaves the 3-step spool and straight down the middle groove on the clamp-on Super Pulley.
3. Weigh the ring and disk to find their masses and record these in your Data Sheet. Next, measure the inside and outside diameters of the ring and calculate the radii, R_1 and R_2; then measure the diameter of the disk and calculate the radius R.

Measure the diameter of the spool about which the thread is to be wrapped and find the radius.

4. Place the disk directly on the spool and place the mass ring on the disk, inserting the ring pins into the holes in the disk.
5. Run Data Studio and install the RMS. This should already be done for you but if not, here is how you can set it up: double click its icon to open the sensor dialog box for the RMS. Ensure that the Divisions / Rotation radio button is in the 360 position, and select the appropriate spool in the linear calibration pop-up menu, then click OK.
6. Click and drag a Graph to the RMS icon and select “Angular Velocity” from the built-in calculations window; click OK. Then put 50 g of mass on the Mass Hanger and wind up the thread. Click on the Start button, and then release the 3-step spool, allowing the mass to fall. Click on the Stop button, , to end the data collection. NOTE: to avoid erroneous data, click the stop button before the mass reaches the floor or the end of the thread.
7. In the Graph Display window, click on the Statistics button, , then select the linear curve fit from the pop-up menu. The slope of the linear fit represents the angular acceleration (α) and should be recorded in the Lab Report.
8. To find the Acceleration of the disk alone, remove the ring from the apparatus and repeat steps 1 through 7 in the procedure. Since the inertia found above is for both disk and ring, it is necessary to repeat the experiment once more to find the inertia of just the ring. This value can be subtracted from the total to find the value of the disk.

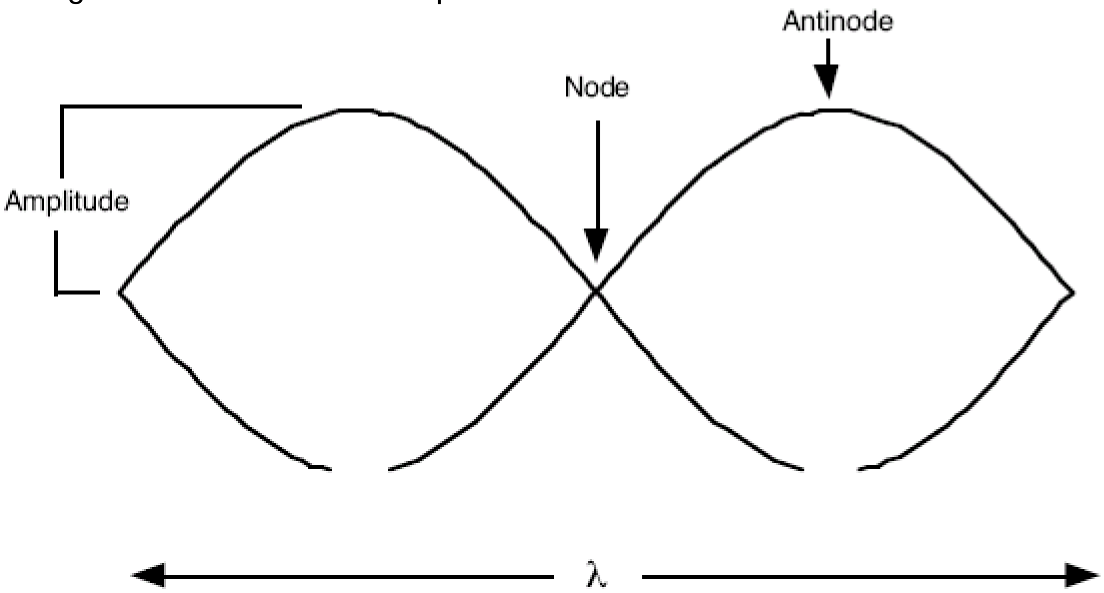
11. Standing (Transverse) Waves using Vibrating Strings

Purpose

The purpose of this lab is to calculate the driving frequency causing standing waves on a string.

Introduction and Theory

A standing wave is composed of two waves traveling in opposite directions, which are generating an additive interference pattern.



If the amplitudes are much less than the length of the string, then the speed of the wave through the string in terms of the mechanical properties of the string (inertia and elasticity) can be parameterized as:

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

where v = phase velocity (the speed of the wave along the string)

$F = mg$, the tension on the string

μ = mass per unit length of the string

Wave length and frequency are related to phase velocity as: $v = \mu f$

where f = frequency (In this case, of the driving source, and so is fixed.)

