Investigative Physics
Activity Units for IQS Physics-S1

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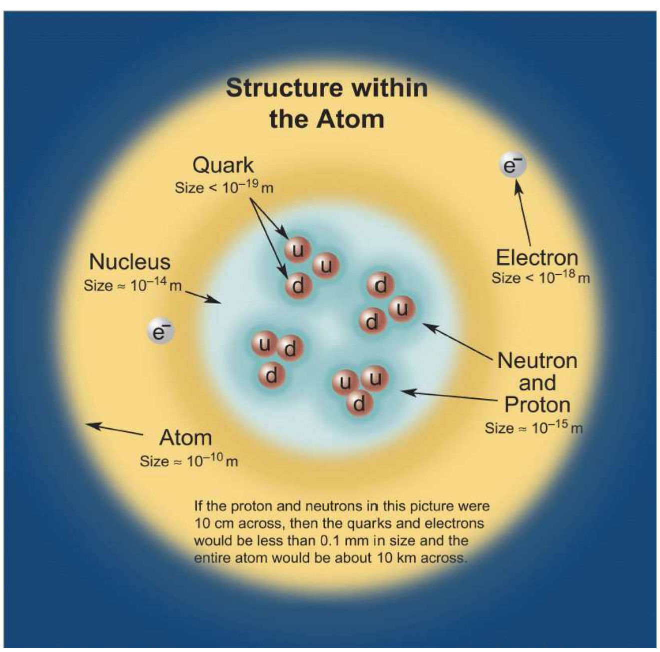
Abstract

The exercises in this manual have been developed to support an investigative physics course that emphasizes active learning. Some of these units have been taken from the Workshop Physics project at Dickinson College and the Tools for Scientific Thinking project at Tufts University and modified for use at the University of Richmond. Others have been developed locally.

The units are made up of activities designed to guide your investigations in the laboratory. The written work will consist primarily of documenting your class activities by filling in the entries in the spaces provided in the units. The entries consist of observations, derivations, calculations, and answers to questions. Although you may use the same data and graphs as your partner(s) and discuss concepts with your classmates, all entries should reflect your own understanding of the concepts and the meaning of the data and graphs you are presenting. Thus, each entry should be written in your own words. Indeed, it is very important to your success in this course that your entries reflect a sound understanding of the phenomena you are observing and analyzing.

We wish to acknowledge the support we have received for this project from the University of Richmond and the Instrumentation and Laboratory Improvement program of the National Science Foundation. Also, we would like to thank our laboratory directors for their invaluable technical assistance.



Cover art: The atom consists of smaller electrons and a nucleus consisting of protons and neutrons. The protons and neutrons, in turn, are formed from objects called quarks and gluons. Courtesy, the American Institute of Physics.

Contents

1 Work and Kinetic Energy **4**

2 Conservation of Mechanical Energy **15**

3 Force and Momentum Conservation **19**

4 Two-Dimensional Collisions **29**

5 Impulse, Momentum, and Interactions **35**

6 Heat, Temperature, and Internal Energy **39**

7 Calorimetry **41**

8 Kinetic Theory of Ideal Gases **44**

9 Applying the Kinetic Theory **50**

10 Stefan's Law **56**

A Treatment of Experimental Data **60**

B Introduction to DataStudio **62**

C Introduction to Excel **64**

C.1 Data and formulae 64

C.2 Graphs 64

C.3 Making Histograms 65

D Video Analysis **67**

E Instrumentation **70**

1 Work and Kinetic Energy[1]

Name ______________________ Section ____________ Date ____________

Objectives

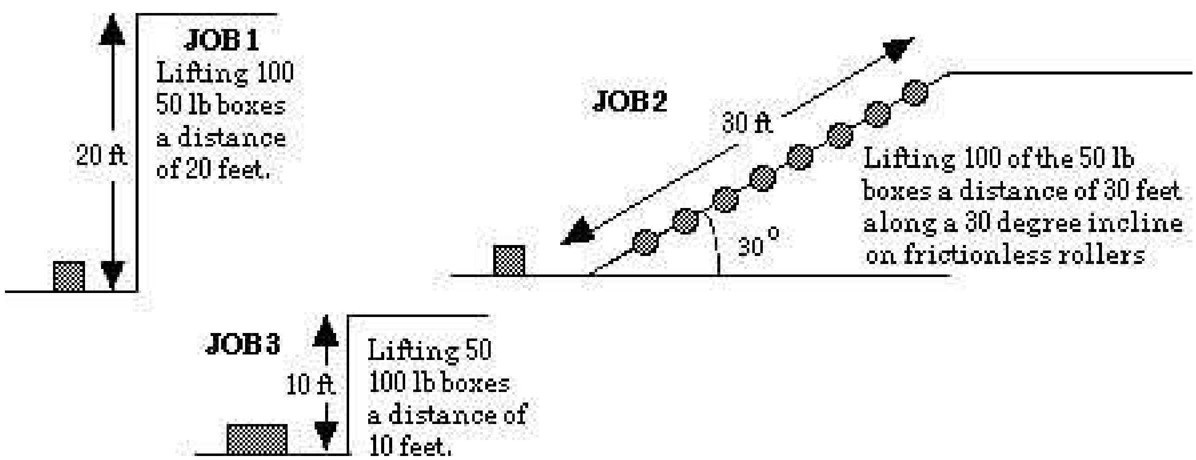
- To extend the intuitive notion of work as physical effort to a formal mathematical definition of work as a function of force and distance.
- To discover Hooke's law.
- To understand the concept of kinetic energy and its relationship to work as embodied in the work-energy theorem.

Apparatus

spring scale	variety of masses	support rod to hand spring
wooden block with hook	large spring	2-meter stick

The Concept of Physical Work

Suppose you are president of the Richmond Load 'n' Go Co. A local college has three jobs available and will allow you to choose which one you want before offering the other two jobs to rival companies. All three jobs pay the same amount of money. Which one would you choose for your crew? **NOTE:** The quantities in this figure are given in British units, where "pounds" = mg, not just m, i.e. the g is already included.

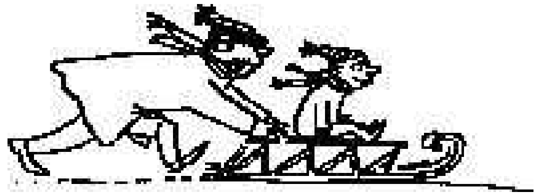


Activity 1: Choosing Your Job

Examine the descriptions of the jobs shown in figure above. Which one would you be most likely to choose? Least likely to choose? Explain the reasons for your answer.

You obviously want to do the least amount of work for the most money. Before you reconsider your answers later in this unit, you should do a series of activities to get a better feel for what physicists mean by work and how the president of Load 'n' Go can make top dollar.

[1] 1990-93 Dept. of Physics and Astronomy, Dickinson College. Supported by FIPSE (U.S. Dept. of Ed.) and NSF. Portions of this material have been modified locally and may not have been classroom tested at Dickinson College.



In everyday language we refer to doing work whenever we expend effort. In order to get an intuitive feel for how we might define work mathematically, you should experiment with moving your textbook back and forth along a table top and a rougher surface such as a carpeted floor.

Activity 2: This is Work!

(a) Pick a distance of a meter or so. Sense how much effort it takes to push a heavy book that distance. How much more effort does it take to push it twice as far?

(b) Pile another similar book on top of the original one and sense how much effort it takes to push the two books through the distance you picked. Comment below.

(c) If the "effort" it takes to move an object is associated with physical work, guess an equation that can be used to define work mathematically when the force on an object and its displacement (i.e., the distance it moves) lie along the same line.

In physics, work is not simply effort. In fact, the physicist's definition of work is precise and mathematical. In order to have a full understanding of how work is defined in physics, we need to consider its definition in a very simple situation and then enrich it later to include more realistic situations.

A Simple Definition of Physical Work: If an object that is moving in a straight line experiences a constant force in the direction of its motion during the time it is undergoing a displacement, the work done by the external force, F_{ext}, is defined as the product of the force and the displacement of the object,

$$W = F_{ext} \Delta x$$

where W represents the work done by the external force, F_{ext} is the magnitude of the force, and Δx is the displacement of the object.

What if the force of interest and the displacement are in opposite directions? For instance, what about the work done by the force of sliding friction, F_f, when a block slides on a rough surface? The work done by the friction force is

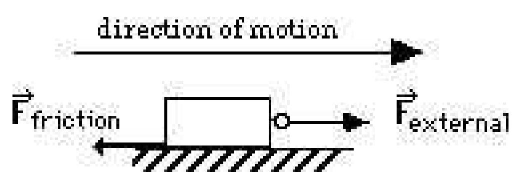
$$W_f = -F_f \Delta x$$

Activity 3: Applying the Physics Definition of Work

(a) Does effort necessarily result in physical work? Suppose two guys are in an evenly matched tug of war. They are obviously expending effort to pull on the rope, but according to the definition of physical work, are they doing any physical work? Explain.

(b) A wooden block with a mass of 0.30 kg is pushed along a sheet of ice that has no friction with a constant external force of 10 N which acts in a horizontal direction. After it moves a distance of 0.40 m how much work has been done on the block by the external force?

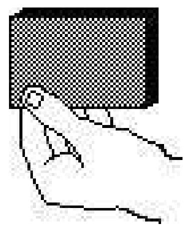
(c) The same wooden block with a mass of 0.30 kg is pushed along a table with a constant external force of 10 N which acts in a horizontal direction. It moves a distance of 0.40 m. However, there is a friction force opposing its motion with magnitude $|\mathbf{F}_{friction}| = \mu N$ where N is the normal force exerted on the block by by the table. Here N is perpendicular to the surface of the table and equal to the weight of the block (since the table is holding up the block). The coefficient of sliding friction μ is an experimental factor that relates N to the friction force. Here μ_k, is 0.20.



1. According to the definition of work done by a force, what is the work associated with the external force? Is the work positive or negative? Show your calculation.

2. According to our discussion above of the work done by a friction force, what is the work associated with the friction force? Is the work positive or negative? Show your calculation.

(d) Suppose you lift a 0.3 kg object through a distance of 1.0 m at a constant velocity.

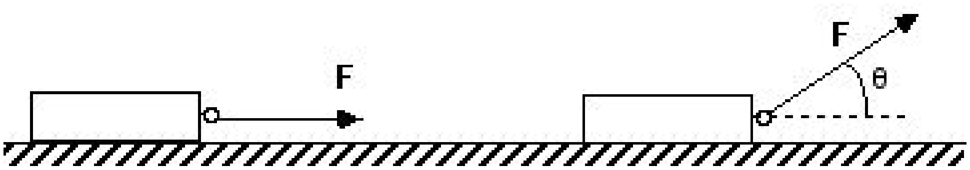


1. What is the work associated with the force that the earth exerts on the object? Is the work positive or negative? Show your calculation.

2. What is the work associated with the external force you apply to the object? Is the work positive or negative? Show your calculation.

Pulling at an Angle What Happens When the Force and the Displacement Are Not Along the Same Line?

Let's be more quantitative about measuring force and distance and calculating the work. How should work be calculated when the external force and the displacement of an object are not in the same direction?



To investigate this, you will use a spring scale to measure the force necessary to slide a block along the table at a constant speed. Before you make your simple force measurements, you should put some weights on your block so that it slides along a smooth surface at a constant velocity even when it is being pulled with a force that is 30 or 60 degrees from the horizontal.

Activity 4: Calculating Work

(a) Hold a spring scale horizontal to the table and use it to pull the block a distance of 0.5 meters along the horizontal surface in such a way that the block moves at a constant speed. Record the force in newtons and the distance in meters in the space below and calculate the work done on the block in joules. (Note that there is a special unit for work, the joule, or J for short. One joule is equal to one newton times one meter, i.e., J = N m.)

(b) Repeat the measurement, only this time pull on the block at a 30° angle with respect to the horizontal. Pull the block at about the same speed. Is the force needed larger or smaller than you measured in part (a)?

(c) Repeat the measurement once more, this time pulling the block at a 60° angle with respect to the horizontal. Pull the block at about the same speed as before.

(d) Assuming that the actual physical work done in part (b) is the same as the physical work done in part (a) above, how could you enhance the mathematical definition of work so that the forces measured in part (b) could be used to calculate work? In other words, use your data to postulate a mathematical equation that relates the physical work, W, to the magnitude of the applied force, F, the magnitude of the displacement, Δs, and the angle, θ, between F and Δs. Explain your reasoning. Hint: $\sin 30° = 0.500$, $\sin 60° = 0.866$, $\cos 30° = 0.866$, $\cos 60° = 0.500$.

Work as a Dot Product

Review the definition of dot (or scalar) product as a special product of two vectors in your textbook, and convince yourself that the dot product can be used to define physical work in general cases when the force is constant but not necessarily in the direction of the displacement resulting from it.

$$W = \mathbf{F} \cdot \mathbf{\Delta s}$$

Activity 5: How Much Work Goes with Each Job?

(a) Re-examine the descriptions of the jobs shown in the figure on the first page of this experiment. What is the minimum physical work done in job 1? Note that the data are given in British units, so the work will be expressed in foot pounds (ft lbs), not newton meters. Remember, the "pounds" are mg, so you don't need to multiply by g.

(b) What is the minimum physical work done in job 2?

(c) What is the minimum physical work is done in job 3?

(d) Was your original intuition about which job to take correct? Which job should Richmond Load 'n' Go try to land?

The Force Exerted on a Mass by an Extended Spring

So far we have pushed and pulled on an object with a constant force and calculated the work needed to displace that object. In most real situations the force on an object can change as it moves.

What happens to the average force needed to stretch a spring from 0 to 1 cm compared to the average force needed to extend the same spring from 10 to 11 cm? How does the applied force on a spring affect the amount by which it stretches, i.e., its displacement?

Activity 6: Are Spring Forces Constant?

Hang the spring from a support rod with the large diameter coils in the downward position. Extend the spring from 0 to 1 cm. Feel the force needed to extend the spring. Extend the spring from 10 to 11 cm. Feel the force needed to extend the spring again. How do the two forces compare? Are they the same?

The Force and Work Needed to Stretch a Spring

Now we would like to be able to quantify the force and work needed to extend a spring as a function of its displacement from an equilibrium position (i.e., when it is "unstretched").

Activity 7: Force vs. Displacement for a Spring

(a) The table below shows the results of a series of measurements of the distance s from the floor to the position of a mass m hung from a spring like the one you have. Calculate and record the external force, F_{ext}, and the stretch of the spring, x $(= s_0 - s)$, for each mass. The last four columns will not be filled in until you get to Activities 8 and 9.

m (kg)	s (m)	F_{ext} (N)	x (m)	Δx (m)	$\langle x \rangle$ (m)	$\langle F_{ext} \rangle$ (N)	ΔW (J)	W_{total} (J)
0.0	1.508							
0.1	1.390							
0.2	1.220							
0.3	1.153							
0.4	1.032							
0.5	0.911							
0.6	0.789							
0.7	0.669							
0.8	0.547							
0.8	0.420							
1.0	0.301							

(b) Using *Excel*, create a graph of F_{ext} (vertical axis) vs. x. Is the graph linear? If the force, F_{ext}, increases with the displacement in a proportional way, fit the data to find the slope of the line. Insert a copy of the graph into your notebook. Use the symbol k to represent the slope of the line. What is the value of k? What are its units? Note: k is known as the spring constant.

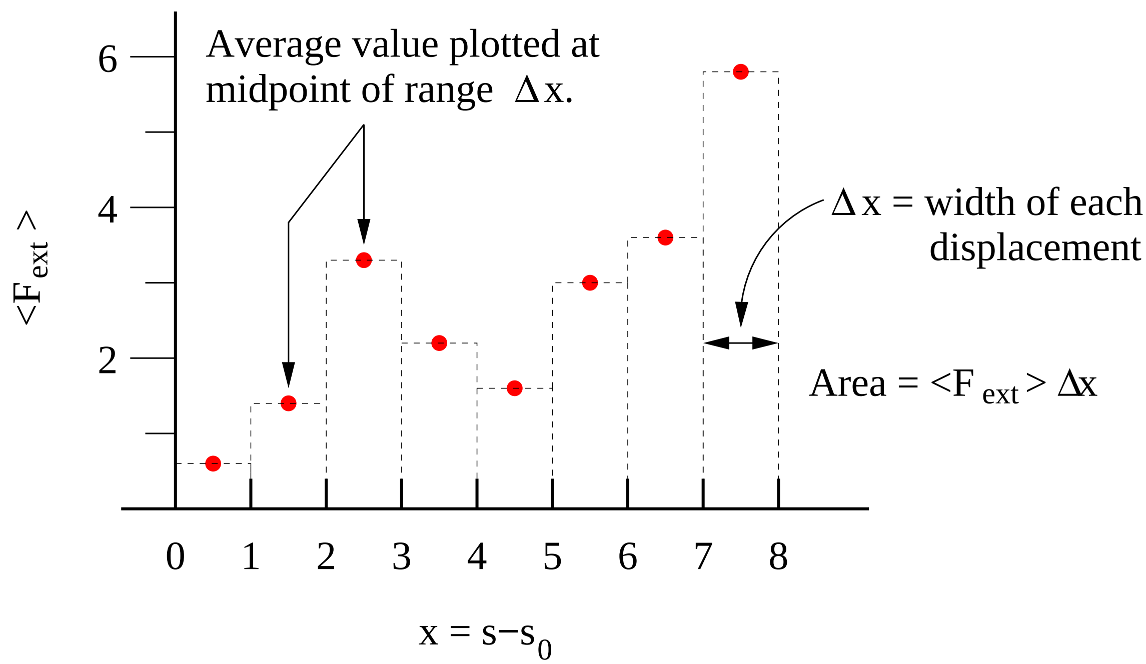
(c) Write the equation describing the relationship between the external force, F_{ext}, and the total displacement, x, of the spring from its equilibrium using the symbols F_{ext}, k, and x.

Note: Any restoring force on an object which is proportional to its displacement is known as a Hooke's Law Force. There was an erratic, contentious genius named Robert Hooke who was born in 1635. He played with springs and argued with Newton.

