

Physics 2511 Laboratory Manual



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The following is a list of fifteen experiments prepared for Physics 2511, University Physics Laboratory. Of this list, ten to twelve will be selected by the instructor to be performed during a given semester. Many of these labs involve use of computer interface equipment which works with the Macintoshes in room NSCI 307. In general, the computerized version of a particular lab is presented alongside the traditional version, giving the class a choice of whether or not to use the computer interface equipment for that particular lab. Many of the labs have the option to be performed with the assistance of electronic workbooks, which guide the student step-by-step through the experiment. The introductory part of this version of each is included in this manual, then the student would transition to the workbook at a particular point in the exercise. Help for using the computers and the computer-interfaced laboratory equipment is located in a separate manual.

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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. 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-majors). Since this is a manual for the University Physics Laboratory, a discussion on error propagation follows.

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

$$\begin{array}{l} y = f(x, z) \\ \text{or} \quad y = f(x_1, x_2, \dots, x_n) \end{array}$$

In all experimental measurements there is a certain amount of error or uncertainty. We need to determine how sensitive the calculated independent values are with respect to the measured dependent values. Using statistics we find that if $y = f(x_1, x_2, \dots, x_n)$, and if $(\sigma_1, \sigma_2, \dots, \sigma_n)$ are the errors on (x_1, x_2, \dots, x_n) , then: $\sigma_y = \sigma_1$

$$\sigma_y = \sqrt{\left(\sigma_1 \frac{\partial f}{\partial x_1}\right)^2 + \left(\sigma_2 \frac{\partial f}{\partial x_2}\right)^2 + \dots + \left(\sigma_n \frac{\partial f}{\partial x_n}\right)^2}$$

where σ_y is the error in the calculated value of y . For example: suppose you measure x and z and then wish to calculate the functional dependence given by:

$$\begin{array}{ll} y = xz^2 & y = x + z \\ \sigma_y = \sqrt{\sigma_x^2(z^2)^2 + \sigma_z^2(2xz)^2} & \text{or} \quad \sigma_y = \sqrt{\sigma_x^2(1)^2 + \sigma_z^2(1)^2} \\ \sigma_y = y \sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{2\sigma_z}{z}\right)^2} & \sigma_y = \sqrt{\sigma_x^2 + \sigma_z^2} \end{array}$$

The expression for error is the same for both x/y and xy . Why?

The steps required to correctly propagate error through a physics equation:

1. Find your answer.
2. Use the error propagation equation to plug in numbers and find the error.
3. Write the final answer as: $y \pm \sigma_y$.

The measured errors can be estimated from:

1. If only one measurement was taken, use $\frac{1}{2}$ 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:

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

Experimental Errors

- **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

- exact factors have no error (e.g., 10, 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 $\rightarrow 2.3 \pm 0.4$ units
 - NOTE: hand-held calculators give answers that generally have a false amount of precision.

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

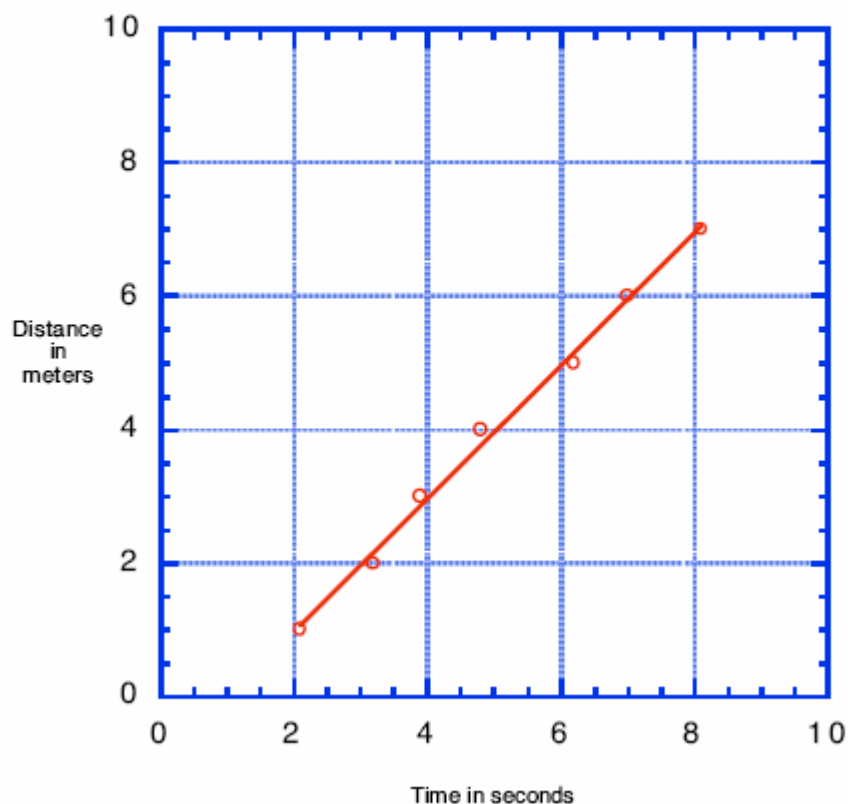
Graphing Techniques

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:
$$x = x_0 + vt$$
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.

Determination of Velocity



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 many 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: $\sqrt{x} + 2$ is not the same as $\sqrt{x + 2}$, nor is x^2 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 next 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.

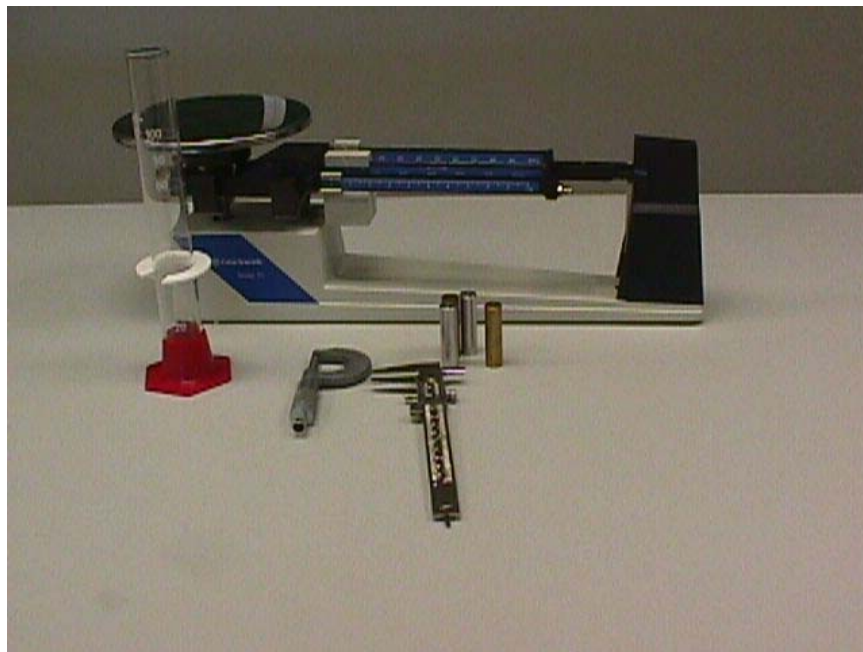
Results and Discussion: Include a discussion of some of the sources of experimental error or uncertainty. If appropriate, should also include a comparison of various experimental errors. For example: We found that our value of the density, within one standard deviation, has a range of 2.68 to $2.78 \times 10^3 \text{ kg/m}^3$. 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 $(2.73 \pm 0.05) \times 10^3 \text{ kg/m}^3$. We selected aluminum as the material composing our cylinder because the density of aluminum, $2.70 \times 10^3 \text{ kg/m}^3$, 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.