λ = wave length (Note, the distance between two adjacent nodes is λ / 2)

The above two equations can be combined to obtain an equation in terms of the measurables:

$$\lambda = \left(\frac{\sqrt{g}}{f\sqrt{\mu}} \right) \sqrt{m}$$

This equation has *m* as the independent variable and λ as the dependent variable. It is similar in form to the equation of a straight line: $y = a + bx$. By comparison of the coefficients of the independent variable we obtain for the slope:

$$b = \frac{\sqrt{g}}{f\sqrt{\mu}}$$

Solving for the frequency, we find:

$$f = \frac{\sqrt{g}}{b\sqrt{\mu}}$$

where f = driving frequency

μ = mass per unit length

b = slope of the best fit line for λ versus *m*

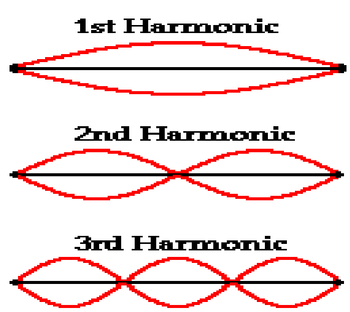
$g = 9.80 \text{ m / s}^2$

When musical instruments are set into vibration (either by striking, plucking, or blowing) standing waves are produced and the object vibrates at its natural frequency or resonant frequency. The vibrating source comes in contact with air and pushes the air column to produce sound waves that travel outward. Some of the widely used instruments that make use of vibrating strings are violin, guitar and piano.

Consider a guitar. If we strike one end of the guitar keeping the other end fixed, a continuous wave will travel down to the fixed end and will be reflected back. This vibration traveling back and forth produces the sound at a particular frequency. The same is true for violin and piano. The diagram at the start of this write-up above depicts one of the natural patterns of vibrations for a string.

(*www.howstuffworks.com*)

The above pattern is not the only pattern of vibration for a guitar string. There are number of patterns by which the guitar string could naturally vibrate. Three other patterns are shown in the diagram below. Each and every standing wave pattern is referred to as a harmonic of the instrument. Three diagrams below represent the standing wave patterns for the first, second, and third harmonics of a guitar string. First harmonic is the first lowest fundamental frequency, second harmonic is the second lowest fundamental frequency and the third harmonic is the third lowest fundamental frequency.



(*www.howstuffworks.com*)

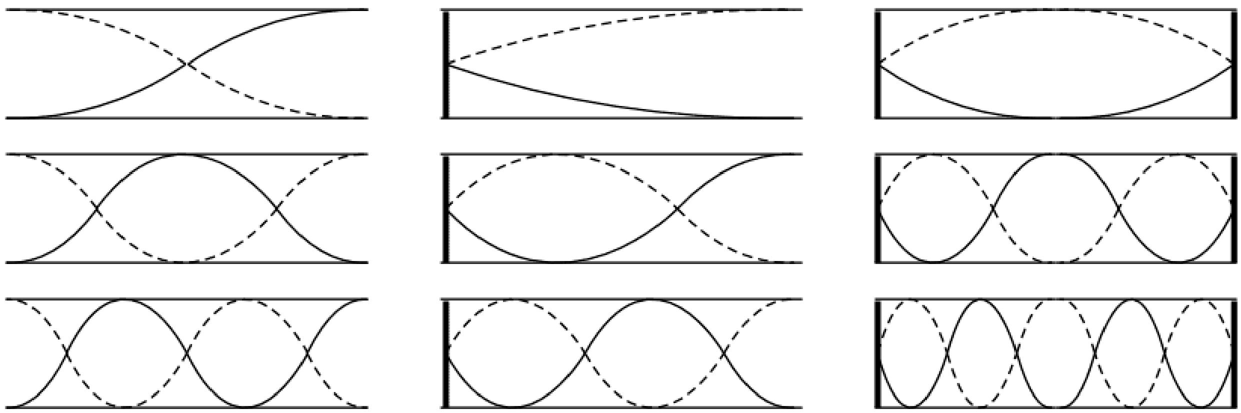
Equipment

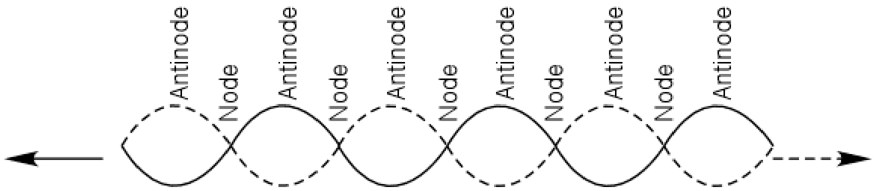
Equipment Needed	Qtty.
Electronic String Vibrator	1
Clamps & Support Rod	1
Pulley with rod support	1
String	~1.5m
Weight Hangers & Slotted Weights	1 set
Laboratory Balance	1
Cartesian graph paper	1 sheet