Calculating Work when the Force is not Constant

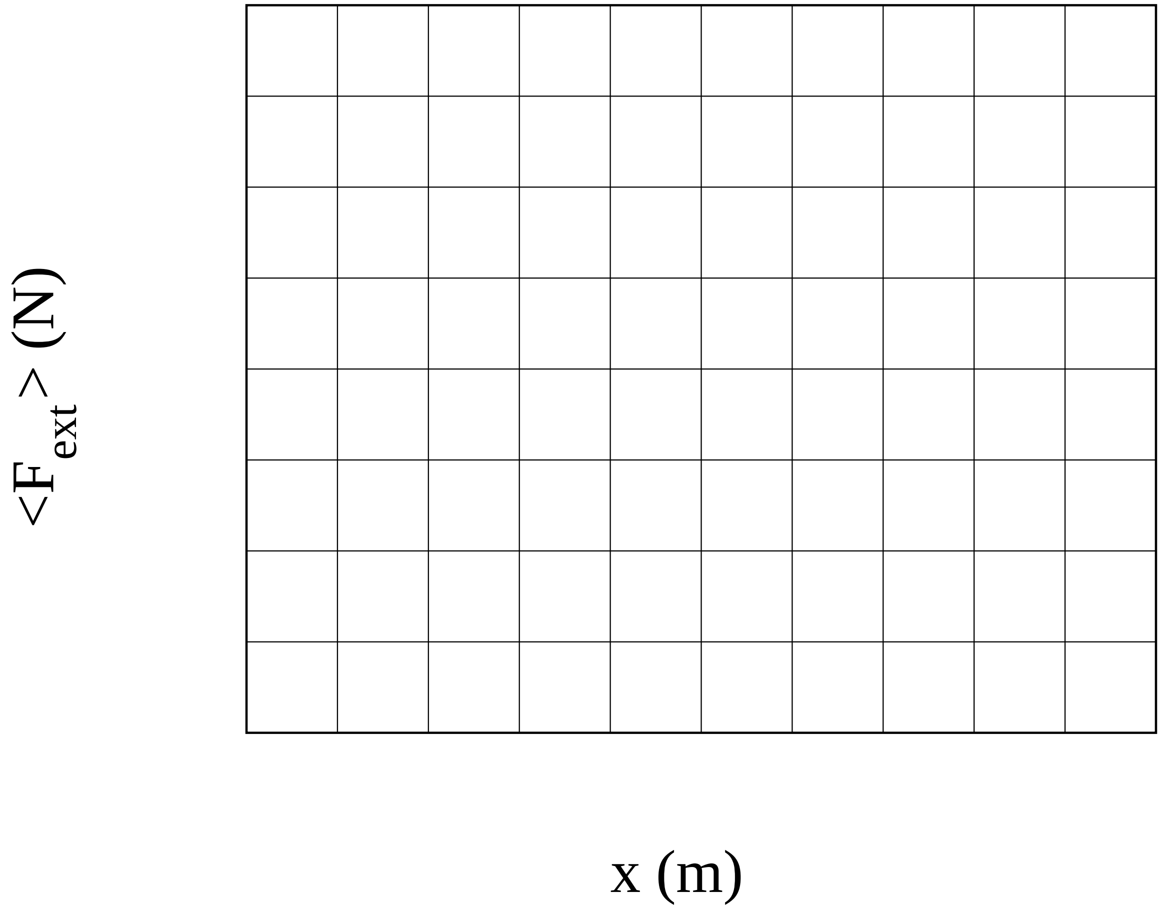
We would like to expand the definition of work so it can be used to calculate the work associated with stretching a spring and the work associated with other forces that are not constant. A helpful approach is to plot the average force needed to move an object for each successive displacement Δx as a bar graph like that shown in the figure below. The figure shows a graph representing the average applied force causing each unit of displacement of an object. This graph represents force that is not constant but not the force vs. displacement of a typical spring.

Note: The bar graph below is intended to illustrate mathematical concepts. Any similarity between the values of the forces in the bar graph and any real set of forces is purely coincidental. In general, the force causing work to be done on an object is not constant.



Activity 8: Force vs. Distance in a Bar Graph

(a) Using your data from Activity 7, calculate the width of each displacement Δx, the average position for each displacement $\langle x\rangle$, and the average external force $\langle F_{ext}\rangle$ for each displacement, and record the values in the table above. Plot $\langle F_{ext}\rangle$ vs. x as a bar graph on the grid below. (Choose appropriate scales for the axes before making the graph.)



How can we calculate the work done in stretching the spring? We can use several equivalent techniques: (1) adding up little pieces of $\langle F_{ext} \rangle \Delta x$ from the above bar graph, (2) finding the area under the "curve" you created in Activity 7, or (3) using mathematical integration.

All three methods should yield about the same result. If you have studied integrals in calculus you may want to consult your instructor or the textbook about how to set up the appropriate definite integral to calculate the work needed to stretch the spring.

Activity 9: Calculation of Work

(a) Calculate the work needed to stretch the spring by adding up small increments of $\langle F_{ext} \rangle \Delta x$ (this is ΔW) in your table. Also record the running sum in the table and indicate the final value of W_{total} below. Don't forget to specify units.

$W_{total} =$

(b) Calculate the work needed to stretch the spring by computing the area under the curve in the graph of F_{ext} vs. x that you created in Activity 7.

(c) How does adding up the little rectangles in part (a) compare to finding the area under the curve in part (b)?

Note that in the limit where the x values are very small the sum of $\langle F_{ext}\rangle \Delta x$, known by mathematicians as the Riemann sum, converges to the mathematical integral and to the area under the curve.

Defining Kinetic Energy and Its Relationship to Work

What happens when you apply an external force to an object that is free to move and has no friction forces on it? Obviously it should experience an acceleration and end up being in a different state of motion. Can we relate the change in motion of the object to the amount of work that is done on it?

Let's consider a fairly simple situation. Suppose an object is lifted through a distance s near the surface of the earth and then allowed to fall. During the time it is falling it will experience a constant force as a result of the attraction between the object and the earth glibly called the force of gravity. You can use the theory we have already developed for the gravitational force to compare the velocity of the object to the work done on it by the gravitational field as it falls through a distance y. This should lead naturally to the definition of a new quantity called kinetic energy, which is a measure of the amount of "motion" gained as a result of the work done on the mass.

Activity 10: Equations for Falling v vs. y

(a) An object of mass m is dropped near the surface of the earth. What are the magnitude and direction of its acceleration g?

(b) If the object has no initial velocity and is allowed to fall for a time t under the influence of the gravitational force, what kinematic equation describes the relationship between the distance the object falls, y, and its time of fall, t? Assume $y_0 = 0$ and take positive down.

(c) Do you expect the magnitude of the velocity to increase, decrease or remain the same as the distance increases? Note: This is an obvious question!!

(d) Differentiate the equation you wrote down in part (b) to find a relationship between v, the acceleration g, and time t.

(e) Eliminate t from the equations you obtained in parts (b) and (d) to get an expression that describes how the velocity, v, of the falling object depends on the distance, y, through which it has fallen.

You can use the kinematic equations to derive the functional relationship you hopefully discovered experimentally in the last activity. If we define the kinetic energy (K) of a moving object as the quantity $K = \frac{1}{2}mv^2$, then we can relate the change in kinetic energy as an object falls to the work done on it. Note that for an object initially at rest the initial kinetic energy is $K_i = 0$, so the change in kinetic energy is given by the difference between the initial and final kinetic energies. $\Delta K = K_f - K_i = \frac{1}{2}mv^2$.

Activity 11: Computing Work and Kinetic Energy of a Falling Mass

(a) Suppose the mass of your falling object is 0.35 kg. What is the value of the work done by the gravitational force when the mass is dropped through a distance of $y = 1.2$ m?

(b) Use the kinematic equation you derived in Activity 10(e) that relates v and y to find the velocity of the falling object after it has fallen 1.2 m.

(c) What is the kinetic energy of the object before it is dropped? After it has fallen 1.2 m? What is the change in kinetic energy, ΔK, as a result of the fall?

(d) How does the work done by the gravitational force compare to the kinetic energy change, ΔK, of the object?

Activity 12: The Mathematical Relationship between Work and Kinetic Energy Change In a Fall

(a) Since our simplified case involves a constant acceleration, write down the equation you derived in Activity 10(e) to describe the speed, v, of a falling object as a function of the distance y which it fell.

(b) Using the definition of work, show that $W = mgy$ when the object is dropped through a distance y.

(c) By combining the equations in parts (a) and (b) above, show that in theory the work done on a mass falling under the influence of the gravitational attraction exerted on it by the earth is given by the equation $W = \Delta K$.

(d) You have just proven an example of the work-energy theorem which states that the change in kinetic energy of an object is equal to the net work done by all the forces acting on it.

$$W = \Delta K \qquad \text{[Work-Energy Theorem]}$$

Although you have only shown the work-energy theorem for a special case where no friction is present, it can be applied to any situation in which the net force can be calculated. For example, the net force on an object might be calculated as a combination of applied, spring, gravitational, and friction forces.

2 Conservation of Mechanical Energy[2]

Name ______________________ Section ____________ Date ____________

Objectives

- To understand the concept of potential energy.
- To investigate the conditions under which mechanical energy is conserved.

Overview

The last unit on work and energy culminated with a mathematical proof of the work-energy theorem for a mass falling under the influence of the force of gravity. We found that when a mass starts from rest and falls a distance y, its final velocity can be related to y by the familiar kinematic equation

$$v_f^2 = v_i^2 + 2gy \qquad \text{or} \qquad gy = \frac{1}{2}\left(v_f^2 - v_i^2\right) \qquad [Eq.\,1]$$

where v_f is the final velocity and v_i is the initial velocity of the mass.

We believe this equation is valid because: (1) you have derived the kinematic equations mathematically using the definitions of velocity and constant acceleration, and (2) you have verified experimentally that masses fall at a constant acceleration. We then asked whether the transformation of the mass from a speed v_i to a speed v_f is related to the work done on the mass by the force of gravity as it falls.

The answer is mathematically simple. Since $F_g = mg$, the work done on the falling object by the force of gravity is given by

$$W_g = F_g y = mgy \qquad [Eq.\,2]$$

But according to Equation 1, $gy = \frac{1}{2}v_f^2 - \frac{1}{2}v_i^2$, so we can re-write Equation 2 as

$$W_g = mgy = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 \qquad [Eq.\,3]$$

The $\frac{1}{2}mv_f^2$ is a measure of the motion resulting from the fall. If we define it as the energy of motion, or, more succinctly, the kinetic energy, we can define a work-energy theorem for falling objects:

$$W = \Delta K \qquad [Eq.\,4]$$

or, the work done on a falling object by the earth is equal to the change in its kinetic energy as calculated by the difference between the final and initial kinetic energies.

If external work is done on the mass to raise it through a height y (a fancy phrase meaning "if some one picks up the mass"), it now has the potential to fall back through the distance y, gaining kinetic energy as it falls. Aha! Suppose we define *potential energy* to be *the amount of external work, W_{ext}, needed to move a mass at constant velocity through a distance y against the force of gravity.* Since this amount of work is positive while the work done by the gravitational force has the same magnitude but is negative, this definition can be expressed mathematically as

$$U = W_{ext} = mgy \qquad [Eq.\,5]$$

Note that when the potential energy is a maximum, the falling mass has no kinetic energy but it has a maximum potential energy. As it falls, the potential energy becomes smaller and smaller as the kinetic energy increases. The kinetic and potential energy are considered to be two different forms of mechanical energy. What about the total mechanical energy, consisting of the sum of these two energies? Is the total mechanical energy constant

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during the time the object falls? If it is, we might be able to hypothesize a law of conservation of mechanical energy as follows: *In some systems, the sum, E, of the kinetic and potential energy is a constant.* This hypothesis can be summarized mathematically by the following statement.

$$E = K + U = \text{constant} \qquad [Eq.\,6]$$

The idea of mechanical energy conservation raises a number of questions. Does it hold quantitatively for falling masses? How about for masses experiencing other forces, like those exerted by a spring? Can we develop an equivalent definition of potential energy for the mass-spring system and other systems and re-introduce the hypothesis of conservation of mechanical energy for those systems? Is mechanical energy conserved for masses experiencing frictional forces, like those encountered in sliding?

In this unit, you will explore whether or not the mechanical energy conservation hypothesis is valid for a falling mass.

Activity 1: Mechanical Energy for a Falling Mass

Suppose a ball of mass m is dropped from a height h above the ground.

(a) Where is U a maximum? A minimum?

(b) Where is K a maximum? A minimum?

(c) If mechanical energy is conserved what should the sum of $K + U$ be for any point along the path of a falling mass?

Mechanical Energy Conservation

How do people in different reference frames near the surface of the earth view the same event with regard to mechanical energy associated with a mass and its conservation? Suppose the president of your college drops a 2.0-kg water balloon from the second floor of the administration building (10.0 meters above the ground). The president takes the origin of his or her vertical axis to be even with the level of the second floor. A student standing on the ground below considers the origin of his coordinate system to be at ground level. Have a discussion with your classmates and try your hand at answering the questions below.

Activity 2: Mechanical Energy and Coordinate Systems

(a) What is the value of the potential energy of the balloon before and after it is dropped according to the president? According to the student? Show your calculations and don't forget to include units!

The president's perspective is that $y = 0.0$ m at $t = 0$ s and that $y = -10.0$ m when the balloon hits the student):

$U_i =$

$U_f =$

The student's perspective is that $y = 10.0$ m at $t = 0$ s and that $y = 0.0$ m when the balloon hits:

$U_i =$

$U_f =$

Note: If you get the same potential energy value for the student and the president, you are on the wrong track!

(b) What is the value of the kinetic energy of the balloon before and after it is dropped according to the president? According to the student? Show your calculations. Hint: Use a kinematic equation to find the velocity of the balloon at ground level.

President's perspective:

$K_i =$

$K_f =$

Student's perspective:

$K_i =$

$K_f =$

Note: If you get the same values for both the student and the president for values of the kinetic energies you are on the right track!

(c) What is the value of the total mechanical energy of the balloon before and after it is dropped according to the president? According to the student? Show your calculations. Note: If you get the same values for both the student and the president for the total energies you are on the wrong track!!!!!

President's perspective:

$E_i =$

$E_f =$

Student's perspective:

$E_i =$

$E_f =$

(d) Why don't the two observers calculate the same values for the mechanical energy of the water balloon?

(e) Why do the two observers agree that mechanical energy is conserved?

Activity 3: Energy Analysis for a Falling Mass

(a) Perform a video analysis of one of the movies which can be found at

`http://facultystaff.richmond.edu/~ggilfoyl/genphys/IQS/projectiles/links.html`

to obtain the vertical position of the the ball as a function of time. Check with your instructor to see which movie to use. Make sure you scale the graph. See the Appendix for details on video analysis.

(b) Calculate the vertical distance the ball moves during the time intervals between adjacent frames. Suppose, for example, your time data are in column `A` and your vertical position data are in column `D` and the first entry is in row 14. Click in row 14 of an empty column like column `N`. In the formula box above the spreadsheet table enter '`=D15-D14`' (don't include the quotation marks) and hit `Return`. This will calculate the distance the ball covered in going from the first entry in row 14 to the second entry in row 15. Next, click on the new entry you just made. You should see a small box in the lower right corner of the cell. Grab it and drag it straight down to the second-to-last row of your data and release. You should now see the distance covered between adjacent entries in all the rows above. If you don't see this consult your instructor. Label the column dy (m). Verify the results for one or two cells. Why did you drag down to the second-to-last cell and not the last one?

(c) Calculate the average velocity for each time interval. To do this, recall our example above. If you calculated the difference in vertical position between adjacent frames in column `N` starting in row 14, then click in column `O` row 14. In the formula box above the spreadsheet table enter '`=N14/(A15-A14)`' and hit `Return`. This will calculate the average velocity going from cell `O14` to cell `O15`. We will use this as an approximate measure of the instantaneous velocity. Last, click on the new entry you just made. You should see a small box in the lower right corner of the cell. Grab it and drag it straight down to the second-to-last row of your data and release. You should now see the velocity in all the rows above. If you don't see this consult your instructor. Label the column v (m/s). Verify the results for one or two cells.

(d) Calculate the kinetic energy for each time interval (the mass of the ball is $m = 0.058\ kg$). To do this, recall our example above. If you calculated the velocity in column `O` starting in row 14, then click in column `P` row 14. In the formula box above the spreadsheet table enter '`=0.5*0.058*O14*O14`' and hit `Return`. This will calculate the kinetic energy for cell `O14`. Last, click on the new entry you just made. You should see a small box in the lower right corner of the cell. Grab it and drag it straight down to the second-to-last row of your data and release. You should now see the kinetic energy in all the rows above. If you don't see this consult your instructor. Label the column $K(J)$. Verify the results for one or two cells.

(e) Calculate the potential energy U for each frame using the same techniques you used above. Label the column $U(J)$. Verify the results for one or two cells.

(f) Calculate the total energy $E = K + U$ for each frame. Label the column $E(J)$. Verify the results for one or two cells.

(g) Create a graph of K, U, and E vs. time. Put all three on the same graph. Print the graph and put a copy in your notebook.

(h) Does mechanical energy appear to be conserved within experimental uncertainties? How would you quantitatively estimate the value of the experimental uncertainty? Once you establish the method apply it to your data.

3 Force and Momentum Conservation[3]

Name ______________________ Section ____________ Date ____________

Objectives

- To understand the definition of momentum and its vector nature and its relationship to Newton's second law.
- To develop the concept of impulse to explain how forces act over time when an object undergoes a collision.
- To use Newton's second law to develop a mathematical equation relating impulse and momentum change for any object experiencing a force.
- To formulate the Law of Conservation of Momentum as a theoretical consequence of Newton's laws and to test it experimentally.

Overview

In the next few units we will explore the forces of interaction between two or more objects and study the changes in motion that result from these interactions. We are especially interested in studying collisions and explosions in which interactions take place in fractions of a second or less. Early investigators spent a considerable amount of time trying to observe collisions and explosions, but they encountered difficulties. This is not surprising, since the observation of the details of such phenomena requires the use of instrumentation that was not yet invented (such as the high speed camera). However, the principles of the outcomes of collisions were well understood by the late seventeenth century, when several leading European scientists (including Sir Isaac Newton) developed the concept of "quantity of motion" to describe both elastic collisions (in which objects bounce off each other) and inelastic collisions (in which objects stick together). These days we use the word momentum rather than motion in describing collisions and explosions.

We will begin our study of collisions by exploring the relationship between the forces experienced by an object and its momentum change. It can be shown mathematically from Newton's laws and experimentally from our own observations that the integral of force experienced by an object over time is equal to its change in momentum. This time-integral of force is defined as a special quantity called impulse, and the statement of equality between impulse and momentum change is known as the impulse-momentum theorem.