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 and 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.

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	Qty.
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
 - 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 Trendline” from the list
 - i. A box will appear entitled “Add Trendline”. 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^2 value (an index of goodness of fit) in your report.
 - j. Save your file as groupxphys2511-00y.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. Calculate the error in the density using the following formula (The factor of 2 in the 3rd term is due to the power of 2 for d in the equation for density).

$$\sigma_{\rho} = \rho \sqrt{\left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{\sigma_l}{l}\right)^2 + \left(\frac{2\sigma_d}{d}\right)^2}$$

- Estimate the error in the mass measurement using one half the smallest scale division.
- Estimate the error in the cylinder dimension measurements using the standard deviation as obtained from your calculator or defined by the formulas on page 4.
- What do you use as the best estimation for σ if all measurements produce the same value?

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 the densities in the following table?

Aluminum	2.70×10^3	kg / m ³
Chromium	7.19×10^3	kg / m ³
Copper	8.93×10^3	kg / m ³

Iron	7.86×10^3	kg / m ³
Steel	7.82×10^3	kg / m ³
Brass	8.40×10^3	kg / m ³
Nickel	8.75×10^3	kg / m ³

6. Use of the micrometer. (For this section write all measured values in micrometers.)
- 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.

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:

$$\mathbf{A} = A_x \hat{i} + A_y \hat{j} \text{ or } \mathbf{A} = \{A, \theta_A\}$$

Where \hat{i} , \hat{j} 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 \mathbf{A} upon the Cartesian axis are: (i.e., polar to Cartesian transformation)

$$A_x = \mathbf{A} \cdot \hat{i} = A \cos \theta_A, A_y = \mathbf{A} \cdot \hat{j} = A \sin \theta_A$$

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:

$$\mathbf{B} = B_x\hat{i} + B_y\hat{j}$$

The sum of the two vectors is:

$$\mathbf{R} = \{R, \theta_R\} = \mathbf{A} + \mathbf{B} = (A_x + B_x)\hat{i} + (A_y + B_y)\hat{j}$$

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:

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

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

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

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	Qty.
Force Table with 4 pulleys	1
Four Weight hangers	1
Set of slotted weights (masses)	1
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: \mathbf{A} has an angle of 30° and a mass of 200 grams
 \mathbf{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.
 - 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 experimental, graphical, and analytical results of part one. Which method do you think gives the more accurate results? Why?
3. For the experimental results of part 1 show that: $\sum \mathbf{F}_i = 0$
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 \mathbf{A} and \mathbf{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 \mathbf{A} is a force vector and so must be in Newtons ($A = mg$). Values should be stated using 3 significant figures

3. Introduction to Computer Interface Experiments, the Linear Air Track, and Linear Motion

(Adapted from Halliday/Resnick/Walker *Probeware Lab Manual*, 6th Ed., pp. 5-9, © 2003 John Wiley & Sons, Inc.)



Purpose

The purpose of this lab is to become familiar with the Data Studio software through an investigation of basic linear motion. In doing so, the student gains an understanding of the relationships between position, velocity, and acceleration and how these relationships can be used to describe an object's motion.

Introduction and Theory

Velocity is simply the change of position of an object over a unit of time. The velocity at any instant can be obtained from the average velocity by shrinking the time interval Δt closer and closer to 0. As the Δt approaches 0, the average velocity approaches a limiting value, which is the velocity at that instant. In summary:

$$v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$$

Two features of the instantaneous velocity v are noticed here. First, v is the rate the particle's position x is changing with respect to t , that is, v is a derivative of x with respect to t . Second, v at any instant is the slope of the curve describing the particle's position as a function of time. Unlike speed, a scalar quantity that has a magnitude but not a direction, velocity is a vector quantity with magnitude and direction.

When the velocity of the particle changes, it is said to accelerate. Considering its motion along an axis, the average acceleration, a_{avg} over a time interval Δt is given by:

$$a_{\text{avg}} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}$$

The particle has velocity v_1 at time t_1 then velocity v_2 at time t_2 , with the instantaneous acceleration (or simply acceleration) being the derivative of the velocity with respect to the time:

$$a = \frac{dv}{dt} = \frac{d}{dt} \left(\frac{dx}{dt} \right) = \frac{d^2x}{dt^2}$$

In summary, the acceleration of a particle is the rate at which its velocity is changing at that instant; the velocity of the particle is the rate that the position is changing at that instant. The acceleration at a particular point in time can be found graphically by finding the slope at that corresponding point on the curve of $v(t)$.

Equipment

Equipment Needed	Qty.
Air Track with Air Supply	1
Laboratory Lift or Wooden block	1
Motion Sensor	1
Cart with rectangular 100 mm flag attachment	1



Science Workshop 750 Interface






Motion Sensor II

Procedure

1. Lift the end of the track closest to the computer using the wooden block or laboratory lift and align the sensor.
2. The motion sensor should be set to the narrow beam setting (for distances up to 2 m for a cleaner return signal) and placed on the support rod at the high end of the track (which should be immediately next to the computer).
3. Make sure the sensor is lined up with the “sail”, or rectangular flag (100 mm in length) on the cart and nothing else is blocking the sensor. The sail should be set

perpendicular to the long axis of the track, to provide the maximum surface area for the motion sensor to “see”.