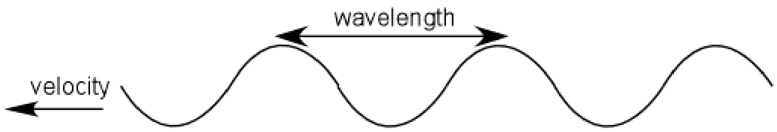
Procedure

1. The instructor will give you the mass per unit length of the string.

2. How would you determine the mass per unit length of the string?
3. Use the apparatus to generate a table of wavelength versus hanging mass. Vary the amount of mass on the weight hanger to find maximum amplitudes for each of 2 nodes, 3 nodes, . . . , 6 nodes(see the diagram below). Measure the associated wavelengths. Remember that the wavelength is the distance between any two nodes or antinodes.







4. Plot a graph with wavelength on the ordinate and the square root of the mass on the abscissa.
5. Draw a best-fit “average” line through the points.
6. Using a large baseline, find the slope of the graph. Do not use data points to find the slope!
7. Calculate the frequency of the driving source. Use the slope of the graph in this calculation. Do not use some arbitrary set of data points!
8. Assume that the overall relative error in the calculated frequency was no more than 10% and calculate the absolute error in the calculated frequency.
9. Correctly write your results in SI units (including the error). Compare with the expected result of either 60 or 120 Hertz. Is your value within experimental error of one of the expected results?

10. Remember the lab report is to consist of: Group, date, purpose, apparatus, theory, data, graph, discussion, and conclusion.
11. The discussion should include sources of error and an answer to the question in step two.
12. Your instructor may substitute a variable wave driver for the fixed frequency driver and ask you to find the standing waves that appear as you change the frequency (at constant tension).

Bonus Question:

Stringed musical instruments, such as violins and guitars, use stretched strings to create musical tones. Use the following equation as reference (and any previous equations, if necessary) to explain:

a. How tightening and loosening the strings tune them to their designated tone pitch.
b. Why the strings of lower tones are thicker or heavier than strings of higher tones.

$$F = (\lambda f)^2 \mu$$

12. Computer Experiment Simulation (Classical Mechanics)

Introduction

One of the many conveniences of computers is their powerful ability to simulate natural phenomena. Computer simulations save scientists billions of dollars per year by avoiding expensive experiments in wind tunnels and blast chambers as two examples. Computer simulations can be performed to simulate a phenomenon that we cannot readily access, such as the gas flows inside a star in the process of going supernova, the fluctuations of an atom, and the evolution of a solar system over billions of years' time. Back on Earth, much simpler simulations can be used in the classroom to repeat live experiments using an array of initial conditions, enabling students to see clearly and quickly how changing parameters can change the outcome of an experiment.

In this Lab, we are going to run such a simulation. The assignment is to select an experiment of your choosing in the realm of Classical Mechanics and run through that experiment several times, virtually, changing the initial conditions and recording the outcomes of each run. Alternatively, the assignment may be to work with the CPU simulation program that resides on all of the computers.

Equipment

Equipment Needed
Computer with Internet access (the instructor will decide whether to use the website given below, another website, or a CD-ROM simulation program),
-OR-
Physics Computer Simulation Programs such as Constructing Physics Understanding or equivalent

Procedure

There is a large number of simulation packages available, from CD's and DVD's in the Physics Learning Center, to websites that offer applets and downloads that demonstrate various principles of physics. The instructor may use one or more of these or another website for this experiment. This lab will focus on one such simulation within the area of classical mechanics from a source determined by the professor.

Write up a brief report, similar to those you have been doing all semester. Be sure to indicate the experiment name, the variables involved (both the ones you changed and the ones not allowed to change), and the differences in the outcomes of the experiment resulting from changing the variables. If you did this experiment as an extension of another performed earlier this semester, state which one, how the outcome(s) of this one were different or similar to that performed earlier, and the advantages/disadvantages (including the presence and extent of error) of doing the experiment either "live" in the lab or on computer as a simulation.

Suggested Pre-lab Activities

Activities written by Dr. Gary Erickson

Pre-Lab #2: Vectors on a Force Table

Name: ___________________________ **Course:** ___________________

Date: _____________________

Answer the following questions.