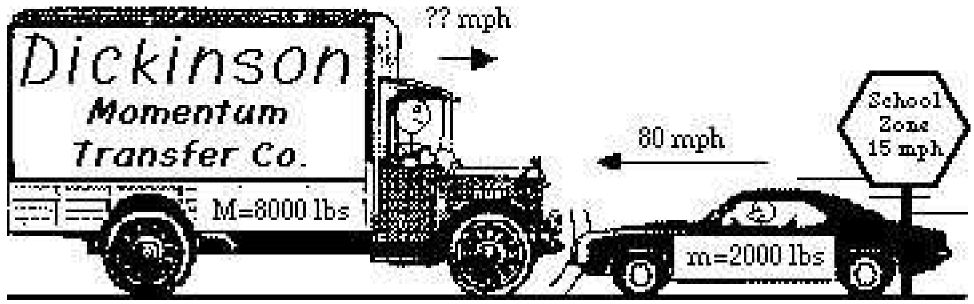
Apparatus

Dynamics carts (2) and track	2 force probes (force sensors)	*Science Workshop 750 Interface*
Graphing and curve fitting software (*Excel*)	Circular bubble level	*DataStudio* software (Two Force Probes application)
Weights		

Defining Momentum

In this session we are going to develop the concept of momentum to predict the outcome of collisions. But you don't officially know what momentum is because we haven't defined it yet. Lets start by predicting what will happen as a result of a simple one-dimensional collision. This should help you figure out how to define momentum to enable you to describe collisions in mathematical terms.

[3]1990-93 Dept. of Physics and Astronomy, Dickinson College. Supported by FIPSE (U.S. Dept. of Ed.) and NSF. Portions of this material may have been modified locally and may not have been classroom tested at Dickinson College.



It's early fall and you are driving along a two lane highway in a rented moving van. It is full of all of your possessions so you and the loaded truck were weighed in at 8000 lbs. You have just slowed down to 15 MPH because you're in a school zone. It's a good thing you thought to do that because a group of first graders is just starting to cross the road. Just as you pass the children you see a 2000 lb sports car in the oncoming lane heading straight for the children at about 80 MPH. What a fool the driver is! A desperate thought crosses your mind. You figure that you just have time to swing into the oncoming lane and speed up a bit before making a head-on collision with the sports car. You want your truck and the sports car to crumple into a heap that sticks together and doesn't move. Can you save the children or is this just a suicidal act? For simulated observations of this situation you can use two carts of different masses set up to stick together in trial collisions.

Activity 1: Can You Stop the Car?

(a) Predict how fast you would have to be going to completely stop the sports car. Explain the reasons for your prediction.

(b) Try some head on collisions with the carts of different masses to simulate the event. Describe some of your observations. What happens when the less massive cart is moving much faster than the more massive cart? Much slower? At about the same speed?

(c) Based on your intuitive answers in parts (a) and (b) and your observations, what mathematical definition might you use to describe the momentum (or motion) you would need to stop an oncoming vehicle traveling with a known mass and velocity?

Just to double check your reasoning, you should have come to the conclusion that momentum is defined by the vector equation

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

Expressing Newton's Second Law Using Momentum

Originally Newton did not use the concept of acceleration or velocity in his laws. Instead he used the term "motion," which he defined as the product of mass and velocity (a quantity we now call momentum). Let's examine a translation from Latin of Newton's first two laws (with some parenthetical changes for clarity).

Newton's First Two Laws of Motion

1. *Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed on it.*
2. *The (rate of) change of motion is proportional to the motive force impressed: and is made in the direction in which that force is impressed.*

The more familiar contemporary statement of the second law is that the net force on an object is the product of its mass and its acceleration where the direction of the force and of the resulting acceleration are the same. Newton's statement of the law and the more modern statement are mathematically equivalent, as you will show.

Activity 2: Re-expressing Newton's Second Law

(a) Write down the contemporary mathematical expression for Newton's second law relating net force to mass and acceleration. Please use vector signs and a summation sign where appropriate.

(b) Write down the definition of instantaneous acceleration in terms of the rate of change of velocity. Again, use vector signs.

(c) It can be shown that if an object has a changing velocity and a constant mass then $m\frac{d\mathbf{v}}{dt} = \frac{d(m\mathbf{v})}{dt}$. Explain why.

(d) Show that $\sum \mathbf{F} = m\mathbf{a} = \frac{d\mathbf{p}}{dt}$.

(e) Explain in detail why Newton's statement of the second law and the mathematical expression $\sum \mathbf{F} = \frac{d\mathbf{p}}{dt}$ are two representations of the same statement, i.e., are logically equivalent.

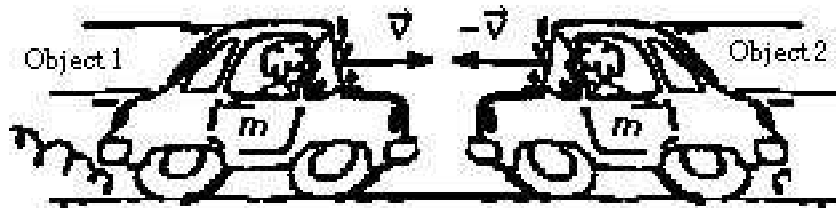
Predicting Interaction Forces between Objects

We recently focused our attention on the change in momentum that an object undergoes when it experiences a force that is extended over time (even if that time is very short!). Since interactions like collisions and explosions never involve just one object, we would like to turn our attention to the mutual forces of interaction between two or more objects. As usual, you will be asked to make some predictions about interaction forces and then be given the opportunity to test these predictions.

Activity 3: Predicting Interaction Forces

(a) Suppose the masses of two objects are the same and that the objects are moving toward each other at the same speed so that

$$m_1 = m_2 \quad \text{and} \quad \mathbf{v}_1 = -\mathbf{v}_2$$



Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction!

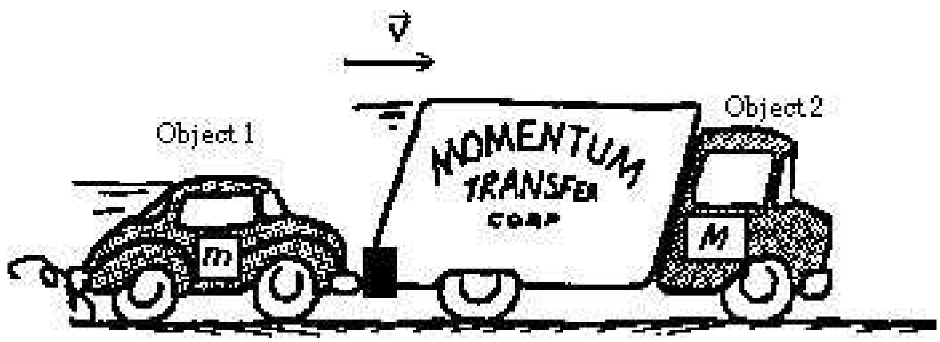
_______ Object 1 exerts more force on object 2.

_______ The objects exert the same force on each other.

_______ Object 2 exerts more force on object 1.

(c) Suppose the mass of object 1 is much less than that of object 2 and that it is pushing object 2 that has a dead motor so that both objects move in the same direction at speed v.

$$m_1 \ll m_2 \quad \text{and} \quad \mathbf{v}_1 = \mathbf{v}_2$$



Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction.

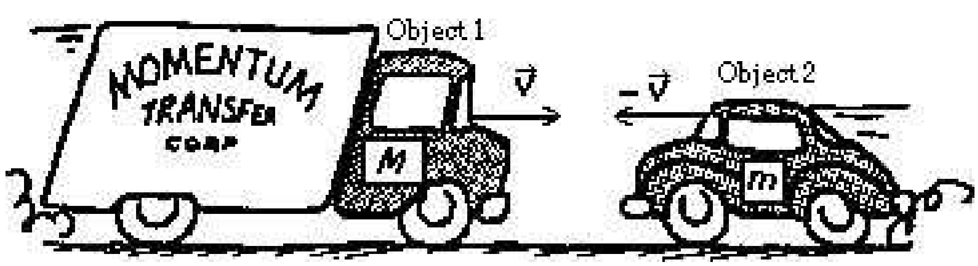
_______ Object 1 exerts more force on object 2.

_______ The objects exert the same force on each other.

_______ Object 2 exerts more force on object 1.

(d) Suppose the mass of object 1 is greater than that of object 2 and that the objects are moving toward each other at the same speed so that

$$m_1 > m_2 \quad \text{and} \quad \mathbf{v}_1 = -\mathbf{v}_2$$



Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction.

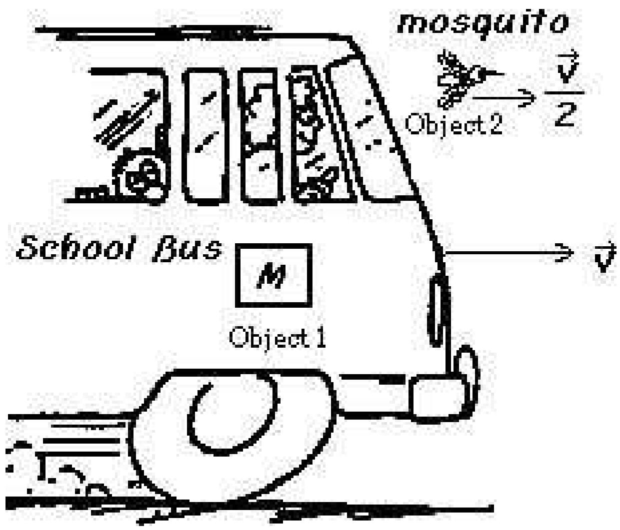
________ Object 1 exerts more force on object 2.

________ The objects exert the same force on each other.

________ Object 2 exerts more force on object 1.

(e) Suppose the mass of object 1 is greater than that of object 2 and that object 2 is moving in the same direction as object 1 but not quite as fast so that

$$m_1 > m_2 \quad \text{and} \quad \mathbf{v}_1 > \mathbf{v}_2$$



Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction.

________ Object 1 exerts more force on object 2.

________ The objects exert the same force on each other.

________ Object 2 exerts more force on object 1.

(g) Provide a summary of your predictions. What are the circumstances under which you predict that one object will exert more force on another object?

Measuring Mutual Forces of Interaction

In order to test the predictions you made in the last activity you can study gentle collisions between two force probes attached to carts. You can strap additional masses to one of the carts to increase its total mass so it has significantly more mass than the other. If a compression spring is available you can set up an "explosion" between the two carts by compressing the spring between the force probes on each cart and letting it go. You can make and display the force measurements with the **Two Force Probes** application in the **131 Workshop** submenu. You can also determine the areas under the force vs. time graphs to find the impulses experienced by the carts during the collisions. See **Appendix B Introduction to DataStudio** for instructions on finding the area under a curve.

Activity 4: Measuring Collision Forces

(a) Use the two carts to explore various situations that correspond to the predictions you made about mutual forces. Your goal is to find out under what circumstances one object exerts more force on another object. Describe what you did in the space below and attach a printout of at least one of your graphs of force 1 vs. time and force 2 vs. time.

(b) What can you conclude about forces of interactions during collisions? Are there any circumstances under which one object experiences a different magnitude of force than another during a collision? How do the magnitudes and directions of the forces compare on a moment by moment basis in each case? Were the predictions you made correct? If not, explain why.

(c) Do your conclusions have anything to do with Newton's third law?

(d) How does the vector impulse due to object 1 acting on object 2 compare to the impulse of object 2 acting on object 1 in each case? Are they the same in magnitude or different? Do they have the same sign or a different sign? Remember $\mathbf{I} = \int_{t_i}^{t_f} \mathbf{F}\, dt$.

Newton's Laws and Momentum Conservation

In your investigations of interaction forces, you should have found that the forces between two objects are equal in magnitude and opposite in sign on a moment by moment basis for all the interactions you studied. This is of course a testimonial to the seemingly universal applicability of Newton's third law to interactions between ordinary masses. You can combine the findings of the impulse-momentum theorem (which is really another form of Newton's second law since we derived it mathematically from the second law) to derive the Law of Conservation of Momentum shown below.

Law of Conservation of Momentum

$$\sum \mathbf{p} = \mathbf{p}_{1i} + \mathbf{p}_{2i} = \mathbf{p}_{1f} + \mathbf{p}_{2f} = \text{constant in time}$$

where 1 refers to object 1 and 2 refers to object 2 and i refers to the initial momenta and f to the final momenta.

Activity 5: Deriving Momentum Conservation

(a) What did you conclude in the last activity about the magnitude and sign of the impulse on object 1 due to object 2 and vice verse when two objects interact? In other words, how does $\mathbf{I}_1$ compare to $\mathbf{I}_2$?

(b) Since you have already verified experimentally that the impulse-momentum theorem holds, what can you conclude about how the change in momentum of object 1, $\Delta\mathbf{p}_1$, as a result of the interaction compares to the change in momentum of object 2, $\Delta\mathbf{p}_2$, as a result of the interaction? Remember $\mathbf{I} = \Delta\mathbf{p}$.

(c) Use the result of part (b) to show that the Law of Conservation of Momentum holds for a collision, i.e. $\sum \mathbf{p} = \mathbf{p}_{1i} + \mathbf{p}_{2i} = \mathbf{p}_{1f} + \mathbf{p}_{2f}$ = constant in time.

In the next few units you will continue to study one- and two-dimensional collisions using momentum conservation. Right now you will attempt to test the Law of Conservation of Momentum for a simple situation by using video analysis. To do this you will make and analyze a video movie in which two carts of different masses undergo a one-dimensional elastic collision. You may not be able to finish this in class, but you can complete the project for homework.

Testing Momentum Conservation

You just used theoretical grounds to derive momentum conservation. This idea still must be tested against experiment. You will make this test by colliding two carts on a track and recording and analyzing their motion before and after they hit.

Activity 6: Colliding Carts

(a) Perform a video analysis of one of the movies which can be found at

`http://facultystaff.richmond.edu/~ggilfoyl/genphys/IQS/collisions/links.html`

to obtain the positions of the the carts as a function of time. Check with your instructor to see which movie to use. Make sure you scale the graph. See the Appendix for details on video analysis.

(b) Determine the position of both carts (the target and the projectile) during the motion. To do this task follow the instructions in **Appendix D: Video Analysis** for recording and calibrating the video data. Mark two objects on each frame; click once on the projectile cart and once on the target cart. The data table should contain five columns with the values of time, x and y positions of the projectile cart, and x and y positions of the target cart. Note: Since this is a horizontal 1D collision the y-coordinates are of no interest. They should be constant for each frame. If they are not, consult your instructor.

(c) Create graphs of position versus time for both carts. See **Appendix C: Introduction to Excel** for more details. Print the graphs and include them with this unit.

(d) Use your data to calculate the momenta of carts 1 and 2 before the collision.

(e) Use the data to calculate the momenta of carts 1 and 2 after the collision.

(f) Using the results of parts (d) and (e), calculate the total momentum before and after the collision. Also calculate the difference between the total momentum before and after the collision $(p_f - p_i)$ and the percent difference, and record them below. Go around to the other lab groups and get their results for the percent difference $(p_f - p_i)/p_i$. Make a histogram of the results you collect and calculate the average and standard deviation. For information on making histograms, see **Appendix C**. For information on calculating the average and standard deviation, see **Appendix A**. Record the average and standard deviation here. Attach the histogram to this unit.

(g) What is your expectation for the difference between the initial and final momentum? Do the data from the class support this expectation? Use the average and standard deviation for the class to quantitatively answer this question.

(h) What does the histogram of the class data tell you? Be quantitative in your answer.

(i) Within the limits of experimental uncertainty, is momentum conserved (i.e., is the total momentum of the two cart system the same before and after the collision)? Be quantitative in your answer.

Momentum Change and Collision Forces

What's Your Intuition?

You are sleeping in your sister's room while she is away at college. Your house is on fire and smoke is pouring into the partially open bedroom door. The room is so messy that you cannot get to the door. The only way to close the door is to throw either a blob of clay or a super ball at the door — there's not enough time to throw both.

Activity 7: What Packs the Biggest Wallop-A Clay Blob or a Super ball?

Assuming that the clay blob and the super ball have the same mass, which would you throw to close the door: the clay blob (which will stick to the door) or the super ball (which will bounce back with almost the same velocity it had before it collided with the door)? Give reasons for your choice, using any notions you already have or any new concepts developed in physics such as force, momentum, Newton's laws, etc. Remember, your life depends on it!

Momentum Changes

It would be nice to be able to use Newton's formulation of the second law of motion to find collision forces, but it is difficult to measure the rate of change of momentum during a rapid collision without special instruments. However, measuring the momenta of objects just before and just after a collision is usually not too difficult. This led scientists in the seventeenth and eighteenth centuries to concentrate on the overall changes in momentum that resulted from collisions. They then tried to relate changes in momentum to the forces experienced by an object during a collision. In the next activity you are going to explore the mathematics of calculating momentum changes.

Activity 8: Predicting Momentum Changes

Which object undergoes the most momentum change during the collision with a door: the clay blob or the super ball? Explain your reasoning carefully.

Let's check your reasoning with some formal calculations of the momentum changes for both inelastic and elastic collisions. This is a good review of the properties of one-dimensional vectors. Recall that momentum is defined as a vector quantity that has both magnitude and direction. Mathematically, momentum change is given by the equation

$$\Delta \mathbf{p} = \mathbf{p}_f - \mathbf{p}_i$$

where $\mathbf{p}_i$ is the initial momentum of the object just before and $\mathbf{p}_f$ is its final momentum just after a collision.

Activity 9: Calculating 1D Momentum Changes

(a) Suppose a dead ball (or clay blob) is dropped on a table and "sticks" in such a way that it has an initial momentum just before it hits of $\mathbf{p}_i = -p_{iy}\widehat{\mathbf{j}}$ where $\widehat{\mathbf{j}}$ is a unit vector pointing along the positive y axis. Express the final momentum of the dead ball in the same vector notation.

(b) What is the change in momentum of the clay blob as a result of its collision with the table? Use the same type of unit vector notation to express your answer.

(c) Suppose that a live ball (or a super ball) is dropped on a table and "bounces" on the table in an elastic collision so that its speed just before and just after the bounce are the same. Also suppose that just before it bounces it has an initial momentum $\mathbf{p}_i = -p_{iy}\widehat{\mathbf{j}}$, where $\widehat{\mathbf{j}}$ is a unit vector pointing along the positive y-axis. What is the final momentum of the ball in the same vector notation? Hint: Does the final $\mathbf{p}$ vector point along the +y or $-y$ axis?

(d) What is the change in momentum of the ball as a result of the collision? Use the same type of unit vector notation to express your result.

(e) The answer is not zero. Why? How does this result compare with your prediction? Discuss this situation.

(f) Suppose the mass of each ball is 0.2 kg and that they are dropped from 1 m above the table. Using this value for mass of the balls and a calculated value for the velocity of each of the balls just before they hit the table, you can calculate the momentum just before the collision $\mathbf{p}_i$ for each of the balls. Also calculate the momentum of the balls just after the collision $\mathbf{p}_f$ and the change in momentum $\Delta\mathbf{p}$ for each ball. Show your calculations in the space below.

4 Two-Dimensional Collisions[4]

Name ______________________ Section ____________ Date ____________

Objectives

To test experimentally that the Law of Conservation of Momentum holds for two-dimensional collisions in isolated systems.