4. (NOTE: at this point, the focus of the experiment switches to the electronic workbook for this exercise. If this is available, and if instructed by your instructor, follow the instructions in the e-workbook for performing this experiment. Otherwise, use the instructions printed in this laboratory manual.)
5. Make sure two graphs (position and velocity) are visible on the computer display, tiled adjacent to each other (one on top, the second on the bottom) at the largest size possible. If this is not the case, notify the instructor or his assistant.
6. Hold the cart still about 15 cm in front of the motion sensor and click **Start**  to begin taking data. Keep the cart stationary for about two seconds, and then release it (again making sure nothing is blocking the beam of the sensor).
7. If the plot is rough, try adjusting the tilt angle of the Motion Sensor and retake the set of data. We can also tape a white index card or piece of paper to the sail to increase its visible cross-section to the motion sensor.
8. Click **Stop**  when the cart has reached the end of the track.
9. Observations (Record in the Data Section of your Lab Report):
 - a. What is the shape of the position versus time graph (make a rough drawing in your Data Sheet or print out the graph)?
 - b. What is the shape of the velocity versus time graph (again, illustrate this with a drawing in your Data Sheet or with a graphical printout)?
10. Analysis (Record your responses in the Results Section of your Lab Report):
 - a. Using the tools available on the computer, find the acceleration from position versus time. Here's how:
 - i. Highlight a smooth part of the position graph.
 - ii. Click the **Fit**  menu and select **Quadratic Fit**.
 - iii. The “A” is the coefficient of the squared term in the curve fit formula...record the value of this coefficient.
 - b. Find the acceleration from velocity versus time:
 - i. Highlight a smooth part of the velocity graph.
 - ii. Click the Fit menu and select Linear Fit.
 - iii. The “m” value is the slope. Record the slope as the acceleration
 - c. Compare the two values of acceleration:
 - i. Multiply the value of “A” from part “a” by 2 to get the acceleration based on position versus time and record this value.
 - ii. Compare this value to the slope (“m”) from part “b” of the Linear Fit for the velocity versus time graph (this is the acceleration based on velocity versus time).
11. Compute the % difference of your two values of acceleration and record this in the Conclusions part of your report. What were the sources of error from this experiment?

$$\% \text{ difference} = \left| \frac{acc.\text{position} - acc.\text{velocity}}{acc.\text{velocity}} \right| \times 100\%$$

Where $acc.\text{position}$ is the acceleration ($= 2 \cdot A$) you derived from the position versus time graph and $acc.\text{velocity}$ is the acceleration ($= m$) from the velocity versus time graph.

4. Uniformly Accelerated Motion (Due to Gravity)



Purpose

The purpose of this lab is to calculate the local value of acceleration due to gravity using an appropriate apparatus (air track, free fall, or picket fence).

Background and Theory

There are several approaches one can take to investigate acceleration due to gravity, including freefall experiments with balls and picket fences (a “picket fence” is a clear rectangular plastic piece with regularly spaced opaque bands used with a photo-timer to measure the velocity and acceleration of the object). An advantage of the linear air track apparatus is that the “action” is “slowed down” for easier analysis. For completeness, in the “procedures” section, three methods will be presented.

The air track apparatus features a nearly frictionless surface provided by air that emerges through a series of small holes in the track. The force that causes the cart to accelerate down the track (inclined at an angle θ) is:

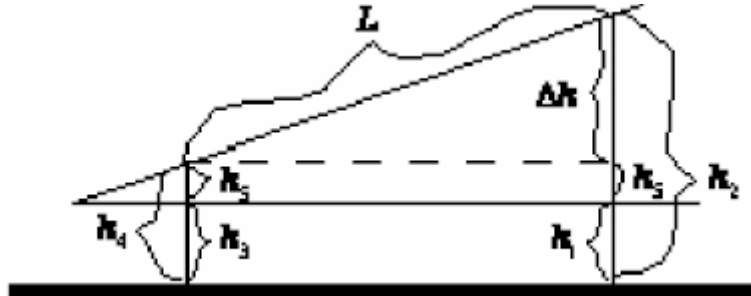
$$F = ma = mg \sin \theta$$

If the cart is started from rest then the initial velocity is zero and a parameterization for the value of gravity can be derived as:

$$g = \frac{v_f^2}{2d \sin \theta}, \quad v_f = \frac{x}{t}, \quad \sin \theta = \frac{\Delta h}{L}$$

where:

- g = acceleration due to gravity
- v_f = final velocity of the cart
- L = length used for elevation measurements
- x = length of cardboard on top of cart
- t = time for cart to go through photo gate
- θ = angle of track
- Δh = height adjustment to allow for uneven table
- d = distance cart goes down the track, from its initial position to the center of the photo gate.



$$\Delta h = (h_2 - h_1) - (h_4 - h_3)$$

Equipment

Equipment Needed

(Version A) Acceleration due to Gravity with the Air Track

	Qty.
Air Track	1
Laboratory Lift	1
Photogates	2
Cart with rectangular 100 mm flag attachment	1

(Version B) Acceleration due to Gravity with Free Fall

Free fall apparatus (Computer Interface Version is preferred)	1
Support Rod and Base	1
Metal Ball	1
Meter stick	1

(Version C) Acceleration of a Freely Falling Picket Fence

Photogate	1
Picket Fence	1
Universal Table Clamp	1

Procedure A (with Linear Air Track)

(Remember to write down all measured quantities!)

1. Level the air track apparatus. Then lift up one end of the track to a convenient angle (about 3 degrees). Take measurements of the track in this position, including the distance L between two photogates (see #2). Calculate the angle. Be sure that you do not move the air track for the rest of the experiment.
2. With one photogate near the $x = 15$ cm point on the air track and the other near the 180 cm point, use the apparatus to take five trials of the cart going through the photogates. Note that Data Studio will have been set up to time the cart's motion, either by the

instructor, or through the electronic workbook associated with this experiment. Record your measurements to 4 significant figures. You will be taking measurements using different units. Insure that you convert your measured values to the SI standard.

3. Calculate the average time and the standard deviation of this average.
4. Calculate the local value of acceleration due to gravity. Use the following calculation formula:

$$g = \left(\frac{x}{t}\right)^2 \frac{L}{2d\Delta h}$$


5. Calculate the error in your calculated value of g using the following formula (in SI units):

$$\sigma_g = g \sqrt{\left(\frac{\sigma_d}{d}\right)^2 + \left(\frac{2\sigma_x}{x}\right)^2 + \left(\frac{2\sigma_t}{t}\right)^2 + \left(\frac{0.002}{\Delta h}\right)^2 + \left(\frac{0.005}{L}\right)^2}$$

6. Is your value of g the same, to within experimental error, as the accepted value, $g = 9.80 \text{ m/s}^2$?
 - Why do the second and third terms in the error equation have coefficients of 2 whereas the first term has a coefficient of one?

Procedure B (with Free Fall)

(Remember to write down all measured quantities!)