1. Scalars are physical quantities that can be completely specified by their __________________.

2. A vector quantity is one that has both _____________________ and _____________________.

3. Classify each of the following physical quantities as vectors or scalars:

(a) Volume _________________

(b) Velocity _________________

(c) Force _________________

(d) Density _________________

(e) Speed _________________

(f) Acceleration ______________

4. Where $\mathbf{F_1}$ stands for a force vector of magnitude 30.0 N and $\mathbf{F_2}$ stands for a force vector of magnitude 40.0 N each acting in the directions shown in the Figure below, what are the magnitude and direction of the resultant vector obtained by the addition of these two vectors?

Magnitude = _______________N Direction (relative to *x* axis) = ________degrees

Pre-Lab #3: Free-Fall and Projectile Motion

Name: _________________________ **Course:** __________________

Date: ____________________

The carts pictured below are all moving in a straight line to the right. The pictures were taken 1.00 s apart. Circle the correct choice (a), (b), (c), or (d) to the questions below.

1. These pictures show a cart that is moving at constant velocity. (a) (b) (c) (d)

2. These pictures show a cart that has positive acceleration. (a) (b) (c) (d)

3. These pictures show a cart that travels at a constant velocity and then has a positive acceleration. (a) (b) (c) (d)

4. These pictures show a cart that has negative acceleration. (a) (b) (c) (d)

5. A projectile is fired in Earth's gravitational field with a horizontal velocity of $v = 9.00$ m/s.

(a) How far does it go in the horizontal direction in 0.550 s? _______________

(b) How far does the projectile fall in the vertical direction in 0.550 s? _______________

6. A projectile is launched in the horizontal direction. It travels 2.050 m horizontally while it falls 0.450 m vertically, and then strikes the floor.

(a) How long is the projectile in the air? _______________

(b) What was the original velocity of the projectile? _______________

Pre-Lab #4: Static and Kinetic Friction

Name: ___________________________ **Course:** ___________________

Date: _____________________

Answer the following questions. (Assume $g = 9.80\ \text{m/s}^2$.)

1. Suppose a block of mass 25.0 kg rests on a horizontal plane, and the coefficient of static friction between the surfaces is 0.220. What is the maximum possible static frictional force that could act on the block? _________________

2. What is the actual static frictional force that acts on the block if an external force of 25.0 N acts horizontally on the block? _________________

3. A 5.00 kg block rests on a horizontal plane. A force of 10.0 N applied horizontally causes the block to move horizontally at constant velocity. What is the coefficient of kinetic friction between the block and the plane? _________________

4. For either type of coefficient of friction, what is generally assumed about the dependence of the value of the coefficient on the area of contact between the two surfaces? _________________

5. Suppose a block of mass M lies on a plane inclined at an angle θ. Let θ_s be the maximum angle at which the mass can remain static on the plane. Let θ_k be the angle at which the block slides down the incline at constant speed. Show that the coefficient of static friction is $\mu_s = \tan\theta_s$ and that the coefficient of kinetic friction is $\mu_k = \tan\theta_k$. (Provide a force diagram.)

Pre-Lab #5: Centripetal Force

Name: ________________________ **Course:** _________________

Date: ___________________

Answer the following questions.

1. If a particle moves in a circle of radius R at constant speed v, its acceleration is

(a) directed toward the center of the circle
(b) equal in magnitude to v^2/R
(c) because the direction of the velocity vector changes continuously
(d) all of the above are true.

2. A particle of mass 0.350 kg moves in a circle of radius R = 1.35 m at a constant speed of v = 6.70 m/s. What is the magnitude and direction of the centripetal force acting on the particle?

Answer: _________________________

3. A 0.500-kg particle moves in a circle of radius R = 0.150 m at constant speed. The time for 20 complete revolutions is 31.7 s.

(a) What is the period T of the motion? Answer: ___________________

(b) What is the frequency f of the circular motion? Answer: ___________________

(c) What is the speed v of the particle? Answer: ___________________

(d) What is the magnitude of the centripetal acceleration? Answer: ___________________

Pre-Lab #6: Hooke's Law for a Spring

Name: ________________________ **Course:** _________________

Date: ___________________

Answer the following questions. (Assume $g = 9.80\ \text{m/s}^2$.)