Apparatus

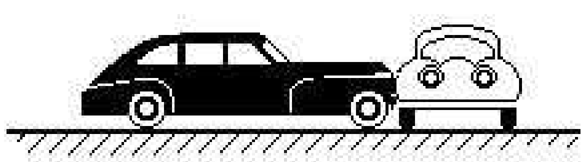
ball bearing	pendulum bob	protractor
level	carts	wooden board
video analysis software		

2-D Collisions: Intelligent Guesses & Observations

Conservation of momentum can be used to solve a variety of collision problems. So far we have only considered momentum conservation in one dimension, but real collisions lead to motions in two and three dimensions. For example, air molecules are continually colliding in space and bouncing off in different directions.

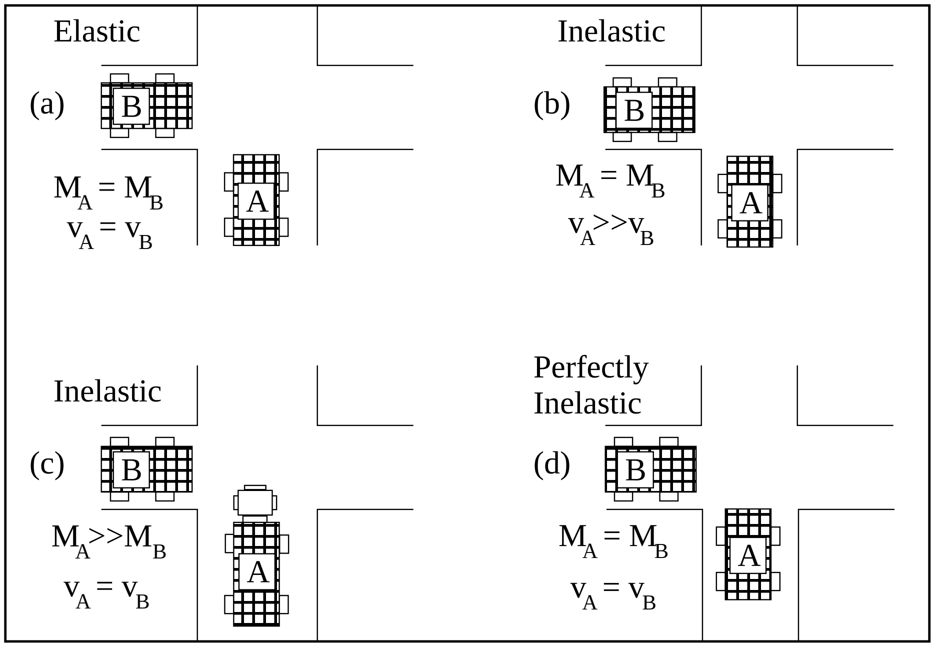
You probably know more about two-dimensional collisions than you think. Draw on your prior experience with one-dimensional collisions to anticipate the outcome of several two-dimensional collisions. Suppose you were a witness to several accidents in which you closed your eyes at the moment of collision each time two vehicles heading toward each other crashed. Even though you couldn't stand to look, can you predict the outcome of the following accidents?

You see car A enter an intersection at the same time as car B coming from its left enters the intersection. Car B is the same make and model as car A and is traveling at the same speed. The two cars collide and bounce off one another. What happens? Hint: You can use a symmetry argument, your intuition or a quick analysis of 1-D results. For example, pick a coordinate system and think about two separate accidents: the x accident in which car B is moving at speed v_{bx} and car A is standing still, and the y accident in which car A is moving at speed $v_{ay} = v_{bx}$ and car B is standing still.



The diagram below shows an aerial view of several possible two-dimensional accidents that might occur. The first is a collision at right angles of two identical cars.

[4]1990-93 Dept. of Physics and Astronomy, Dickinson College. Supported by FIPSE (U.S. Dept. of Ed.) and NSF. Portions of this material may have been modified locally and may not have been classroom tested at Dickinson College.



Activity 1: Qualitative 2-D Collisions

(a) Using the diagram above, draw a dotted line in the direction you think your two cars will move after a collision between cars with equal masses and velocities. Explain your reasoning in the space below.

(b) Draw a dotted line for the direction the cars might move if car A were traveling at a speed much greater than that of car B. Explain your reasoning in the space below.

(c) If instead of a car, the vehicle A were a large truck traveling at the same speed as car B, in what direction will the vehicles move? Draw the dotted lines. Explain your reasoning in the space below.

(d) Now suppose that the two vehicles are traveling at the same speed. If the two vehicles were to stick together; in what direction would they move after the collision, if they undergo a perfectly inelastic collision? Explain your reasoning in the space below.

(e) Finally, set up these types of collisions. Observe each type of collision several times. Draw solid lines in the diagram above for the results. How good were your predictions? Explain your reasoning in the space below.

(f) What rules have you devised to predict more or less what is going to happen as the result of a two-dimensional collision?

Theory of 2D Momentum Conservation

Since momentum is a vector, the Law of Conservation of Momentum in two dimensions requires that if the vector conservation equation is broken into components then the conservation law must also hold for each of the vector components. Thus, if we consider the interaction of several objects, and if

$$\sum \mathbf{p} = \mathbf{p}_{1i} + \mathbf{p}_{2i} + \mathbf{p}_{3i} + \ldots = \mathbf{p}_{1f} + \mathbf{p}_{2f} + \mathbf{p}_{3f} + \ldots = \text{a constant}$$

then

$$\sum p_x = p_{1ix} + p_{2ix} + p_{3ix} + \ldots = p_{1fx} + p_{2fx} + p_{3fx} + \ldots = \text{a constant}$$

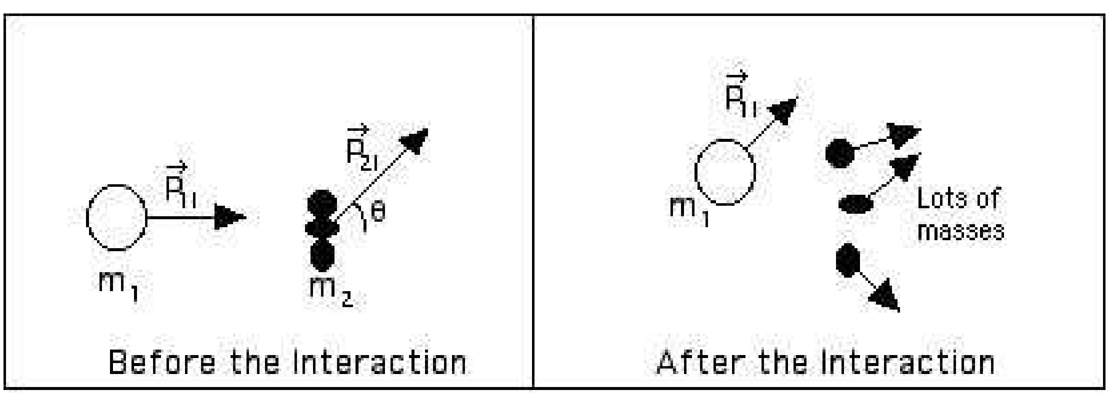
and

$$\sum p_y = p_{1iy} + p_{2iy} + p_{3iy} + \ldots = p_{1fy} + p_{2fy} + p_{3fy} + \ldots = \text{a constant}$$

If a coordinate system is chosen and a given momentum vector makes an angle θ with respect to the designated x-axis then the momentum vector can be broken into components in the usual way:

$$\mathbf{p} = p_x \widehat{\mathbf{i}} + p_y \widehat{\mathbf{j}} = p \cos\theta \widehat{\mathbf{i}} + p \sin\theta \widehat{\mathbf{j}}$$

Let's consider an interaction in which a large mass collides with two smaller hard masses connected by a blob of clay. Assume that this interaction causes the bundle of masses to divide into three fragments as shown in the figure below.



Activity 2: Taking Components

(a) Consider mass #1. Suppose $m_1 = 2.0$kg and the speed $v_{1i} = 1.5$ m/s. What is the initial x-component of momentum? The initial y-component of momentum? Show your calculations.

$p_{1ix} =$

$p_{1iy} =$

(b) Consider mass #2. Suppose $m_2 = 1.8$ kg and the speed $v_{2i} = 2.3$ m/s. If $\theta = 40°$, what is the initial x-component of momentum? The initial y-component of momentum? Show your calculations.

Is Momentum Conserved in Two Dimensions?

During the last few sessions we have placed a lot of faith in the power of Newton's second and third laws to predict that momentum is always conserved in collisions. We have tested the conservation of momentum for one-dimensional collisions and have shown mathematically and experimentally for one-dimensional collisions that if momentum is conserved the center- of-mass of a system will move at a constant velocity regardless of how many internal interactions take place. Now, let's test whether a collision in an isolated two body system will conserve momentum within the limits of experimental uncertainty.

Consider two ball bearings that are free to move in two dimensions on a table. We will record and analyze a video of the two bearings colliding. You can then find the x- and y-components of the momentum for each bearing and test the conservation of momentum in a closed system.

Activity 3: Testing the Conservation of Momentum

(a) Make a movie of two ball bearings colliding by following these steps.

1. Turn the camera on and center the wooden board in the field of view. The camera should be about 1 m above the center of the board where one bearing(the target) will sit. The target bearing should be located straight down below the camera. Use the pendulum bob to position the camera and bearing. Make sure the board is flat by using the small level available at each station. Place a ruler somewhere in the field of view where it won't interfere with the collision and parallel to one edge of the field of view. This ruler will be user later to determine the scale.

2. Make a movie of one bearing (the projectile) rolling into the other, stationary bearing (the target). See **Appendix D: Video Analysis** for details on making the movie. Make the collision a glancing one so that the projectile is scattered to some large angle (otherwise, you will only test momentum conservation in one dimension).

(b) Determine the position of both bearings (the target and the projectile) during the motion. To do this task follow the instructions in **Appendix D: Video Analysis** for creating, calibrating, and analyzing movie data. On each frame click once on the projectile bearing and once on the target. The data table should contain five columns with the values of time, x and y positions of the projectile, and x and y positions of the target. When you calibrate the movie data, note the number of frames per second and record the time interval between successive frames.

$\Delta t =$

(c) Record the masses of the two ball bearings.

$m_1 =$ $m_2 =$

(d) Create a graph of vertical position versus horizontal position for the projectile, and plot the position of the target on the same graph. See **Appendix C: Introduction to Excel** for more details. Make sure the x and y axes cover intervals of the same size so the plot is not distorted. You can adjust the range of an axis by double-clicking anywhere along the axis and modifying the parameters in the pop-up window that appears. Print out the graph.

(e) Draw by eye a best-fit line through the points corresponding to the trajectory of the projectile before the collision. This line will become a new x-axis when you analyze the momentum components of the system. Draw best-fit lines through the points for both ball bearings after the collision. What are the angles of the paths of the target and projectile after the collision with respect to trajectory of the incoming projectile before the collision?

(f) Use the graph to measure the distance each bearing covered before and after the collision. What is the average velocity for each ball bearing before and after the collision? (Hint: Use the value of Δt that you found earlier).

$v_{1i} =$ $v_{1f} =$

$v_{2i} =$ v_{2f}

(g) What are the momentum components for each ball bearing before and after the collision? What is the momentum of the system before the collision along the path of the incoming projectile? What is the momentum of the entire system after the collision?

$p_{1ix} =$ $p_{1iy} =$

$p_{2ix} =$ $p_{2iy} =$

$p_{1fx} =$ $p_{1fy} =$

$p_{2fx} =$ $p_{2fy} =$

$p_{ix} =$ $p_{iy} =$

$p_{fx} =$ $p_{fy} =$

(h) Calculate the difference between the initial, total momentum in the x direction and the final, total momentum in the x direction from your data ($p_{fx} - p_{ix}$). Calculate the difference between the initial, total momentum in the y direction and the final, total momentum in the y direction from your data ($p_{fy} - p_{iy}$). Record your results here. Go around to the other lab groups and get their results for the same calculations. Make a histogram of the results you collect and calculate the average and standard deviation for each component. For information on making histograms, see **Appendix C**. For information on calculating the average and standard deviation, see **Appendix A**. Record the averages and standard deviations here. Attach the histogram to the unit.

(i) What would you expect for the difference between the initial and final total momentum in the x and y directions? Do the data from the class support this expectation? Use the averages and standard deviations for the class to quantitatively answer this question.

(j) What does the histogram of the class data tell you? Be quantitative in your answer.

(k) Does momentum seem to be conserved? Be quantitative in your answer.

5 Impulse, Momentum, and Interactions[5]

Name ______________________ Section ____________ Date ____________

Objectives

- To verify the relationship between impulse and momentum experimentally.
- To study the forces between objects that undergo collisions and other types of interactions in a short time period.

Apparatus

Dynamics cart with flag and track	Force probe	Motion sensor
Science Workshop 750 Interface	compact scale	*DataStudio*

The Impulse-Momentum Theorem

Real collisions, like those between eggs and hands, a Nerfball and a wall, or a falling ball and a table top are tricky to study because Δt is so small and the collision forces are not really constant over the time the colliding objects are in contact. Thus, we cannot calculate the impulse as $F\,\Delta t$. Before we study more realistic collision processes, let's redo the theory for a variable force. In a collision, according to Newton's second law, the force exerted on a falling ball by the table top at any infinitesimally small instant in time is given by

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} \qquad [Eq.\,1]$$

To describe a general collision that takes place between an initial time t_i and a final time t_f , we must take the integral of both sides of the equation with respect to time. This gives

$$\int_{t_i}^{t_f} \mathbf{F}dt = \int_{t_i}^{t_f} \frac{d\mathbf{p}}{dt}dt = (\mathbf{p}_f - \mathbf{p}_i) = \Delta\mathbf{p} \qquad [Eq.\,2]$$

Impulse is a vector quantity defined by the equation

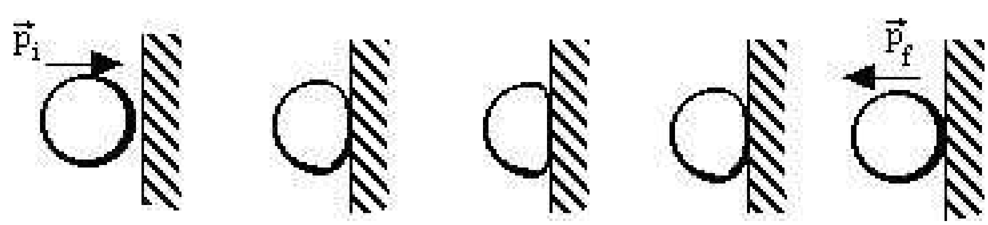
$$\mathbf{I} = \int_{t_i}^{t_f} \mathbf{F}\,dt \qquad [Eq.\,3]$$

By combining equations [2] and [3] we can formulate the impulse-momentum theorem in which

$$\mathbf{I} = \Delta\mathbf{p} \qquad [Eq.\,4]$$

If you are not used to mathematical integrals and how to solve them yet, don't panic. If you have a fairly smooth graph of how the force F varies as a function of time, the impulse integral can be calculated as the area under the F-t curve.

Let's see qualitatively what an impulse curve might look like in a real collision in which the forces change over time during the collision. In particular, let's consider the collision of a Nerfball with a wall as shown below.



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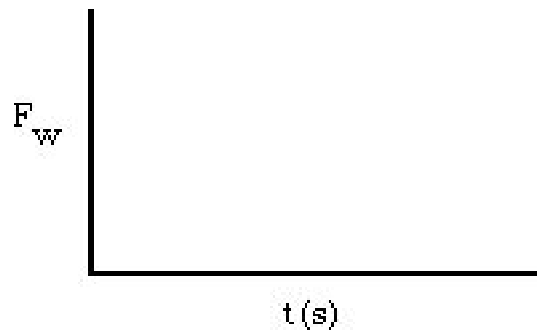
Activity 1: Predicting Collision Forces That Change

(a) Suppose a tennis ball is barreling toward a wall and collides with it. If friction is neglected, what is the net force exerted on the object just before it starts to collide?

(b) When will the magnitude of the force on the ball be a maximum?

(c) Roughly how long does the collision process take? Half a second? Less? Several seconds?

(d) Attempt a rough sketch of the shape of the force the wall exerts on a moving object during a collision.

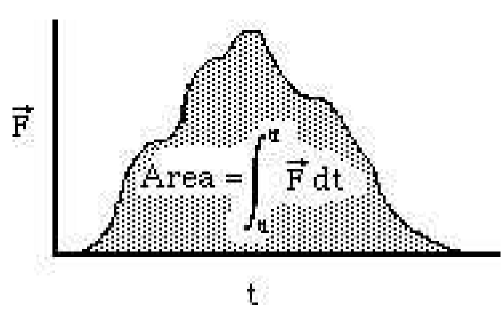


Verification of the Impulse-Momentum Theorem

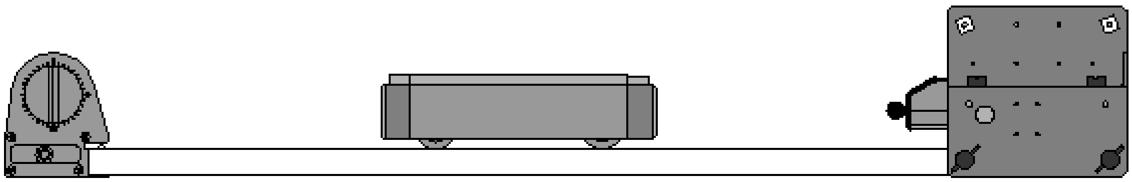
To verify the impulse-momentum theorem experimentally we must show that for an actual collision involving a single force on an object the equation

$$\int_{t_i}^{t_f} \mathbf{F}\, dt = \Delta \mathbf{p}$$

holds, where the impulse integral can be calculated by finding the area under the curve of a graph of F vs. t.



In this experiment you will investigate this theorem by measuring the impulse and the change in momentum of a cart undergoing a one-dimensional collision. The experimental setup is shown in the figure below. The end of the track with the motion detector should be raised about 1.5 cm so that, when released, the cart will collide with the force probe. The force probe will measure the force as a function of time during the collision. The motion detector is used to measure the velocity of the glider before and after the collision. You will use the Impulse-Momentum application to make these measurements.



Activity 2: Verification of the Impulse-Momentum Theorem

(a) Measure and record the mass of the cart, m, using the compact scale.

(b) Calibrate the force probe (see *Calibrating Force Sensors* in **Appendix E: Instrumentation**). **NOTE:** The force probe must be removed from its bracket and the rubber bumper replaced by a hook so that the force probe can be held VERTICALLY for the calibration. After calibrating, return the rubber bumper to the force probe, attach the force probe to its bracket, and close V, A & F Graphs Application.

(c) Construct a data table in the space below with the column headings Trial #, Area, v_i, and v_f. Make enough room to record seven trials.

(d) Position the force probe part way up the track (to be closer to the motion sensor). Open the **Impulse-Momentum** application in the **131 Workshop** submenu.