1. The free fall timing apparatus should be set up already as well as Data Studio on the computer; practice securing the ball in the apparatus before beginning. Measure the height from the pad to the bottom of the suspended ball and record the height.
2. On the computer, click **Start**  to start the timer on the computer, then drop the ball and record the time given. Take five total measurements of the height and the drop time. Use 4 significant figures and insure that you convert your measured values to the SI standard.
3. Calculate the average time and the standard deviation of this average.
4. Calculate the local value of acceleration due to gravity. Use the following calculation formula:

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



5. Calculate the error in your calculated value of g using the following formula (in SI units):

$$\sigma_g = g \sqrt{\left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{2\sigma_t}{t}\right)^2}$$

6. Is your value of g the same, to within experimental error, as the accepted value, $g = 9.80 \text{ m/s}^2$?

Procedure C (with Picket Fence)

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

1. Prepare to drop the Picket Fence through the photogate beam—hold the Picket Fence at one end between your thumb and forefinger (long axis of the fence perpendicular to the ground) so that the bottom edge of the Picket Fence is just above the photogate Beam.
2. Hit **Start** to begin recording data, then drop the fence through the Photogate beam. Note, the data collection begins when the Photogate beam is first blocked.
3. After the Picket Fence passes completely through the beam, stop recording.
4. Examine the plot of Velocity versus Time in the Graph display  Graph. Determine the slope of the 'best fit' line for velocity versus time. To do this, select Linear from the Fit  Fit menu.
5. Repeat this procedure four more times to get a total of five values for acceleration. The slope of the line is the acceleration of the picket fence through the photogate. Take the mean of the five values as your experimental value for this acceleration. The standard deviation of these values will be your error.
6. The experimental value is simply the acceleration of the picket fence due to gravity, or g . Is the value of g the same, to within experimental error, as the accepted value, $g = 9.80 \text{ m/s}^2$?

If time allows, or if one wishes to expand this exercise to two laboratory periods, it may be useful to use all three methods and compare the results from them.

Conclusion

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 (you may not be able to answer all of them, depending on which procedure you followed, answer as many as you can):

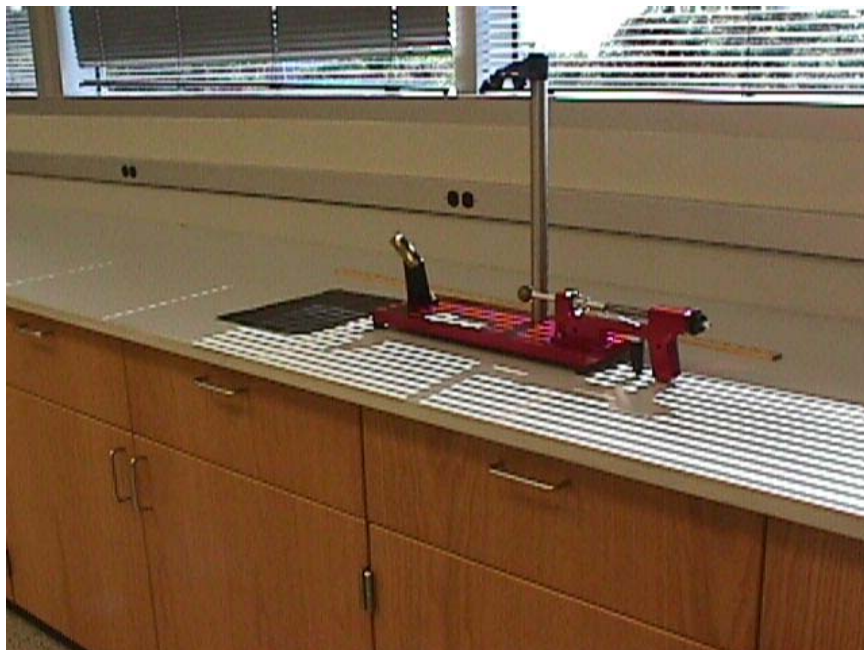
- What are the major sources of error in this experiment? (Explicit items, not generic terms such as human or systematic error!)
- Which experiment is a more accurate method of determining the local value of g , this experiment or the prior free fall experiment?
- (Procedure A only) Was your air track level? How do you know?
- (Procedure A only) In the last term of the error equation, why was the value "0.005" meters used?
- σ_d is much larger than 0.5 mm. Why?

Two point bonus if you correctly derive the equation for g . Hint: Start from one of the standard equations of motion as given in your physics text.

One possible variation of this lab is to have each group use a different procedure to take the measurements to obtain g . When each group has determine its average value for g , take a class average. Is the error in the class average greater or less than that of each of the groups within the class? Why?

5. Projectile Motion

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



Note

One can combine this lab and Laboratory #9 into a single lab, which can be entitled “The Ballistic Pendulum”. Doing so would give two ways to investigate conservation of linear momentum and enable students to see how the two compare.

Purpose

The purpose of this experiment is to study the motion of an object in two dimensions.

Safety reminder

Follow all directions for using the equipment. It is recommended 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.

Introduction and Theory

Projectile motion is simply the motion of an object in a plane (two dimensions) under the influence of gravity. 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. In the laboratory setting, however, the initial velocity is unknown and will need to be determined through measurements.

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_{x_o} from a height of y , it will describe an arc. The projectile will travel a horizontal distance x (the range of the projectile) while falling the vertical distance y .

The initial vertical velocity is $v_o = 0$, 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

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

Eliminating t from these equations, then solving for v_{x_o} , we have (neglecting air resistance):

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

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

Equipment

Equipment Needed	Qty.
Ballistic Pendulum (with pendulum removed) or projectile launcher	1
Sheets of plain (and carbon) paper	several
Meterstick	1
Masking Tape	--
Photogates (Optional computer-based component)	2

Procedure

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. Fire the ball from the gun and note where the ball hits the floor (note well that the range of the ball is appreciable, so you will probably need to shoot the ball down an aisle—take a practice shot or two to find the approximate range). Be careful not to point the launcher at anyone or hit anyone with the ball, especially your instructor!
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