1. A massless spring having a spring constant $k = 8.75$ N/m is hung vertically. If the spring is displaced 0.150 m from its equilibrium position, what is the force that the spring exerts? _______________

2. A 400-g mass is suspended from this spring. What is the displacement of the end of the spring due to the weight of the mass? _______________

3. Suppose this mass is allowed to oscillate on the spring. What is the period of the oscillation? _______________

4. What is the frequency of the oscillation? _______________

5. A 0.100-kg mass suspended vertically on a spring takes 10.94 s to undergo 20 oscillations. What is the spring constant of the spring? ______________

Pre-Lab #7: Conservation of Momentum

Name: __________________________ **Course:** ___________________

Date: _____________________

Before **After**

Referring to the figure above, answer the following questions:

1. A particle of mass m_1 = 1.000 kg moves at speed v_1 = 0.500 m/s. It collides with a particle of mass m_2 = 2.000 kg at rest.

(a) What is the total momentum of the system in the x direction before the collision?

Answer: ________________

(b) What is the total momentum of the system in the y direction before the collision?

Answer: ________________

2. After the collision, m_1 moves with speed v_3 at an angle $\theta_3 = 315.0^o$ with respect to the x axis, and m_2 moves with speed v_4 at an angle $\theta_4 = 30.0^o$ with respect to the x axis. Write an expression for the total momentum of the system in the x direction and another expression for the total momentum in the y direction after the collision in terms of the symbols m_1, m_2, v_3, v_4, and angles θ_3 and θ_4.

x momentum: ____________________________

y momentum: ____________________________

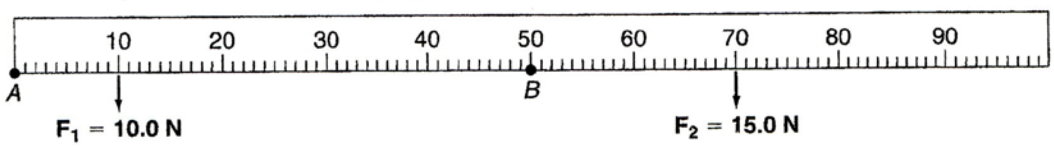
3. Equate the expression for the x component in Question 2 to the value of the x component in Question 1. Equate the expression for the y component in Question 2 to the value of the y component in Question 1. In the resulting two equations v_3 and v_4 are the only two unknowns. Solve the two equations for v_3 and v_4. Show work below.

v_3 = ________________ v_4 = ________________

Pre-Lab #8: Torque, Equilibrium, and Center of Gravity

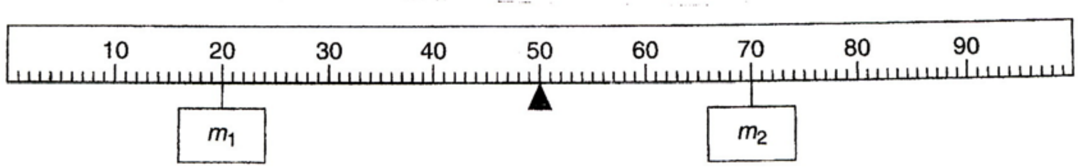
Name: ___________________________ **Course:** ___________________

Date: _____________________



1. For the meter stick shown above, the force $F_1 = 10.0$ N acts at 10.0 cm. What is the magnitude of the torque due to F1 about an axis through point A perpendicular to the page? Is the torque clockwise, or is it counterclockwise? _________________

2. In the figure the force $F_2 = 15.0$ N acts at the point 70.0 cm. What is the magnitude of the torque due to F_2 about an axis through point B and perpendicular to the page? Is the torque clockwise, or is it counterclockwise? _________________



3. In the figure above, if the mass $m_1 = 0.100$ kg acts at 20.0 cm, what is the value of mass m_2 that must be placed at the position 70.0 cm shown to put the system in equilibrium? Assume the meter stick is uniform and symmetric. Show your work. _________________

Pre-Lab #9: Rotational Inertia

Name: ___________________________ **Course:** ___________________

Date: _____________________

(Show your work in the space provided. Even if you substitute an incorrect answer from an earlier part, if your approach is correct, then credit will be given.)

1. A mass hung on a string that is wrapped around an axle on a wheel produces a tension in the string of 6.00 N. The axle has a radius of 0.050 m. The wheel has a mass of 4.00 kg, a radius of 0.100 m, and a thickness of 0.050 m. What is the torque produced by the tension on the axle?

Answer: _________________

2. Regarding the shape of the wheel as that of a uniform, solid cylinder, what is the moment of inertia of the wheel?

Answer: _________________

3. What is the angular acceleration α of the system?

Answer: ________________

4. With what linear acceleration a does the mass on the end of the string fall?

Answer: _______________