(e) Set the cart on the track about mid-way between the motion sensor and the force probe. Start recording data and release the cart. Stop recording data after the cart collides with the force probe and bounces back. The computer will then display graphs of velocity and force versus time.

(f) Determine the area under the force vs. time graph and record the value in your data table. See **Appendix B: Introduction to DataStudio** for instructions on how to determine the area under a curve.

(g) Use the smart tool to find the velocity just before the collision and the velocity just after the collision from the velocity versus time graph. Record these values in your data table.

(h) Repeat parts (e) through (g). For these trials, the area function and the smart tool must be turned on and off for each trial. Print the graphs for one of your trials and include it with this report.

(i) Construct another data table below with the column headings Trial #, I, Δp, Diff., and Percent diff. For each trial, calculate and record the impulse, I, and the change in momentum, Δp, in kg m/s. Also, determine the difference between I and Δp for each trial, and the percent difference. Also, show a sample calculation of I and Δp for one of your trials.

(j) What do you expect for the values in the last column of your table (Percent diff)? Make a histogram of your results in that column and calculate the average and standard deviation. For information on making histograms, see **Appendix C**. For information on calculating the average and standard deviation, see **Appendix A**. Record the average and standard deviation here. Attach the histogram to this unit. Is your data consistent with your expectation? Be quantitative in your answer.

(k) Do your results verify the impulse-momentum theorem? Explain quantitatively.

(l) What does the histogram of your data tell you? Be quantitative in your answer.

(m) Is there any indication of a systematic uncertainty? What are the possible sources of error?

6 Heat, Temperature, and Internal Energy

Name ____________________ Section ____________ Date ____________

Objective

- To investigate the relationship between heat and temperature.

Apparatus

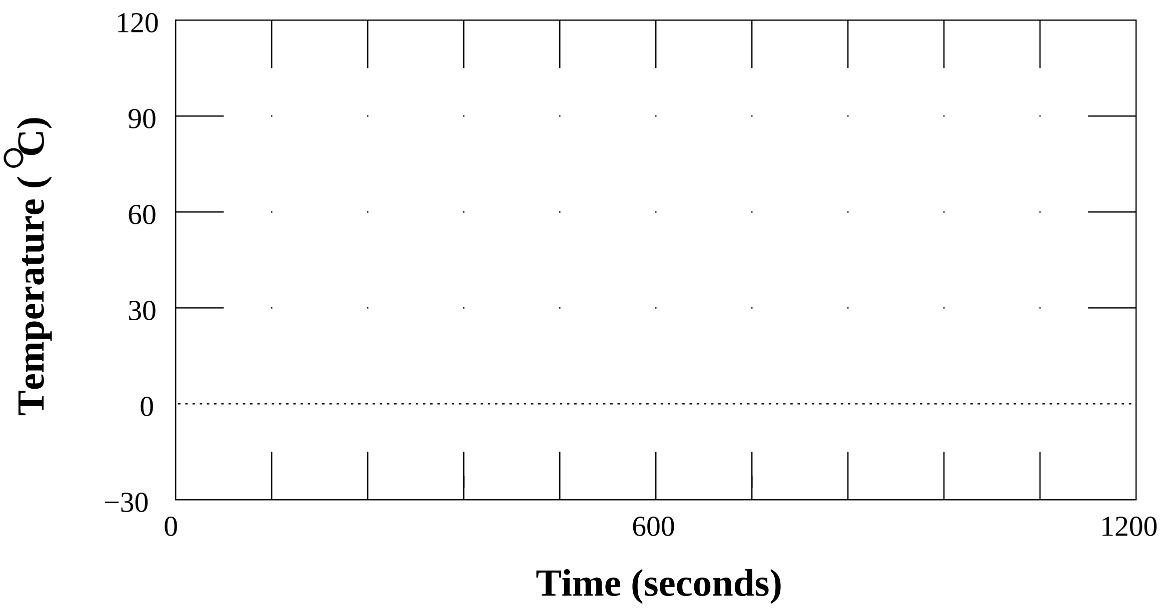
Glass beaker	Hot plate	Ice
Data Studio software	temperature probe	Clamp and stand
Safety goggles		

Temperature of a Substance as a Function of Heat Transfer

As part of our quest to understand heat energy transfer, temperature, and internal energy of a substance, let's consider the temperature change as ice is changed to water and then to steam.

Activity 1: Predicting T vs. t for Water

Suppose you were to add heat at a constant rate to a container of ice water at 0°C until the water begins to boil. Sketch the predicted shape of the heating curve on the graph below using a dashed line. Mark the points at which the ice has melted and the water begins to boil.



Activity 2: Measuring T vs. t for Water

(a) To test your prediction:

1. Fill the glass beaker at least half full of ice water and set it on top of the hot plate.
2. Suspend the temperature probe so that the end is submerged in the ice water but not touching the side or bottom of the beaker. You will need to use the clamp and stand to do this.
3. Open the *Heat, Temp, & Internal Energy* application in the 132 Workshop folder on the **Start** menu.

4. Turn on the hot plate and click the **Start** button on the monitor to begin recording data. The temperature of the water will be recorded on the graph shown on the monitor. While there is still ice, stir gently.
5. After the water begins to boil, turn off the hot plate and stop collecting data using the **Stop** button on the monitor.
6. Sketch the shape of the measured heating curve on the above graph using a solid line. Ignore small variations due to noise and uneven heating. Mark the points at which the ice has melted and the water begins to boil.

(b) Does your prediction agree with the measured heating curve? If not, what are the differences?

(c) What is the relationship between the temperature and the added heat while the ice is melting?

(d) What is the relationship between the temperature and the added heat after the ice has melted, but before the water begins to boil?

(e) What is the relationship between the temperature and the added heat while the water is boiling?

(f) If there are regions of the heating curve in which the temperature is not changing, what do you think is happening to the added heat in these regions?

7 Calorimetry

Name ______________________ Section ____________ Date ____________

Objective

- To learn to use a method for measuring heat called calorimetry.
- Measure the specific heat of aluminum and the heat of fusion of ice.

Apparatus

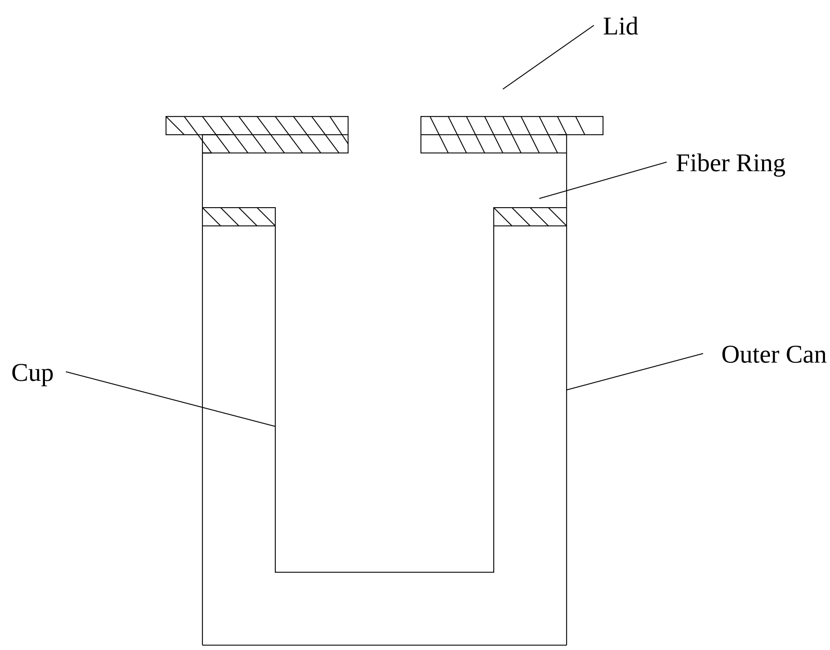
Hypsometer and stand	Hot plate	Ice
Data Studio software	Temperature probe	Clamp and stand
Safety goggles	Aluminum pellets	Compact scale
Calorimeter		

Introduction to Calorimetry

Calorimetry is a method for measuring heat. As applied in this experiment, the method involves the mixing together of substances initially at two different temperatures. The substances at the higher temperature lose heat and the substances at the lower temperature gain heat until thermal equilibrium is reached.

Activity 1: Statement of Conservation of Energy

If no heat is transferred to the surroundings, what is the relationship between the heat lost by the substances initially at high temperature and the heat gained by the substances initially at low temperature? Note: This is simply a statement of conservation of energy.



Experimental Equipment

A calorimeter, shown in the above figure, is used in this experiment to minimize the exchange of heat between the system and the surroundings. The inner calorimeter cup is thermally insulated from the surroundings by suspending it on a ring of material with low heat conductivity and surrounding it with a layer of air. Also the cup is shiny to minimize radiation loss. Hence, if the mixture of substances is placed inside the calorimeter cup, the heat lost to or gained from the surroundings can be ignored, and the above relationship can be used. The only part of the calorimeter which is involved in the calculation is the inner calorimeter cup which contains water and in which an exchange of heat between the hot and cold bodies takes place. The cup will undergo the same temperature change as the contained water. Of course, an instrument will have to be introduced to measure the temperature of the system, but the heat gained or lost by the instrument is small and can be ignored.

Activity 2: Specific Heat of Aluminum

(a) Fill the hypsometer (boiler) at least half full of water and start heating the water.

(b) Determine and record the mass of the hypsometer cup, m_h. Then fill it about half full with dry aluminum pellets. Determine and record the mass of the cup and pellets, m_{hp}, and calculate the mass of the pellets, m_p. Record the measurements in the space below.

(c) Fill the plastic beaker with ice water. Open the *Calorimetry* application in the 132 Workshop folder in the **Start** menu and start collecting data. To make sure the temperature probe is working properly place it in the ice water and check that it is reading approximately 0°C. If not, then consult your instructor.

(d) Place the hypsometer cup in the top of the hypsometer and put the temperature probe into the middle of the pellets. To do this, remove the pellets from the cup, place the temperature probe in the proper position (using the clamp and stand), then return the pellets to the cup.

(e) Determine and record the mass of the calorimeter cup, m_c. Fill this cup about half full of cold tap water. Determine and record the mass of the cup and water, m_{cw}, and calculate the mass of the water, m_w. Then place the calorimeter cup in the outer can and put the lid on.

(f) When the temperature of the pellets becomes constant, at or near 100°C, record the temperature of the pellets as T_p. Remove the probe from the pellets and put it in the cold water in the calorimeter cup. When the temperature of the water levels off, record it as T_w.

(g) Now, quickly but carefully, pour the pellets into the water in the calorimeter cup. Stir the water occasionally with the temperature probe and monitor the temperature of the mixture. When the temperature levels off, record this value as T. Click the **Stop** button on the monitor, print your graph of temperature as a function of time and include it in this unit.

(h) Write the complete heat equation and solve for the unknown specific heat of the metal. The specific heat of the calorimeter cup is 900 J/kg-°C.

(i) Collect the other measurements of the specific heat from the other groups in the class. Look up the accepted value for the specific heat of aluminum and calculate the difference between this value and the average. Do the two values agree within experimental uncertainties? Comment on possible sources of error.

Activity 3: Heat of Fusion of Ice

(a) The heat of fusion of ice is found experimentally as follows: A known mass of warm water is placed in the calorimeter cup and its temperature recorded. A known mass of ice at 0°C (with no water) is added to the water and allowed to melt. The final temperature of the mixture after the ice has melted is recorded. Perform the experiment and record the data in the space below.

(b) Write the complete heat equation and solve for the unknown heat of fusion of ice.

(c) Collect the other measurements of the heat of fusion from the other groups in the class. Look up the accepted value and calculate the difference between this value and average. Do the two values agree within experimental uncertainties? Comment on possible sources of error.

8 Kinetic Theory of Ideal Gases[6]

Name ______________________ Section ____________ Date ____________

Objective

- To derive a relationship between the macroscopic properties of an ideal gas and the microscopic motion of the unseen atoms that make up the gas.

Apparatus

- A computer with an atomic and molecular motion simulation

Introduction

Do you believe in atoms? Our forefathers believed in the reality of witches. In fact, they thought that they had good evidence that witches existed, good enough evidence to accuse some people of being witches. We believe in atoms. Are we truly more scientific than they were?

Activity 1: Why Atoms!?

(a) List reasons why you do or do not believe that matter consists of atoms and molecules, even though you have never seen them with your own eyes.

(b) What happens when heat energy is being transferred into a substance? If you believe that substances are made of atoms and molecules, how would you use their existence to explain the change in volume of a heated gas?

Models of Pressure Exerted by Molecules

So far in physics we have talked about matter as if it were continuous. We didn't need to invent aluminum atoms to understand how a ball rolled down the track. But ever since the time of the fifth century B.C. Greek philosophers Leucippus and Democritus, some thinkers have believed in "atomism", a picture of the universe in which everything is made up of tiny "eternal" and "incorruptible" particles, separated by "the void". Today, we think of these particles as atoms and molecules.

In terms of every day experience molecules and atoms are hypothetical entities. In just the past 40 years or so, scientists have been able to "see" molecules using electron microscopes and field ion microscopes. But long before atoms and molecules could be "seen" experimentally, nineteenth century scientists such as James Clerk Maxwell and Ludwig Boltzmann in Europe and Josiah Willard Gibbs in the United States used these imaginary microscopic entities to construct models that made the description and prediction of the macroscopic behavior of thermodynamic systems possible. Is it possible to describe the behavior of an ideal gas that obeys the first law of thermodynamics as a collection of moving molecules? To answer this question, let's observe the pressure exerted by a hypothetical molecule undergoing elastic collisions with the walls of a 3D box. By using the laws of mechanics we can derive a mathematical expression for the pressure exerted by the molecule as a function

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of the volume of the box. If we then define temperature as being related to the average kinetic energy of the molecules in an ideal gas, we can show that kinetic theory is compatible with the ideal gas law and the first law of thermodynamics. This compatibility doesn't prove that molecules exist, but allows us to say that the molecular model would enable us to explain the experimentally determined ideal gas law.

Atomic Motion and Pressure

Consider a spherical gas molecule that has velocity $\overrightarrow{v} = v_x\hat{i}+v_y\hat{j}+v_z\hat{k}$ and makes perfectly elastic collisions with the walls of a three-dimensional, cubical box of length, width, and height l. Start the program called "*Atoms in Motion*" (in "*Physics Applications*"). You will see a screen like the one shown below. Experiment with it for a few moments. The *Run* and *Stop* buttons control the processing of the simulation of the gas atoms while the *Step* button allows you to watch the 'movie' one frame at a time.

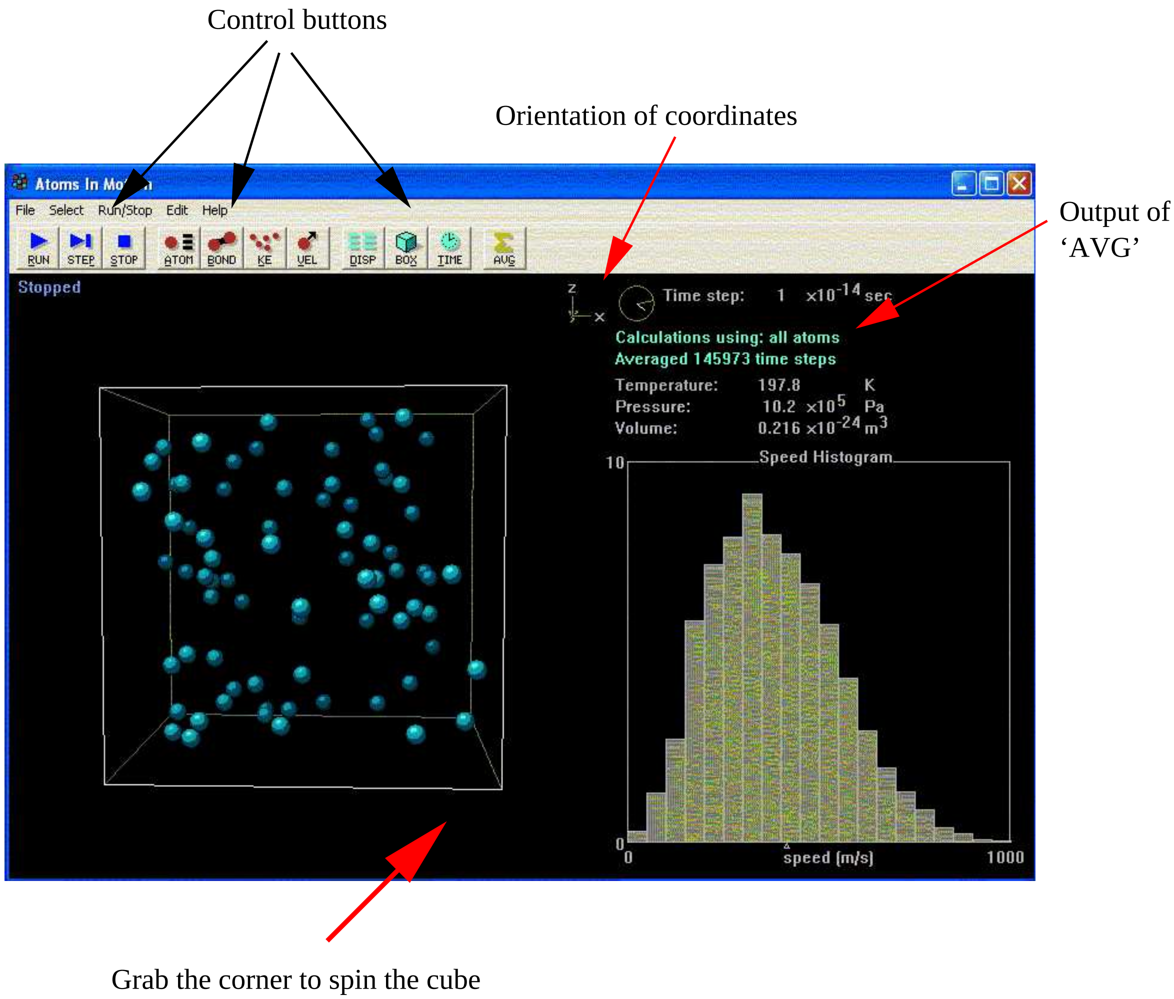

Figure 1: *Atoms in Motion* window.

Can we use the concept of molecules behaving like little billiard balls to explain why the ideal gas law relationship might hold? In the next activity you are to pretend you are looking under a giant microscope at a single spherical molecule as it bounces around in a three-dimensional box by means of elastic collisions and that you can time its motion and measure the distances it moves as a function of time.