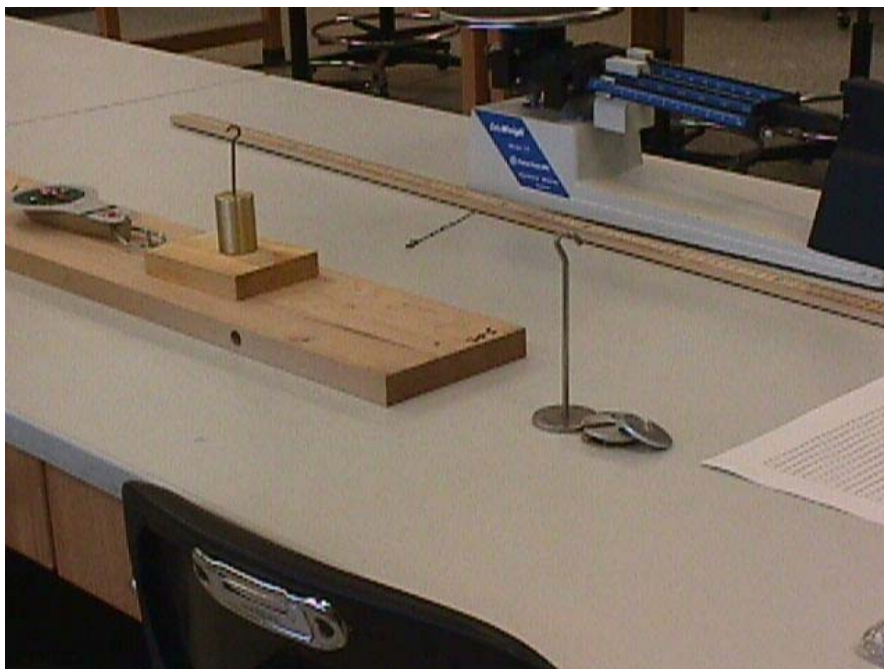
putting the ball on the gun without loading the spring) to the centers of the marks on the paper on the floor. Make sure the gun is fired from the same position each time.

4. Take five trials and measure the range x of each trial and record your measurements. Find the average of the five as well as the standard deviation. Also 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.
5. Using the equation below, calculate the magnitude of the initial velocity of the ball ($g = 9.80 \text{ m/s}^2 = 980 \text{ cm/s}^2$).

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

6. 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?

6. Static and Kinetic Friction



Purpose

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

Introduction and Theory

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.

Equipment

Equipment Needed (Without Computer Assistance)	Qty
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)	Qty
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
Photogate / 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 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 Photogate / Pulley system until the hanging mass is almost up to the pulley. Hold the block in place while turning the pulley so that the photogate's beam is not blocked (red LED on the photogate 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.

7. Conservation of Mechanical Energy



Purpose

The purpose of this lab is to calculate the energy lost in an inelastic collision.

Background and Theory

The Law of Conservation of Energy can be represented mathematically by the following expression:

$$\Delta E_k + \Delta E_p + \Delta E_r = 0$$

The first two terms are the total mechanical energy, that is, the kinetic and gravitational potential energy of the system. The last term is the resistive (or internal) energy, that is, the energy lost to nonconservative forces.

$$E_k = \frac{1}{2}mv^2, \quad E_p = mgh, \quad h = d \sin \theta, \quad \sin \theta = \frac{\Delta h}{L}$$

where: g = acceleration due to gravity

v = velocity of the cart when it hits end of the track

m = mass of cart

d = length along incline from center of mass of the resting cart to the arbitrary point chosen as the origin of the coordinate system

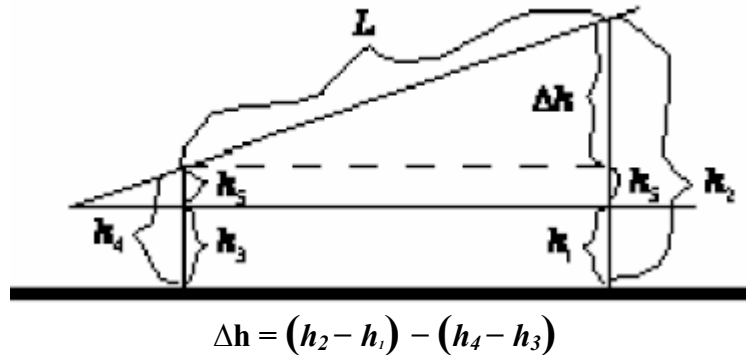
h = vertical distance from the x-axis to the center of mass of the cart (resting at the top of the track)

L = length used for elevation measurements

θ = angle of track

Δh = height of angled track, adjusted to allow for an uneven table

Δd = distance cart did not make it back up the track.



If the cart is released from the top of the track and there are no frictional forces involved, then it should return to its starting point. If it does not return to its starting point, then the distance by which it did not return is a measure of the energy lost to resistive forces. When the cart is not moving all of the energy is in the form of potential energy, so the resistive energy can be given by:

$$\Delta E_r = -\Delta E_p \text{ or } E_{r,f} - E_{r,i} = (-E_{p,f} - E_{p,i})$$

The lost energy when the cart is at rest is zero. Substitute in the expressions for potential energy.

$$E_{r,f} - 0 = -(mgh_f - mgh_i) = mg(h_i - h_f) = mg(d_i \sin \theta - d_f \sin \theta) = mg(d_i - d_f) \sin \theta$$

$$E_r = E_{r,f} = mg\Delta d \sin \theta$$

This reduces to the calculation formula:

$$E_r = mg \left(\frac{\Delta d \Delta h}{L} \right)$$

Equipment

Equipment Needed (Without computer assistance)	Qty
Air Track with Air Supply	1
Cart with 100 mm flag attachment and rubber band stop attachment	1
Masking Tape (optional)	1
Meter Stick	1
Laboratory Lift	1
Equipment Needed (With computer assistance)	Qty
Motion Sensor	1

Air Track with Air Supply	1
Laboratory Balance	1
Base and Support Rod	1
Cart with 100 mm flag attachment and rubber band stop attachment	1
Meter Stick	1
String	0.5 m

Procedure

Without the Assistance of the Computer

1. Level the air track apparatus and then set it at no more than a 3-degree angle. Take measurements to determine the actual angle. Then let the cart glide down the track and measure the distance where the cart stops on the return trip. This measurement should be made from the top of the track to the top of the cart. Repeat this procedure five times.
2. Use the leading or trailing edge of the cart for measurements. For practical purposes, this is the same as measuring to the center of mass. Why?
3. Calculate the average return position and use this value as Δd .
4. Calculate the amount of energy lost during the collision of the rubber band on the cart with the end stop of the track.
5. Calculate the error in your measured value using the following formula (in SI units):

$$\sigma_E = E \sqrt{\left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{2\sigma_{\Delta d}}{\Delta d}\right)^2 + \left(\frac{0.002}{\Delta h}\right)^2 + \left(\frac{0.005}{L}\right)^2}$$

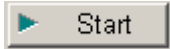
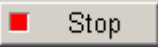


The error in the mass is due to one measurement; the error in the distance is due to many measurements. Choose the correct method of error calculation for these two terms.