If the molecule obeys Newton's Laws, you can calculate how the average pressure that the molecule exerts on the walls of its container is related to the volume of the box. The questions we have to consider are the following. What is the momentum change as the molecule bounces off a wall? How does this relate to the change in the velocity component perpendicular to the wall? How often will our molecule "hit the wall" as a function of its component of velocity perpendicular to the wall and the distance between opposite walls? What happens when the molecule is more energetic and moves even faster? Will the results of your calculations based on mechanics be compatible with the ideal gas law?

Activity 2: The Theory of Atomic Motion

(a) Stop the simulation if it's running and set the number of molecules to one. Do this by clicking on the *ATOM* button and getting a dialog box. Enter '1' for the number of Type A atoms and zero for all the others. Record the mass of the Type A atom. Click *OK* and the cube should now contain a single atom. If not, consult your instructor.

(b) The orientation of coordinates can be seen just above the right-hand corner of the cube (consult Figure 1 also). Suppose the molecule moves a distance $2l$ (across the cube and back) in the x-direction in a time Δt_x. What is the equation needed to calculate its x-component of velocity in terms of l and Δt_x?

(c) Suppose the molecule moves a distance $2l$ in the y-direction in a time Δt_y. What is the equation needed to calculate its y-component of velocity in terms of l and Δt_y?

(d) Suppose the molecule moves a distance $2l$ in the z-direction in a time Δt_z. What is the equation needed to calculate its z-component of velocity in terms of l and Δt_z?

(e) We will now measure the average time Δt_y for one complete round trip from the left side of the cube to the right side and back again. Click *AVG* and you will see some information printed in the color blue on the right-hand side of the *Atoms-in-Motion* window (see also Figure 1). The simulation takes small steps in time and calculates the positions of the atoms at the end of each time step. The number of these time steps taken is shown on the right-hand side and the size of each time step is printed at the top, right-hand-side of the window. Using the *Step* button let the atom in the cube move until it bounces off the left wall of the cube. Stop the motion and record the number of the time step in the space below.

(f) Now run or step the simulation until the atom bounces across the cube, hits the right-hand wall, comes back and strikes the left hand wall again. Stop the motion and record the number of the time step. Calculate Δt_y and record it below.

(g) Each side of the cube has a length $l = 50 \times 10^{-10}$ m. Combine this with the previous result to determine v_y and record it.

(h) Repeat the above procedure for the top and bottom walls of the cube to get v_z.

(i) Rotate the cube by clicking and dragging one of the corners of the cube. Spin it until you can see the atom bounces between the walls in the direction of the x coordinate. Measure the x component of the speed of the atom using the same procedure as before.

(j) Write the expression for v_{total} in terms of the x, y, and z components of velocity. (Hint: This is an application of the 3-dimensional Pythagorean theorem.) Determine v_{total} for your atom. We will use these results in a little while to calculate the pressure exerted by our one-atom 'gas'.

(k) Record the value of the pressure and temperature for your 'gas' (as printed on the screen).

(l) We would like to eventually find the average kinetic energy of each atom or molecule in a gas so we now have to think about a gas with many atoms. Since the kinetic energy of a molecule is proportional to the square of its total speed, you need to show that if *on the average* $\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2}$, then $\overline{v_{total}^2} = 3\overline{v_x^2}$.

(m) If the collisions with the wall perpendicular to the x direction are elastic, show that the force exerted on that wall for each collision is just $F_x = 2m\frac{v_x}{\Delta t_x}$ where m is the mass of the particles and Δt_x the mean interval between collisions with the wall. (Hint: Think of the form of Newton's second law in which force is defined in terms of the change in momentum per unit time so that $F = \frac{\Delta p}{\Delta t}$.)

Warning: Physicists too often use the same symbol to stand for more than one quantity. In this case, note that Δp (where "p" is in lower case) indicates the change in *momentum*, not pressure.

(n) Substitute the expression from part (b) for Δt_x to show that

$$F_x = \frac{mv_x^2}{l}$$

(o) We have assumed from the beginning that we have a cubical box of edge length l. Show that the pressure on the wall perpendicular to the x axis caused by the force F_x due to *one* molecule is described by the following expression.

$$P = \frac{mv_x^2}{l^3}$$

(p) Let's say that there are not one but N molecules in the box. What is the pressure on the wall now?

(q) Next, show that if we write the volume of our box as $V = l^3$, and recalling (part (l) above) that

$$\overline{v_x^2} = \frac{\overline{v_{total}^2}}{3}$$

we can write the following expression.

$$P = N\frac{m\overline{v_{total}^2}}{3V}$$

(r) Finally, since the average kinetic energy of a molecule is just

$$< E_{kin} >= \frac{1}{2} m \overline{v_{total}^2}$$

show that the pressure in the box can be written in the following way.

$$P = \frac{2N < E_{kin} >}{3V}$$

(s) Use the previous result to calculate the pressure using v_{total}, the mass of the atom, N and V for your one-atom gas. Compare your result with the pressure you recorded above from the output of the simulation (part (k) above). Do they agree? Explain any differences.

9 Applying the Kinetic Theory[7]

Name ______________________ Section ____________ Date ____________

Objective

- To derive the relationship between temperature and the kinematic properties of the monatomic molecules of an ideal gas. We will also calculate the specific heat per mole of an ideal, monatomic gas at constant volume using the kinetic theory and compare the prediction with data.

Apparatus

- A computer with an atomic and molecular motion simulation

Kinetic Energy, Internal Energy, and Temperature

We have hypothesized the existence of non-interacting molecules to provide the basis for a particle model of ideal gas behavior. We have shown that the pressure of such a gas can be related to the average kinetic energy of each molecule:

$$P = \frac{2N\langle E_{kin}\rangle}{3V} \text{ or } PV = \frac{2}{3}N\langle E_{kin}\rangle$$

Pressure increases with kinetic energy per molecule and decreases with volume. This result makes intuitive sense. The more energetic the motions of the molecules, the more pressure we would expect them to exert on the walls. Increasing the volume of the box decreases the frequency of collisions with the walls, since the molecules will have to travel longer before reaching them, so increasing volume should decrease pressure if $\langle E_{kin}\rangle$ stays the same.

The Molar Specific Heat

The kinetic theory of gases uses the atomic theory to relate the macroscopic properties of gases to the microscopic features of the atoms and molecules that make up the gas. In this laboratory we will extend the calculations that we have made so far to include the molar specific heat of an ideal, monatomic gas. The success of that extension of the theory depends on how well the calculations reproduce the measured heat capacities of a variety of real (not ideal) gases.

Activity 1: Experimenting with the Gas Simulation Program

Open the *Atoms in Motion* program (in *Physics Applications*) on the *Start* menu. We are first going to explore the relationship between pressure and volume in our kinetic theory using the simulation.

(a) According to the ideal gas law $PV = nRT = Nk_BT$, where R is the universal gas constant and k_B is Boltzmann's constant. What should happen to the pressure of an ideal gas as its volume increases or decreases?

(b) We now want to run a more realistic simulation. Under the *ATOM* menu set the number of Type A atoms to 50 and set all the others to zero. Click on the *BOX* button and a new dialog box will appear. Check the box beside 'Floor conducts heat' and set the temperature to 200 K. Notice at the top that the box width is $l = 50 \times 10^{-10}\ m$. We have now set up a situation where one side of the cube is held at a constant temperature

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(*e.g.* it's sitting on a stove) so the collisions of the atoms with the floor are no longer elastic. The remaining sides of the cube do not transfer any energy (they're insulated) so elastic collisions still occur at those walls.

Start the simulation and make sure you are averaging the pressure over many time steps. You should see the number of averaged time steps increasing on the right-hand side of the *Atoms-in-Motion* window. If you don't see this information, click on *AVG* and it should appear.

(c) What happens to the pressure? What happens to the temperature of the gas? You will find that it can take several minutes of computer time for the temperature of the gas to reach equilibrium with the floor. Once the gas temperature is within $8 - 10\ K$ of the floor temperature, we can consider the gas and the floor to be in thermal equilibrium. Record the volume, pressure and temperature of the gas in the first line of the table below.

(d) Record the volume, pressure and temperature of the gas for five more volumes of the cube. Change the volume of the cube using the *BOX* menu and adjusting the box width. The volume is printed on the *Atoms-in-Motion* window. Plot your results and attach the graph to this unit. Are your results consistent with the ideal gas law and your prediction in part (a)? Are they consistent with the results of Experiment 4?

Volume of Box	Average Pressure	Temperature

(e) In the procedure above you should have found the pressure to be inversely proportional to the volume. How could you modify your plot to show the pressure is proportional to $1/V$? Make such a plot and fit it. How close is your data to following a straight line? Attach the plot to this unit.

(f) According to the ideal gas law $PV = nRT = Nk_BT$. What should happen to the pressure of an ideal gas as the number of particles increases or decreases? We will explore this idea with the simulation next.

(g) Start off with the gas parameters from the last 'run' of the simulation. Record the number of atoms, temperature, and pressure in the table below. Use the *ATOM* menu to change the number of atoms (or molecules) in the cube. Start the simulation. What happens to the pressure? Record the pressure and the number of molecules for four more values of the number of molecules and plot your results. Attach the plot to this unit. Are your results consistent with the ideal gas law and your prediction in part (f)?

Number of Molecules	Average Pressure	Temperature

Kinetic Theory and the Definition of Temperature

The model of an ideal gas we have just derived requires that

$$PV = \frac{2}{3} N \langle E_{kin} \rangle$$

But we have determined experimentally the ideal gas law:

$$PV = N k_B T$$

What can we say about the average kinetic energy per molecule for an ideal gas? You can derive a relationship between temperature and the energy of molecules that serves as a microscopic (i.e. molecular) definition of temperature.

Activity 2: Microscopic Definition of Temperature

(a) From the two equations above, derive an expression relating $\langle E_{kin} \rangle$ and T. Show the steps in your derivation.

(b) In general, molecules can store energy by rotating or vibrating, but for an ideal gas of *point* particles (monatomic gas), the only possible form of kinetic energy is the translational motion of the particles. If we can ignore potential energy due to gravity or electrical forces, then the internal energy E_{int} of a gas of N particles is $E_{int} = N \langle E_{kin} \rangle$. Use this to show that for an ideal gas of point particles, E_{int} *depends only on N and T*. Derive the equation that relates E_{int}, N and T. Show the steps.

The microscopic and the macroscopic definitions of temperature are equivalent. The microscopic definition of temperature which you just derived is fundamental to the understanding of all thermodynamics!

Activity 3: Calculating the Molar Specific Heat

In this section we will generate a series of equations that we will then bring together in order to predict the molar specific heat at constant volume.

(a) Consider an ideal gas in a rigid container that has a fixed volume. How is the molar specific heat defined in terms of the heat added Q?

(b) If the gas is heated by an amount Q, then how much work is done against the fixed container? Recall the first law of thermodynamics and incorporate this result into your statement of the first law.

(c) Now use the equations of parts (a) and (b) to relate the change in internal energy ΔE_{int} to the molar specific heat.

(d) Write down an expression for the change in internal energy of the ideal gas in terms of $\langle E_{kin}\rangle$. (Suggestion: see part (b) of Activity 2.) How is $\langle E_{kin}\rangle$ related to the temperature? Incorporate this relationship into your expression for the change in the internal energy. You should find that

$$\Delta E_{int} = \tfrac{3}{2} N k_B \Delta T$$

where k_B is Boltzmann's constant and N is the number of molecules in the gas.

(e) Use the equations is parts (c) and (d) to relate the molar specific heat to the number of particles N and Boltzmann's constant k_B. You should find that

$$nC_V = \tfrac{3}{2} N k_B$$

where n is the number of moles.

(f) How is the number of molecules in the gas N related to the number of moles n and Avogadro's number N_A? Use this expression and the result of part (e) to show

$$C_V = \tfrac{3}{2} N_A k_B \text{ or } \tfrac{C_V}{N_A k_B} = \tfrac{3}{2}$$

Since $N_A k_B = R$, this can be written as

$$C_V = \tfrac{3}{2} R \text{ or } \tfrac{C_V}{R} = \tfrac{3}{2}$$

Activity 4: Comparing Calculations and Data

We now want to compare our calculation of the molar specific heat of an ideal, monatomic gas with the measured molar specific heats of some real gases. The table below lists some of those measurements.

Molecule	$\frac{C_V}{R}$	Molecule	$\frac{C_V}{R}$
He	1.50	CO	2.52
Ar	1.50	Cl_2	3.08
Ne	1.51	H_2O	3.25
Kr	1.49	SO_2	3.77
H_2	2.48	CO_2	3.42
N_2	2.51	CH_4	3.25
O_2	2.53		

(a) Has our theoretical calculation been successful at all? Which gases appear to be consistent with our calculation? Which gases are not? How do these two groups of real gases differ?

(b) Can you suggest an explanation for the partial success of the theory? Which one of the original assumptions that went into our kinetic theory might be wrong?

10 Stefan's Law

Name ______________________ Section ____________ Date ____________

Objective

- To discover the relationship between temperature and the radiation from a light source.

Introduction

Heat transfer via radiation is an essential process in the flow of energy in the atmosphere so it has a large impact on climate change. Stefan's Law relates the power of a radiation source $\mathscr{P}$ (the energy radiated by an object per time) to T, the absolute temperature of the object. In this experiment, you will make measurements of the power emitted from a hot object, namely a Stefan-Boltzmann Lamp, as a function of temperature and reveal that function.

Apparatus

Radiation Sensor	Stefan-Boltzmann Lamp	Ammeter (0-3 A)
Ohmmeter (2)	Voltmeter (0-12 V)	Millivoltmeter
Thermometer	Foam insulation	

Predictions

(a) The intensity of a light source is the power radiated per area. For your experiment what do you think will happen to the intensity (and the emitted power) of the lamp as the filament you turn up the voltage and it heats up? Explain your guess.

(b) How do you expect the intensity (and the power) to be related to the temperature T? Will it be linear, exponential (e^{aT}), a power law (T^n), or something else?

Activity 1: Measuring Radiation versus Temperature

To make these measurements we need a device to measure the power emitted from the lamp and some way to determine the temperature of the lamp. The radiation sensor in the figure converts the light falling on it into an electrical signal proportional to the power striking the sensor. At the same time the current flowing through the lamp quickly heats the lamp to an equilibrium temperature. The electrical resistance R of the lamp changes with temperature in a known way so if we determine R we can correlate it with the temperature T.

(a) BEFORE TURNING ON THE LAMP, measure T_{ref} , the room temperature in degrees Kelvin, ($K =^{\circ}$ C $+ 273$) and R_{ref}, the electrical resistance of the filament of the Stefan-Boltzmann Lamp at room temperature with the ohmmeter. See *Charge Measurements* in **Appendix E: Instrumentation**. Enter your results below.

(b) Set up the equipment as shown in Figure 1. The millivoltmeter should be connected directly to the binding posts of the Stefan-Boltzmann Lamp. The radiation sensor should be at the same height as the filament, with

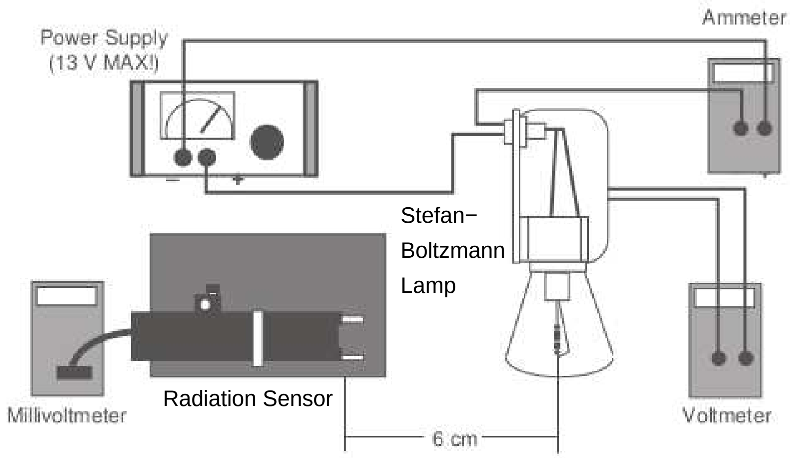


Figure 1: Equipment setup for Stefan's Law.

the front face of the radiation sensor approximately 6 cm away from the filament. The entrance angle of the radiation sensor should include no close objects other than the lamp. Ask you instructor to check the setup before you plug in the power supply and energize the experiment.

(c) Use Table 1 to collect your results. Fill the top row with headings V (volts), I (Amps), $\mathscr{P}$ (mV), R (ohms), R/R_{rel}, and T (K). Leave room for at least twelve rows. You can also create this table in *Excel*, but make sure you save the file and print a copy to put in your notebook.

Table 1: Data table.

(d) Before turning on the power supply turn the voltage dial all the way down (counterclockwise). Now turn on the power supply. The voltage reading should be zero.

(e) To get the electrical resistance R of the lamp we will measure the voltage V and the current I through the lamp and use Ohm's Law $V = IR$ to extract R. The power $\mathscr{P}$ will be measured as a voltage from the millivoltmeter attached to the radiation sensor. Set the voltage on the power supply, V, to the values in the range $1 - 12$ V in steps of one volt. At each voltage setting, record the current I from the ammeter, and $\mathscr{P}$, the reading on the millivoltmeter.

IMPORTANT: Make each radiation sensor reading quickly. Between readings, place sheets of insulating foam between the lamp and the radiation sensor, with the silvered surface facing the lamp, so that the temperature of the radiation sensor stays relatively constant.

Activity 2: Extracting Stefan's Law

(a) Calculate R, the resistance of the filament at each of the voltage settings with Ohm's Law $R = V/I$. Enter your results in your table.

(b) To determine T, the temperature of the lamp filament at each voltage setting we first need to calculate the relative resistance R/R_{rel}. Do this calculation for each entry in your table and enter the results in your table. Use this ratio and the calibration curve in Figure 2 to find T. Enter your results in the table.

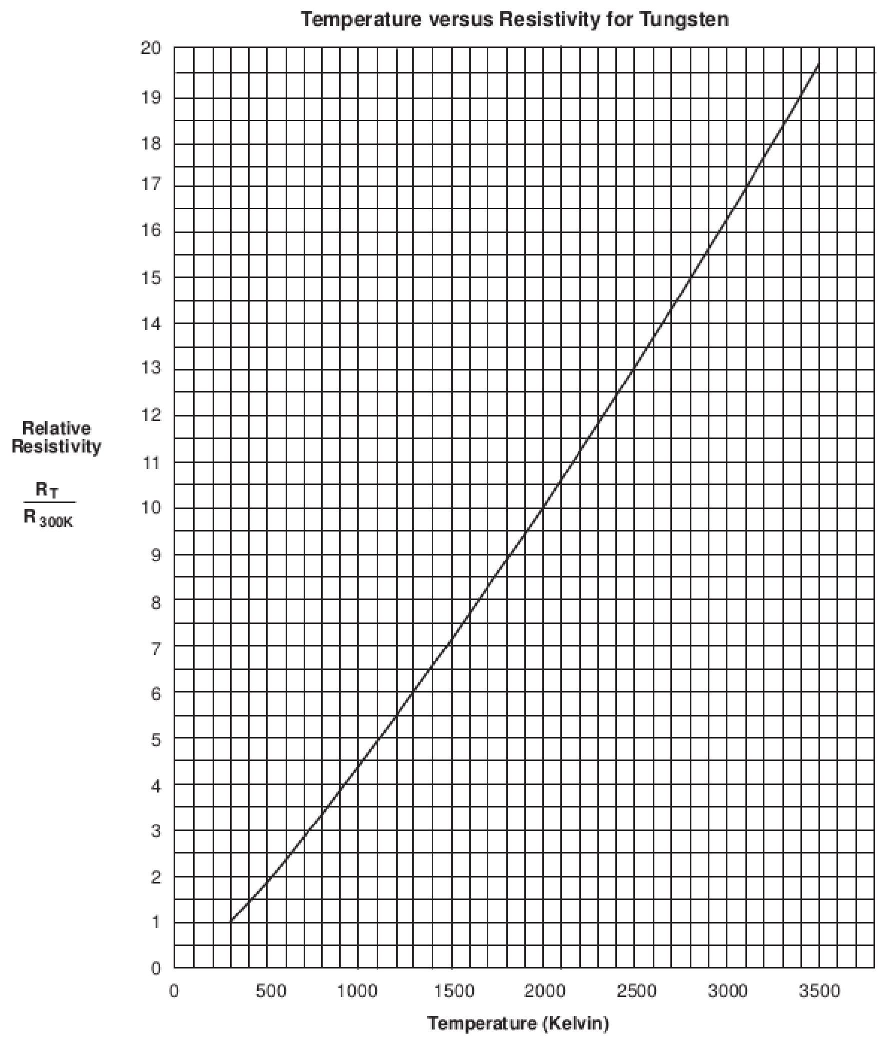


Figure 2: Calibration curve to get the filament temperature.

(c) Plot $\mathscr{P}$ versus T and fit it. Print your plot and insert it into your notebook. Record the fit here. Is the plot linear? Does it follow a power law, *i.e.* $\mathscr{P} \propto T^n$? Does it follow an exponential, *i.e.* $\mathscr{P} \propto e^{aT}$? Record your answer here.

(d) To precisely determine the mathematical form of the your data, make a semi-log plot, *i.e.* plot the common log of $\mathscr{P}$ versus T. If the data follow an exponential curve, then they will form a straight line on a semi-log plot. Show this. Print your plot and insert it into your notebook. Is this plot linear? Do your data lie on an exponential?

(e) Plot the common log of $\mathscr{P}$ versus the common log of T and fit it. This plot can be used to determine if your data follow a power law. Show this too. Print your plot and insert it into your notebook. Record the fit here.

(f) How is the slope of the plot you made in part (e) related to the temperature dependence?

(g) How do your results compare with your prediction?

(e) Stefan's Law is usually expressed as $\mathscr{P} = \sigma A e T^4$ where σ is the Stefan-Boltzmann constant, A is the surface area of the object, and e is a property of the object called the emissivity. From your analysis what did you obtain for the exponent on the temperature T? How does it compare with the expected value?

(h) Collect the results from the class, find the average and standard deviation, and record them here. Do the values agree within experimental uncertainties? Comment on possible sources of error.

(i) Clearly state an equation for Stefan's Law.

A Treatment of Experimental Data

Recording Data

When performing an experiment, record all required original observations as soon as they are made. By "original observations" is meant what you actually see, not quantities found by calculation. For example, suppose you want to know the stretch of a coiled spring as caused by an added weight. You must read a scale both before and after the weight is added and then subtract one reading from the other to get the desired result. The proper scientific procedure is to record both readings as seen. Errors in calculations can be checked only if the original readings are on record.

All data should be recorded with units. If several measurements are made of the same physical quantity, the data should be recorded in a table with the units reported in the column heading.

Significant Figures

A laboratory worker must learn to determine how many figures in any measurement or calculation are reliable, or "significant" (that is, have physical meaning), and should avoid making long calculations using figures which he/she could not possibly claim to know. *All sure figures plus one estimated figure are considered significant.*

The measured diameter of a circle, for example, might be recorded to four significant figures, the fourth figure being in doubt, since it is an estimated fraction of the smallest division on the measuring apparatus. How this doubtful fourth figure affects the accuracy of the computed area can be seen from the following example.

Assume for example that the diameter of the circle has been measured as $.526\underline{4}$ cm, with the last digit being in doubt as indicated by the line under it. When this number is squared the result will contain eight digits, of which the last five are doubtful. Only one of the five doubtful digits should be retained, yielding a four-digit number as the final result.

In the sample calculation shown below, each doubtful figure has a short line under it. Of course, each figure obtained from the use of a doubtful figure will itself be doubtful. The result of this calculation should be recorded as 0.2771 cm^2, including the doubtful fourth figure. (The zero to the left of the decimal point is often used to emphasize that no significant figures precede the decimal point. This zero is not itself a significant figure.)

$$(.526\underline{4}\text{ cm})^2 = .277\underline{09696}\text{ cm}^2 = 0.277\underline{1}\text{ cm}^2$$

In multiplication and division, the rule is that a calculated result should contain the same number of significant figures as the least that were used in the calculation.

In addition and subtraction, do not carry a result beyond the first column that contains a doubtful figure.

Statistical Analysis

Any measurement is an intelligent estimation of the true value of the quantity being measured. To arrive at a "best value" we usually make several measurements of the same quantity and then analyze these measurements statistically. The results of such an analysis can be represented in several ways. Those in which we are most interested in this course are the following:

<u>Mean</u> - The mean is the sum of a number of measurements of a quantity divided by the number of such measurements. (In other words, the mean is the same thing as what people generally call the "average.") It generally represents the best estimate of true value of the measured quantity.

<u>Standard Deviation</u> - The standard deviation (σ) is a measure of the range on either side of the mean within which approximately two-thirds of the measured values fall. For example, if the mean is 9.75 m/s^2 and the standard deviation is 0.10 m/s^2, then approximately two-thirds of the measured values lie within the range 9.65 m/s^2 to 9.85 m/s^2. A customary way of expressing an experimentally determined value is: Mean$\pm\sigma$, or (9.75$\pm$ 0.10) m/s^2. Thus, the standard deviation is an indicator of the spread in the individual measurements, and a small σ implies high precision. Also, it means that the probability of any future measurement falling in this range is approximately two to one. The equation for calculating the standard deviation is

$$\sigma = \sqrt{\frac{\sum (x_i - \langle x \rangle)^2}{N-1}}$$

where x_i are the individual measurements, $\langle x \rangle$ is the mean, and N is the total number of measurements.

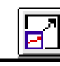
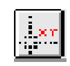
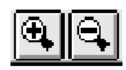
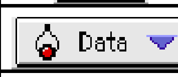
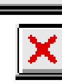
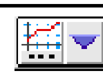
<u>% Difference</u> - Often one wishes to compare the value of a quantity determined in the laboratory with the best known or "accepted value" of the quantity obtained through repeated determinations by a number of investigators. *The % difference is calculated by subtracting the accepted value from your value, dividing by the accepted value, and multiplying by 100.* If your value is greater than the accepted value, the % difference will be positive. If your value is less than the accepted value, the % difference will be negative. The % difference between two values in a case where neither is an accepted value can be calculated by choosing either one as the accepted value.

B Introduction to DataStudio

Quick Reference Guide

Shown below is the quick reference guide for DataStudio.

What You Want To Do	How You Do It	Button
Start recording data	Click the 'Start' button or select 'Start Data' on the Experiment menu (or on the keyboard press CTRL - R (Windows) or Command - R (Mac))	
Stop recording (or monitoring) data	Click the 'Stop' button or select 'Stop Data' on the Experiment menu (or on the keyboard press CTRL - . (period) (Win) or Command - . (Mac))	
Start monitoring data	Select 'Monitor Data'on the Experiment menu (or on the keyboard press CTRL - M (Win) or Command - M (Mac))	**none**

On the Graph Display	In the Graph Toolbar	Button
Re-scale the data so it fills the Graph display window	Click the 'Scale to Fit' button.	
Pinpoint the x- and y-coordinate values on the Graph display	Click the 'Smart Tool' button. The coordinates appear next to the 'Smart Tool'.	
'Zoom In' or 'Zoom Out'	Click the 'Zoom In' or 'Zoom Out' buttons.	
Magnify a selected portion of the plotted data	Click the 'Zoom Select' button and drag across the data section be to magnified.	
Create a Calculation	Click the 'Calculate' button	
Add a text note to the Graph	Click the 'Note' button.	
Select from the Statistics menu	Click the Statistics menu button	
Add or remove a data run	Click the 'Add/Remove Data' menu button	
Delete something	Click the 'Delete' button	
Select Graph settings	Click the 'Settings' menu button	

Selecting a Section of Data

1. To select a data section, hold the mouse button down and move the cursor to draw a rectangle around the data of interest. The data in the region of interest will be highlighted.

2. To unselect the data, click anywhere in the graph window.

Fitting a Section of Data

1. Select the section of data to be fitted.

2. Click on the **Fit** button on the Graph Toolbar and select a mathematical model. The results of the fit will be displayed on the graph.

3. To remove the fit, click the **Fit** button and select the checked function type.

Finding the Area Under a Curve

1. Use the **Zoom Select** button on the Graph Toolbar to zoom in around the region of interest in the graph. See the quick reference guide above for instructions.

2. Select the section of data that you want to integrate under.

3. Click the **Statistics** button on the Graph Toolbar and select **Area**. The results of the integration will be displayed on the graph.

4. To undo the integration, click on the **Statistics** button and select **Area**.

C Introduction to Excel

Microsoft Excel is the spreadsheet program we will use for much of our data analysis and graphing. It is a powerful and easy-to-use application for graphing, fitting, and manipulating data. In this appendix, we will briefly describe how to use Excel to do some useful tasks.

C.1 Data and formulae

Figure 3 below shows a sample Excel spreadsheet containing data from a made-up experiment. The experimenter was trying to measure the density of a certain material by taking a set of cubes made of the material and measuring their masses and the lengths of the sides of the cubes. The first two columns contain her measured results. **Note that the top of each column contains both a description of the quantity contained in that column and its units.** You should make sure that all of the columns of your data tables do as well. You should also make sure that the whole spreadsheet has a descriptive title and your names at the top.

In the third column, the experimenter has figured out the volume of each of the cubes, by taking the cube of the length of a side. To avoid repetitious calculations, she had Excel do this automatically. She entered the formula `=B5∧3` into cell C5. Note the equals sign, which indicates to Excel that a formula is coming. The ∧ sign stands for raising to a power. After entering a formula into a cell, you can grab the square in the lower right corner of the cell with the mouse and drag it down the column, or you can just double-click on that square. (Either way, note that thing you're clicking on is the tiny square in the corner; clicking somewhere else in the cell won't work.) This will copy the cell, making the appropriate changes, into the rest of the column. For instance, in this case, cell C6 contains the formula `=B6∧3`, and so forth.

Column D was similarly produced with a formula that divides the mass in column A by the volume in column C.

At the bottom of the spreadsheet we find the mean and standard deviation of the calculated densities (that is, of the numbers in cells D5 through D8). Those are computed using the formulae `=average(D5:D8)` and `=stdev(D5:D8)`.

C.2 Graphs

Here's how to make graphs in Excel. For those who've used earlier version of Excel but not Excel 2007, note that the locations of some of the menu items have changed, although the basic procedure is similar.

First, use the mouse to select the columns of numbers you want to graph. (If the two columns aren't next to each other, select the first one, then hold down the control key while selecting the second one.) Then click on

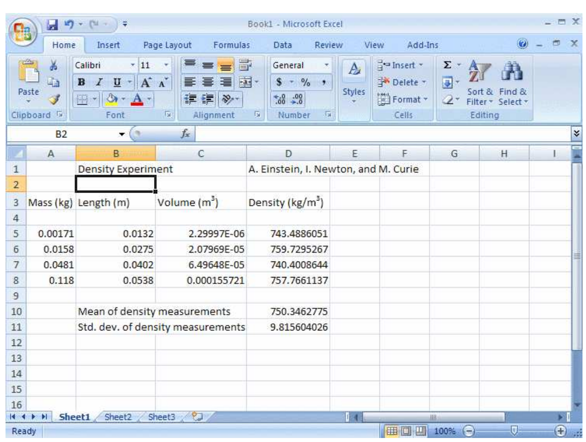


Figure 3: Sample Excel spreadsheet

the `Insert` tab at the top of the window. In the menu that shows up, there is a section called `Charts`. Almost all of the graphs we make will be scatter plots (meaning plots with one point for each row of data), so click on the `Scatter` icon. You'll see several choices for the basic layout of the graph. You usually want the first one, with an icon that looks like this . Click on this icon, and your graph should appear.

Next, you'll need to customize the graph in various ways, such as labeling the axes correctly. Everything you need to do this is in the `Chart Tools` menu, which should be visible in the upper right portion of the window. (If you don't see the words `Chart Tools`, try clicking on your newly-created graph, and it should appear.) The most useful items are under the `Layout` tab, so click on the word `Layout` under the `Chart Tools` menu. Here are some things to do under this menu:

- The most important item here is the `Axis Titles` menu. You can use this to add labels to the x and y axes of your graph, if it doesn't already have them. Edit the text inside of the two axis titles so that it indicates what's on the two axes of your graph *and the appropriate units.*
- It's probably a good idea to give your graph an overall title as well. The options for doing this are under `Chart Title` (not surprisingly).
- If the graph contains only one set of data points, you may wish to remove the legend that appears at the right side of the graph. After all, the information in the legend is probably already contained in the title and axis labels, so the legend just takes up space. Go to the `Legend` menu and click `None` to do this.
- Sometimes, you want your graph to contain a best-fit line passing through your data points. To do this, go to the `Trendline` menu. The easiest thing to do is to click on `More trendline options` at the bottom, which will bring up a dialog box with a bunch of choices. Excel can fit various kinds of curves through data points, but we almost always want a straight line, so you'll probably choose the `Linear` option. If you want to see the equation that describes this line, check the `Display Equation on chart` option near the bottom. Remember that Excel won't include the correct units on the numbers in this equation, but you should. Also, Excel will always call the two variables x and y, even though they might be something else entirely. Bear these points in mind when transcribing the equation into your lab notebook.

Sometimes, you may want to make a graph in Excel where the x column is to the right of the y column in your worksheet. In these cases, Excel will make the graph with the x and y axes reversed. There are at least two ways to fix this problem. Here's the simpler way: before you make your graph, make a copy of the y column in the worksheet and paste it so that it's to the right of the x column. Then follow the above procedure and everything will be fine. If you don't want to do that, here's another way. Click `Select data` (near the left-hand side under the Chart Tools menu). In the box that pops up, highlight `Series1` and click `Edit`. You should see a box that contains entries for `Series X values` and `Series Y values`. You want to swap the entries in those two windows. (But really, it's much easier to do it the first way.)

C.3 Making Histograms

A histogram is a useful graphing tool when you want to analyze groups of data, based on the frequency at given intervals. In other words, you graph groups of numbers according to how often they appear. You start by choosing a set of 'bins', *i.e.*, creating a table of numbers that mark the edges of the intervals. You then go through your data, sorting the numbers into each bin or interval, and tabulating the number of data points that fall into each bin (this is the frequency). At the end, you have a visualization of the distribution of your data.

Start by entering your raw data in a column like the one shown in the left-hand panel of Figure 4. Look over your numbers to see what is the range of the data. If you have lots of values to sift through you might consider sorting your data is ascending or descending order. To do this task, choose the column containing your data by clicking on the letter at the top of the column, go to `Data` in the menubar, select `Sort`, and pick ascending or descending. The data will be rearranged in the order you've chosen and it will be easier to see the range of the data. For an example, see the middle column of data in the left-hand panel of Figure 4. Now to create your bins pick a new column on your spreadsheet and enter the values of the bin edges. Make sure the bins you choose cover the range of the data. See the left-hand panel of Figure 4 again for an example.

You now have the ingredients for making the histogram. Go to `Data` in the menubar, select `Data Analysis`, and choose `Histogram`. You should see a dialog box like the one in the right-hand panel of Figure 4. Click in the box labeled `Input Range` and then highlight the column on the spreadsheet containing your data. Next, click in the box labeled `Bin Range` and highlight the column on the spreadsheet containing the bins. Under `Output Options`, select `New Worksheet Ply` and give the worksheet a name. Click `OK` in the `Histogram` dialog box. You should now see a new worksheet with columns labeled `Bin` and `Frequency` and a new tab at the bottom with the name you put in the `New Worksheet Ply` entry. See the left-hand panel in Figure 5. Your original data are still available on another worksheet (probably labeled `Sheet1`). Now highlight the `Bins` and `Frequency` columns by clicking and dragging across the column headings (the `A` and `B` at the top of the columns in the left-hand panel of Fig. 5). You can then make a graph by following the procedure in Appendix C.2 above. The only difference is that this time you will choose to make a `Column` graph instead of a `Scatter` graph. Make sure you properly label the axes including the units for each quantity. Results should look like the right-hand panel of Figure 5.

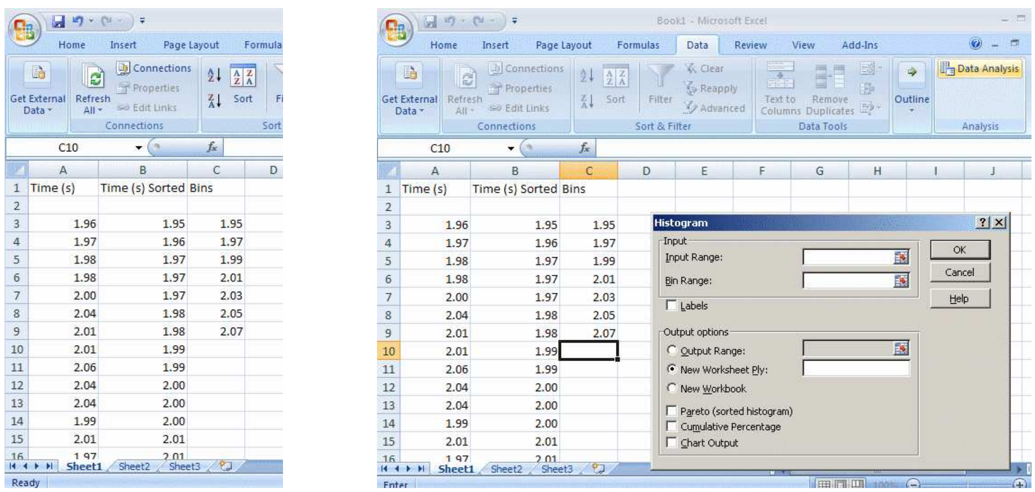


Figure 4: Column data and bins (left-hand panel) and dialog box (right-hand panel) for making a histogram in Excel.