6. 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:
 - What are the major sources of error in this experiment?
 - Where does the lost potential energy go? Think carefully about this. Examine what happens when the cart bounces at the end of the track. (Give at least three sources!)

(It is best not to leave the laboratory room until you are sure that you understand this question.)

With the use of computer

1. Level the air track apparatus and then set it at no more than a 3-degree angle. Take measurements to determine the actual angle. Set up the Motion Sensor on the support rod so that it is at least 15-cm from the starting point of the cart at the top of the track. Measure this initial distance and record it in your Report, using this distance as a correction value in your data.
2. If instructed to do so, at this point in the exercise, go to the electronic workbook for this lab and follow the directions included therein. Otherwise, continue with the procedure as is.

3. In DataStudio, open the graph display and maximize the display to fit the available screen. Make sure position versus time is on display. Make sure the flag, or “sail”, mounted atop the cart is at right angles to the cart’s motion to maximize the surface area for the motion sensor. (If need be, we can tape an index card or piece of paper on the “sail” to increase its effective area, but don’t forget to include this in place at the time you weigh the cart)
4. With the cart at the upper end of the track, click **Start**  to activate the motion sensor, then let the cart glide down the track and bounce back up after colliding with the end stop. You may need to do a few practice runs to make sure the data is being collected appropriately, if necessary, increase the reflecting area by adding a 10x15 cm piece of paper to the “sail”. After the cart reaches its return position and begins to return to the stop, click . Repeat this procedure five times.
5. Find the average return position and use this value as Δd . Don’t forget to subtract the correction value, the distance from the motion sensor to the cart at its initial position. To find the average position on the graph, find the smart tool button, , click on it, and use the smart tool cursor, , to measure the lowest point on the “dip” on the graph. This “dip” represents the position of the cart the instant it stopped and reversed direction to fall back down the track after its initial bounce.
6. Calculate the amount of energy lost during the collision of the rubber band on the cart with the end stop of the track.
7. Calculate the error in your measured value using the following formula (in SI units):

$$\sigma_E = E \sqrt{\left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{2\sigma_{\Delta d}}{\Delta d}\right)^2 + \left(\frac{0.002}{\Delta h}\right)^2 + \left(\frac{0.005}{L}\right)^2}$$

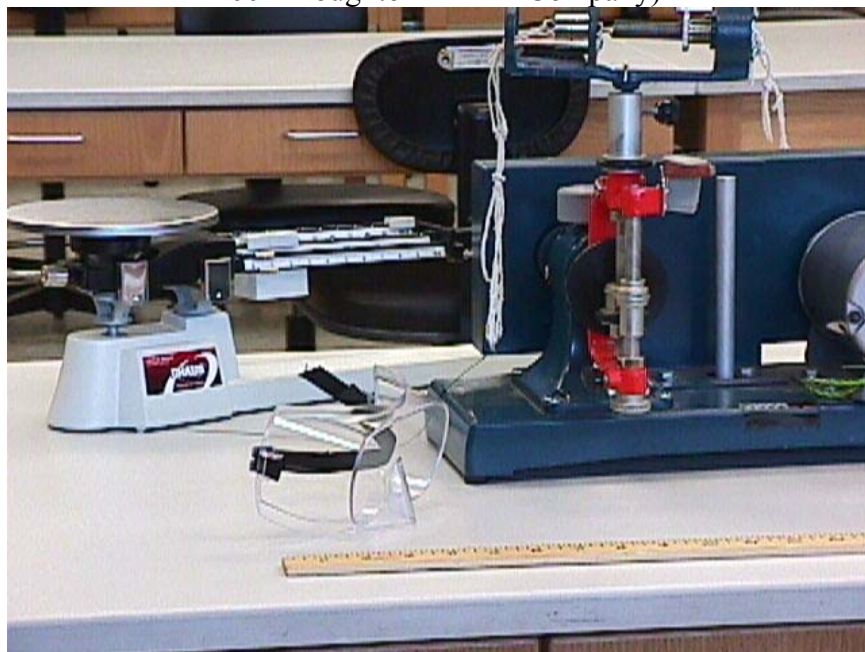
The error in the mass is due to one measurement; the error in the distance is due to many measurements. Choose the correct method of error calculation for these two terms.

8. 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:
 - What are the major sources of error in this experiment?
 - Where does the lost potential energy go? Think carefully about this. Examine what happens when the cart bounces at the end of the track. (Give at least three sources!)
 (It is best not to leave the laboratory room until you are sure that you understand this question.)

An optional extension to this exercise is to find the coefficient of restitution for several bounces of the air track cart. The procedure is the same as that immediately above, with the exception of allowing the cart to bounce at least three times. These bounces show up on the Motion Sensor’s position versus time plot. The instructor will provide further instructions on what to do next.

8. 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.

This 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.

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	Qty.
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 two types of Centripetal Motion Apparatus. Both devices are operated by motors, but are 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. Both 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 a hand-operated apparatus, with the added feature in the form of 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.

9. 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 either the simulation program outlined in Appendix A, or the website and list in Appendix B, or another source.

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.

10. Conservation of Linear Momentum



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.

Background and Theory

Note: One can combine this with Experiment #5 and present both as a single lab entitled “Ballistic Pendulum”. The concepts of conservation of energy can be represented mathematically by the following expressions:

$$\sum F_{ext} = \frac{dp}{dt} = 0 \quad p_b = p_a \quad \Delta E_k + \Delta E_p = 0$$

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:

$$mv_0 = MV \quad \text{where: } m = \text{mass of the particle} \\ M = \text{mass of the projectile plus pendulum}$$

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:

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

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

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

Equipment

Equipment Needed	Qty.
Ballistic Pendulum	1
Laboratory Balance	1
Meter Stick	1
Protractor	1

Safety Reminder

Never aim or fire the projectile launcher at a person.

Procedure

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 and the associated standard deviation.
4. Calculate the pre-collision velocity of the projectile.
5. Calculate the error in the velocity using the following formula (in SI units):

$$\sigma_{v_0} = v_0 \sqrt{\left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{0.005}{2L}\right)^2 + \left(\frac{\sigma_\theta}{2\sin \theta}\right)^2}$$

In this error equation, the error for the angle, σ_θ , must be in terms of radians. Why?

6. 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 photogate timers and the computer can be implemented. Place one photogate 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 error between your theoretical (“Predicted”) value and your measured (“Measured”) value with the following formula:

$$\% \text{ Difference} = \frac{|\text{Predicted} - \text{Measured}|}{\text{Measured}} \times 100$$

11. 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.

Background and Theory

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. 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:

$$\begin{aligned}\sum F &= 0 \\ \sum \tau &= 0\end{aligned}$$

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:

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

with θ the angle between the \mathbf{r} and \mathbf{F} vectors.

This perpendicular distance r is called the lever arm or moment arm and has the units meter-Newton (m-N). 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

$$\sum \tau_{cc} = \sum \tau_{cw}$$

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	Qty.
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

Suggested Procedure

Torque, Equilibrium, and the Center of Gravity

1. Determine the mass of the meter stick. Place a knife-edge clamp on the meterstick 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 meterstick.
2. *Case 1: two known masses.* With the meterstick 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 meterstick. 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 meterstick.

4. *Case 3: Unknown mass.* With the meterstick on the support stand at x_o , suspend the unknown mass (m_1) near one end of the meterstick (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 meterstick 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.

Rotational Inertia of a Disk and Ring

(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

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

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

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.

$$\tau = rT$$

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:

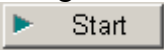
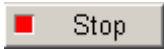

$$T = m(g - a)$$

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

Equipment

Equipment Needed	Qty.
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. 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 Pulley 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 an angle so the thread runs in a line tangent to the point where it leaves the 3-step Pulley 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 pulley about which the thread is to be wrapped and find the radius.
4. Place the disk directly on the pulley and place the mass ring on the disk, inserting the ring pins into the holes in the disk.
5. Run Science Workshop and install the RMS. 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 pulley 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 pulley, 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.

Buoyancy and Specific Gravity

(Adapted from Jerry Wilson, *Physics Laboratory Experiments*, 4th Ed., pp. 281-284, © 1994 Houghton Mifflin Company)

Purpose

The purpose of this experiment is to study Archimedes' principle in one application: determining the densities and specific gravities of solid samples.

Background and Theory

When an object is immersed in a fluid, it experiences an upward buoyant force that may cause it to float. In a fluid, the pressure on the lower surface of the object is greater than that on the upper surface, so a pressure difference results and provides an upward force. This buoyant force is described by Archimedes' principle:

When a body is placed in a fluid, it is buoyed up by a force equal to the weight of the volume of fluid it displaces.

This principle applies to a body wholly or partially immersed in a fluid. The magnitude of the buoyant force depends only on the weight of the fluid displaced by the object, and does not depend on the weight of the object itself.

Archimedes' principle shows that an object:

1. will float in a fluid if the density of the object ρ_o is less than that of the fluid density ρ_f ,
2. will sink if the object's density is greater than that of the fluid, and
3. will float in equilibrium at any submerged depth where it is placed if its density is equal to that of the fluid.

Specific Gravity is defined as the ratio of the weight of a given volume of the substance to an equal volume of water. This is a density-type designation that uses water as the comparison standard. The numerical value of a substance's specific gravity is the same as the magnitude of its density in cgs units (centimeter-grams-seconds). Water has a density of $1 \text{ g} / \text{cm}^3$ over the temperature range at which water is liquid.

Archimedes' principle can be used to determine the specific gravity (and density) of a submerged object

$$\text{sp. gr.} = \frac{w_o}{w_w} = \frac{w_o}{F_b}$$

where w_o is the weight of the object and w_w is the weight of the water it displaces, and by Archimedes' principle, $w_w = F_b$.

For a heavy object that sinks, the net force as it sinks is equal to $w_o - F_b$ (why is this?). If the object were attached to a spring scale while submerged, it would have a measured apparent weight w'_o and $w'_o = w_o - F_b$; so that $F_b = w_o - w'_o$ and the previous equation may be written:

$$\text{sp. gr.} = \frac{w_o}{w_w} = \frac{w_o}{w_o - w'_o}$$

or in terms of mass measured on a balance, with $w = mg$:

$$\text{sp. gr.} = \frac{m_o}{m_o - m'_o} = \rho_o$$

with ρ_o being the magnitude of the density of the object in g / cm^3 . Now we have an experimental method to find the specific gravity (and density) of an object that sinks.

We can use a similar approach to find experimentally the specific gravity of an object that floats. We need, however, the assistance of a heavy object attached to the light object to completely submerge the light object. For such an arrangement, $w_1 = w_o + w'_s$ is the measured weight (mass) of the object and sinker, with only the sinker submerged, and $w_2 = w'_o + w'_s$ is the measured weight with both submerged. Then

$$w_1 - w_2 = (w_o + w'_s) - (w'_o + w'_s) = w_o - w'_o$$

or, in terms of mass, $m_1 - m_2 = m_o - m'_o$

and then the specific gravity can be found as follows:

$$\text{sp. gr.} = \frac{m_o}{m_1 - m_2} = \rho_o$$

Again, ρ_o is the magnitude of the density of the object in g / cm^3 .

Equipment

Equipment Needed	Qty.
Triple beam balance with swing platform	1
Overflow can	1
Catch Bucket	1
Beakers	2
Metal Cylinder, irregularly shaped metal object or metal sinker	1
String	1

Procedure

The following is the recommended procedure for proving Archimedes' Principle and using this principle to find the density of a heavy and a light solid.

1. Weight the metal sample and record the mass m_o and type of metal; also weigh an empty catch bucket and record its mass m_b . Fill the overflow can with water and place it on the balance platform. Attach a string to the sample and suspend it from the balance arm.
2. The overflow from the can is collected in the catch bucket when the sample is immersed. Take a mass reading m'_o of the submerged object, making sure that no bubbles adhere to the object. Next weigh the beaker and water so as to determine the mass of the displaced water m_w . (If the can does not fit on the balance platform, first suspend and immerse the object in the full overflow can and catch the overflow in the beaker and find m_w . Then attach the sample to the balance arm and suspend it in a beaker of water that will fit on the balance platform to find m'_o .)
3. According to Archimedes' Principle, the buoyant force $F_b = m_o g - m'_o g$ should equal the weight of the displaced water $w_w = m_w g$ or:

$$(m_o - m'_o)g = m_w g$$

Compute the buoyant force and compare it with the weight of the displaced water by finding the percent difference.

4. Determine the specific gravity and density of the metal sample. This can be done with the data from Steps 1-3
5. Determine the specific gravity and the density of the light solid by the procedure described in the Background and Theory sections, after first measuring the mass of the light solid in air.
6. Write up your report using the standard format, which is: Purpose, Equipment, Theory, Data, Results and Discussion, and Conclusion.

APPENDIX 1—CPU (*Constructing Physics Understanding*) Simulation Experiment: Projectile Motion in Different Gravity Fields and Different Launch Angles

Purpose

The purpose of this lab exercise is to run a simulation of a projectile motion launcher and ball while varying a number of parameters to include launch angle and planet.

Background

Earlier this semester you performed an experiment entitled “Projectile Motion” where you used a launcher (spring loaded gun, part of a ballistic pendulum setup without the pendulum) and metal ball to shoot the ball across the room, measure its height and range, and find the initial velocity of the ball. In some classes you varied the angle of the launch.

We will see how running a computer experiment can nicely complement a live experiment. With a computer, we can easily and quickly vary parameters that would be time consuming, difficult, or impossible to perform in a lab setting. By varying these parameters, we can see in a very useful way in which they are interrelated. We can run a number of trials in a relatively short amount of time without dealing with setting up and resetting equipment.

In this experiment, we will use the computers to simulate the experiment we did earlier this semester. We will start with a setup similar to what we did earlier, but compare the range and time of flight of the projectile at several different launch angles. We will then keep the launch angle constant and vary first the mass of the projectile, second the power of the gun, and third, the planet we perform the experiment on (Earth, Moon, and Jupiter).

Equipment

Equipment	Qty.
Computer with the CPU software on the machine	1
This sheet	1

Procedure

1. Setting up the simulation environment is done in the following way:
 - a. Find, then doubleclick on the “Run CPU Simulators” icon on the desktop
 - b. When the Internet Explorer window appears, within it will be a list entitled “Simulations & Software”. Click on “Forces & Motion Simulator”
 - c. A rectangle resembling a graph should then appear. Below the graph are two groups of buttons, the program group on the left, and the control group on the right.

- d. Single-click on the pointer (arrow) button. Then move the pointer over the origin point of the graph (marked with a small black square), click and hold on the square and drag it to the lower left corner of the graph.
 - e. Click on the launcher icon button (“mousing over” the buttons will cause the names of each to appear after a fraction of a second; look for the one named “launcher”) with a single click. Move the pointer near the origin and single click again to make a launcher icon appear in the graph.
 - f. Click on the pointer icon again. Then double click on the launcher icon. A small box should appear with two variables: strength ($\text{km}\cdot\text{m/s}$) and direction (degrees). Change the direction by clicking on the slider bar or the arrow tips (these change the angle by 1-2 degrees per click). We will start with 0 degrees. Click “OK” when finished.
 - g. Single click the object button. Then single click on the launcher icon in the graph. Doing so mounts the ball on the launcher and readies it to fire.
 - h. Single click on the pointer button again, then doubleclick on the background (on the graph away from the projectile and ball setup). Change gravitational field to “Earth” by checking this and then click “OK”
2. Run the Simulation (Answer the questions in **bold print** in the “results” section of your Laboratory Report)
- a. Hit arrow to run the experiment (right side “control” group of buttons), pause when the ball crosses the x-axis. Record where the ball crosses the axis and the time (upper left corner, in seconds) it took to get there in the table in the results section. Hit the rewind button when finished, and single click the pointer button to allow access to the simulation
 - b. Double click on the launcher again, and change the angle to 30 degrees. Click the run button again to launch the object, pausing when the object reaches the x axis. Click rewind then the pointer button each time you finish a run.
 - c. Repeat these steps for each of the launch angles in the table (runs 1-5). **Which angle had the maximum range, when all else was held constant?**
 - d. When we get to Run #6, we will now vary the mass of the projectile (ball) and keep the launch strength and angle constant. Double click on the ball icon and set its mass to 10 kg and repeat the experiment. Repeat again for a mass of 15 kg for the projectile while keeping every thing else constant (Runs 6 and 7). **What effect does changing the mass have on the path of the ball?**
 - e. Now we will vary the launch strength while keeping everything else constant. Double click on the projectile icon and return its mass to 5 kg. Click “OK” then double click on the launcher and change the strength to $100 \text{ km}\cdot\text{m/s}^2$. Run the experiment for run #8. Repeat, with every thing else constant, but the launcher strength changed to $400 \text{ km}\cdot\text{m/s}^2$. **What effect does changing the launcher strength have on the flight of the ball?**
 - f. Finally, we will change the gravity field within which we are performing the experiment. We will hold everything else constant (mass of ball = 5kg, launch angle = 45° , launch strength = $200 \text{ km}\cdot\text{m/s}^2$). For Run #9, we will repeat the experiment “on the moon”. Click anywhere away from the launcher-ball system on the graph and change the gravity source to the Moon by clicking

next to Moon. Repeat for Jupiter (#10). **What effect does changing the gravity field (or planet) have on the motion of the projectile?**

Data & Results

Trial	Planet	H (m) above x-axis	mass projectile kg	Launcher Strength (km*m/s)	Launch Angle (deg.)	Range (m)	Time of Flight (s)
1	Earth		5	200	0		
2	Earth		5	200	30		
3	Earth		5	200	45		
4	Earth		5	200	60		
5	Earth		5	200	75		
6	Earth		10	200	45		
7	Earth		15	200	45		
8	Earth		5	400	45		
9	Moon		5	200	45		
10	Jupiter		5	200	45		

Your Instructor may have additional questions with regards to this lab; this particular table is to be included in the Data section of your lab report, and your responses to the bold questions written above are to be included in the **Results** section of your lab report. The answers to the following questions should be included in the **Conclusions** section of the report.

- What would the path of the projectile be if this experiment were repeated in outer space (or on board the International Space station), where the influence of gravity is non-existent?
- What are some advantages and disadvantages (name at least two of each) of doing an experiment on the computer as opposed to doing it in class with actual equipment?

APPENDIX 2—A List of Candidate Simulated Demonstrations in Physics that May be Used in Laboratory Experiment #8

This lab will focus on one such simulation within the area of classical mechanics from the following website:

<http://webphysics.ph.msstate.edu/jc/library/>

Go to this website, and click on one of the choices in the list. The list includes simulations in the following areas:

- 2.6 Motion With Constant Acceleration
- 3.2 Addition of Vectors
- 3.5 Relative Velocity in Two Dimensions
- 3.7 Projectile Motion
- 4.7 Some Applications of Newton's Laws
- 5.1 Uniform Circular Motion
- 5.2 Force Needed for Circular Motion
- 5.3 Kepler's Laws of Planetary Motion
- 6.6 Conservation of Mechanical Energy
 - Elastic Collisions in One Dimension
 - Elastic Collisions in Two Dimensions
- 9.3 Torque
- 9.4 Static Equilibrium
- 9.7 Angular Momentum
- 9.10 Conservation of Energy: Translations and Rotations
- 9.PP Physics in Practice: The Earth, the Moon, and the Tides

Select one or more simulations from this list and do them, varying the parameters and seeing how this varying affects the outcome of the experiment. You could either choose an experiment that will not be done this semester, or an experiment that has been done already. In the latter case, the initial conditions of the experiment can be modified to see how the results differ from that experienced in the classroom.