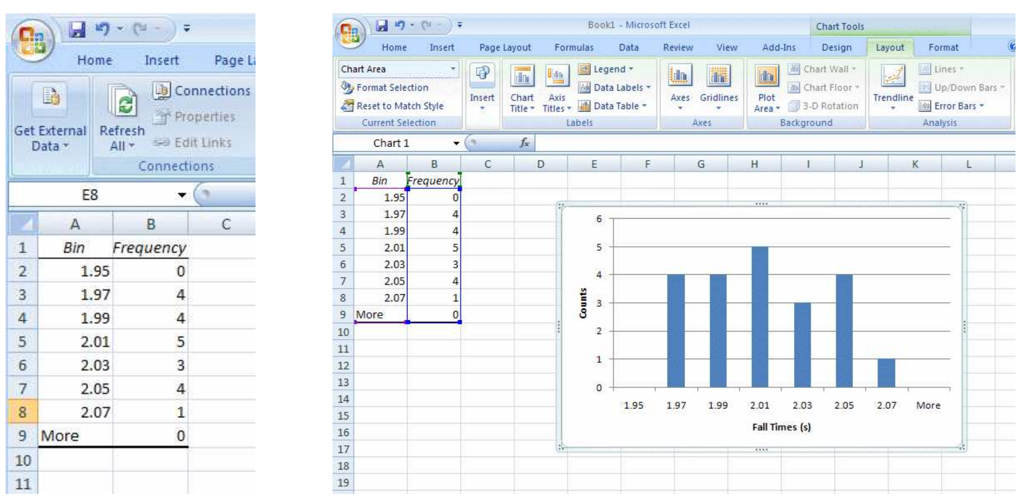


Figure 5: Newly-created worksheet (left-hand panel) and final plot (right-hand panel) for histogram worksheet in Excel.

D Video Analysis

Making a Movie with "Windows Live Movie Maker"

To make a movie, perform the following steps:

1. Make sure the camera is connected to a USB port on your computer. Close all windows, applications, programs, and browsers.
2. Click the **Start** button in the lower-left corner of your screen and type 'movie maker' in the Search programs and files box. Once the search results appear, click on **Windows Live Movie Maker** under **Programs**. After movie maker starts, close any pop-up windows that may appear.
3. Click the **Webcam Video** button. A webcam video window opens. Enlarge the video frame by dragging the vertical line on the right side of the video frame.
4. Position the camera 2-3 meters from the object you will be viewing. Adjust the camera height and orientation so that the field of view is centered on the expected region where the object will move.
5. Place a meter stick or an object of known size in the field of view where it won't interfere with the experiment. The meter stick should be the same distance away from the camera as the motion you are analyzing so the horizontal and vertical scales will be accurately determined. It should also be parallel to one of the sides of the movie frame. Make sure that the meter stick is not far away from the central region of field of view, and that it is perpendicular to the line of sight of camera.
6. One member of your group should perform the computer tasks while the other does the experiment.
7. To start recording your video, click **Record**. When you are done, click **Stop**.

   Save the video on your Desktop with a unique name that you can easily identify. The video will be saved in Windows Media Video format, i.e. with extension wmv. (Do not save the video as a Movie Maker Project file.)

Analyzing the Movie

To determine the position of an object at different times during the motion, perform the following steps:

1. Start up Tracker by going to **Start** → **All Programs** → **Physics Applications** → **Tracker**. When **Tracker** starts it appears as shown below. The menu icons and buttons that we will use are identified by arrows.
2. Click the **Open Video** button on the toolbar (see figure below) to import your video. After your video is imported, Tracker will warn you that the video frames don't have the same time duration. This is okay since Windows Live Movie Maker uses a variable frame rate. Click **Close** on the warning window to ignore Tracker's recommendation.
3. Click the **Clip Settings** button (see figure below) to identify the frames you wish to analyze. A clip settings dialog box appears. Here, you only need to identify and set the start and end frames. Leave everything else in the dialog box unchanged. To find and set the start frame, drag the player's left slider to scan forward through the video, and stop when you get to the first frame of interest. Now, the start frame is set and the corresponding frame number should be displayed in the dialog box. If not, then click on the **Start Frame** in the dialog box, enter the number of the frame (printed in the lower right part of the Tracker window), and click outside the box. Then, click the **Play video** button to go to the last frame in the video. Next, drag the player's right slider to scan backward through the video to find the last frame of interest. Stop when you get to the frame of interest. Now, the end frame is also set and the corresponding frame number should be displayed in the dialog box. If not, then click on the **End Frame** in the dialog box, enter the number of the frame, and click outside the box. Finally, click the **OK** button to close the dialog box, and then click the player's **Return** button to return to the start frame.

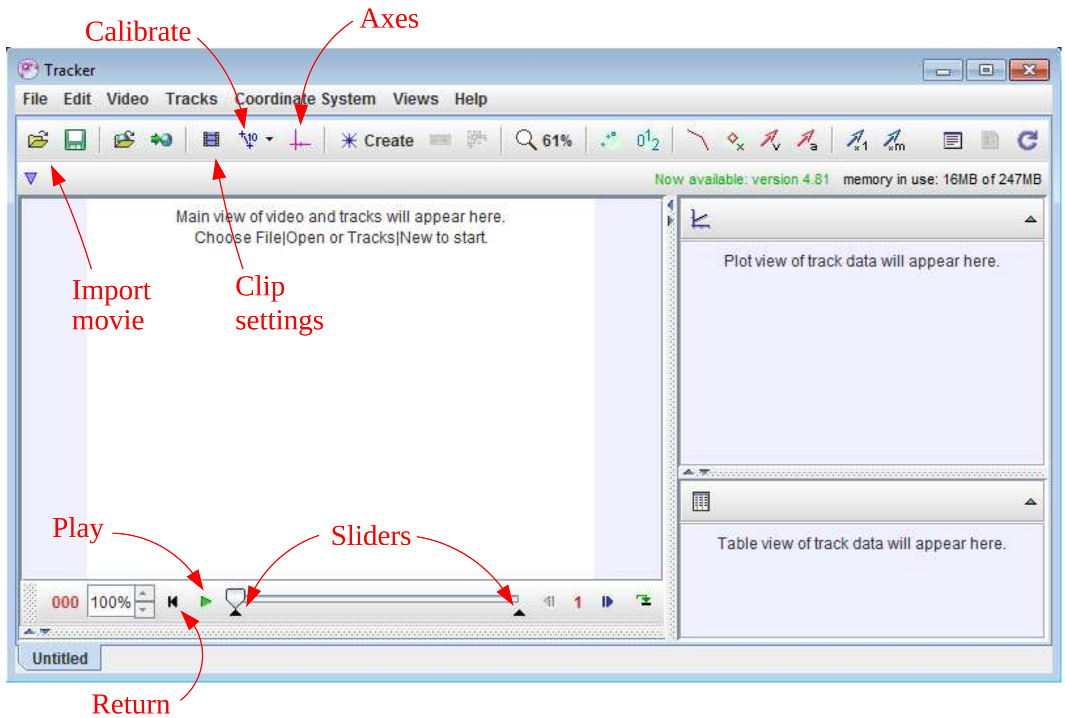


Figure 6: Initial **Tracker** window for video analysis.

4. Click the **Calibration** button (see the figure) and select the **calibration stick**. A blue calibration line appears on the video frame. Drag the ends of this blue line to the ends of your calibration meter stick. Then click the readout box on the calibration line to select it. Enter the length of the meter stick in this box (without units). For example, if your calibration meter stick is 1.00 meter long, enter 1.00 in the box and then click outside the box to accept the value or hit **Return**. At this point, you can right-click the video frame to zoom in for more accurate adjustment of the ends of the calibration stick. Right-click the video again to zoom out.

5. Click the **Axes** button (see the figure) to set the origin and orientation of the x-y coordinate axes. Drag the origin of the axes to the desired position (in most cases the initial position of the object of interest). Click the video outside the origin to fix the position of the origin. To change the orientation (angle) of the axes, drag the x axis. Click the video to fix the new orientation.

6. Click the **Create** button (see the figure) to track the object of interest in the video. From the menu of choices select **Point Mass** for the track type. Make sure the video is at the start frame, which shows the initial position of the object of interest. Mark this position by holding down the **shift key** and clicking the mouse (crosshair cursor) on the object. As the position is marked, the video automatically advances to the next frame. Similarly, mark the position of the object on this and subsequent frames by holding down the **shift key** and clicking the mouse. Do not skip any frames.

   After marking the position on the end frame, you can adjust any one of the marked positions. Advance the video to the frame where you would like to make a fine adjustment. Right-click the video frame to zoom in and drag the marked position with the mouse.

   If you would like to track additional objects, repeat the procedure outlined here for each object.

7. **Plotting and Analyzing the Tracks:** The track data (position versus time) are listed in the Table View and plotted in Plot View sections of the Tracker screen. Click the vertical axis label of the plot to change the variable plotted along that axis. To plot multiple graphs, click the **Plot** button, located above the plot, and select the desired number.

Right-click on a plot to access display and analysis options in a pop-up menu. To fit your data to a line, parabola, or other functions, select the **Analyze** option. On the Data-Tool window that opens up, click on the **Analyze** tab at the top of the plot and check the **Curve Fits** box. Select the fit type from the **Fit Name** drop-down menu. Make sure the **Auto Fit** box is checked.

Note that the curve fitter fits the selected function to the data in the two leftmost columns of the displayed data table. The leftmost column, identified by a yellow header cell, defines the independent variable, and the second leftmost column, identified by a green header cell, defines the dependent variable. So, to fit the data in other columns, their corresponding headers must be dragged to the two leftmost columns.

8. **Printing and Exporting Data:** Track data can also be easily exported to Excel for further analysis by copying the data from the data table to the clipboard and pasting into Excel. Click the **Table** button, located above the data table in the table view section of the main screen, and select from the displayed list the data you would like to display in the data table. Select the desired data in the table by clicking and dragging, then right-click and choose **Copy Data** from the pop-up menu. Now, paste the data into Excel. To print out the displayed plot or data table on Tracker's screen, right-click on the plot or table and choose Print from the pop-up menu.

E Instrumentation

Introduction

Being both quantitative and experimental, physics is basically a science of measurement. A great deal of effort has been expended over the centuries improving the accuracy with which the fundamental quantities of length, mass, time, and charge can be measured.

It is important that the appropriate instrument be used when measuring. Ordinarily, a rough comparison with a numerical scale, taken at a glance and given in round numbers, is adequate. Increasing precision, though, requires a more accurate scale read to a fraction of its smallest division. The "least count" of an instrument is the smallest division that is marked on the scale. This is the smallest quantity that can be read directly without estimating fractions of a division.

Even at the limit of an instrument's precision, however, accidental errors — which cannot be eliminated — still occur. These errors result in a distribution of results when a series of seemingly identical measurements are made. The best estimate of the true value of the measured quantity is generally the arithmetic mean or average of the measurements.

Other errors, characteristic of all instruments, are known as systematic errors. These can be minimized by improving the equipment and by taking precautions when using it.

Length Measurement

Three instruments will be available in this class for length measurements: a ruler (one- or two-meter sticks, for example), the vernier caliper, and the micrometer caliper.

The Meter Stick

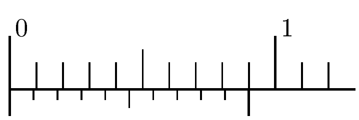
A meter stick, by definition, is 1 meter (m) long. Its scaled is divided, and numbered, into 100 centimeters (cm). Each centimeter, in turn, is divided into 10 millimeters. Thus 1 cm = 10^{-2} m, and 1 mm = 10^{-1} cm = 10^{-3} m.

When measuring a length with a meter stick, different regions along the scale should be used for the series of measurements resulting in an average value. This way, non-uniformities resulting from the meter stick manufacturing process will tend to cancel out and so reduce systematic errors. The ends of the stick, too, should be avoided, because these may be worn down and not give a true reading. Another error which arises in the reading of the scale is introduced by the positioning of the eyes, an effect known as parallax. Uncertainty due to this effect can be reduced by arranging the scale on the stick as close to the object being measured as possible.

The Vernier Caliper

A vernier is a small auxiliary scale that slides along the main scale. It allows more accurate estimates of fractional parts of the smallest division on the main scale.

On a vernier caliper, the main scale, divided into centimeters and millimeters, is engraved on the fixed part of the instrument. The vernier scale, engraved on the movable jaw, has ten divisions that cover the same spatial interval as nine divisions on the main scale: each vernier division is $\frac{9}{10}$ the length of a main scale division. In the case of a vernier caliper, the vernier division length is 0.9 mm. [See figures below.]



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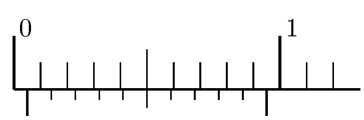

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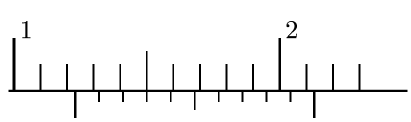

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Examples of vernier caliper readings

To measure length with a vernier caliper, close the jaws on the object and read the main scale at the position indicated by the zero-line of the vernier. The fractional part of a main-scale division is obtained from the first vernier division to coincide with a main scale line. [See examples above.]

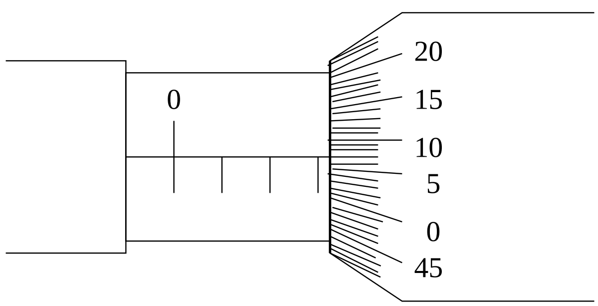
If the zero-lines of the main and vernier scales do not coincide when the jaws are closed, all measurements will be systematically shifted. The magnitude of this shift, called the zero reading or zero correction, should be noted and recorded, so that length measurements made with the vernier caliper can be corrected, thereby removing the systematic error.

The Micrometer Caliper

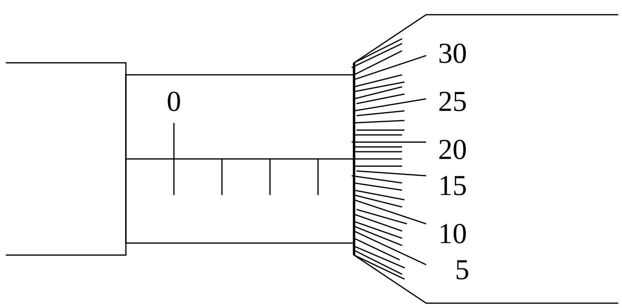
A micrometer caliper is an instrument that allows direct readings to one hundredth of a millimeter and estimations to one thousandth of a millimeter or one millionth of a meter (and, hence, its name). It is essentially a carefully machined screw housed in a strong frame. To measure objects, place them between the end of the screw and the projecting end of the frame (the anvil). The screw is advanced or retracting by rotating a thimble on which is engraved a circular scale. The thimble thus moves along the barrel of the frame which contains the screw and on which is engraved a longitudinal scale divided in millimeters. The pitch of the screw is 0.5 mm, so that a complete revolution of the thimble moves the screw 0.5 mm. The scale on the thimble has 50 divisions, so that a turn of one division is $\frac{1}{50}$ of 0.5 mm, or 0.01 mm.

Advance the screw until the object is gripped gently. Do not force the screw. A micrometer caliper is a delicate instrument.

To read a micrometer caliper, note the position of the edge of the thimble along the longitudinal scale and the position of the axial line on the circular scale. The first scale gives the measurement to the nearest whole division; the second scale gives the fractional part. It takes two revolutions to advance one full millimeter, so note carefully whether you are on the first or second half of a millimeter. The result is the sum of the two scales. (See examples below).



0.307 cm



0.367 cm

As with the vernier caliper, the zero reading may not be exactly zero. A zero error should be checked for and recorded, and measurements should be appropriately corrected.

Mass Measurement

Three kinds of instruments will be available to determine mass: a digital scale and two types of balances. The operation of the first instrument is trivial, and so will not be explained here.

Please understand that with each of these instruments we are really comparing weights, not masses, but the proportionality of weight and mass allows the instruments to be calibrated for mass.

The Equal-Arm Balance

The equal-arm balance has two trays on opposite sides of a pivot. The total mass placed on one tray required to balance the object on the other gives the mass of the object. Most equal-arm balances have a slider, as well, that can move along a scale and allow for greater precision than the smallest calibrated mass available. Typically, this scale has 0.5 g divisions.

The Triple-Beam Balance

The triple-beam balance, so-called because of its three slider scales, can be read to 0.1 g and estimated to half that. With an object on the tray, the masses of the different scales are slid to notches until balanced. Get close with the larger masses first and then fine-adjust with the smallest slider.

Time Measurement

Time measurements in this course will be made either with a computer or with a stop watch. This first is out of your control.

The Stop Watch

The stop watches you will use in class have a time range of from hours to hundredths of a second. There are two buttons at the top: a stop/start button and a reset button. The operation of these should be evident, although once the watch is reset, the reset button also starts the watch (but doesn't stop it). Please be aware of this feature.

Charge Measurements

The magnitude of charge is among the most difficult measurements to make. Instead a number of indirect measurements are undertaken to understand electric phenomena. These measurements are most often carried out with a digital multimeter

The Digital Multimeter

The digital multimeters available for laboratory exercises have pushbutton control to select five ac and dc voltage ranges, five ac and dc current ranges, and six resistance ranges. The ranges of accuracy are 100 microvolts to 1200 volts ac and dc, 100 nanoamperes to 1.999 amperes ac and dc, and 100 milliohms to 19.99 megaohms.

To perform a DC voltage measurement, select the DCV function and choose a range maximum from one of 200 millivolts or 2, 20, 200, or 1200 volts. Be sure the input connections used are V-Ω and COMMON. The same is true for AC voltage, regarding range and inputs, but the ACV function button should be selected.

For DC current choose DC MA (for DC milliamperes), while for AC current choose AC MA. Your choices for largest current are 200 microamperes or 2, 20, 200, or 2000 milliamperes. Check that the input are connected to MA and COMMON.

There are two choices for resistance measurement: Kilohms (kΩ) and Megohms (20MΩ). The input connectors are the same as when measuring voltage, namely V-Ω and COMMON. The range switches do not function with the Megohm function, but one of the range buttons must be set. The maximum settings for Kilohm readings are 200Ω or 2, 20, 200, or 2000kΩ.

Calibrating Force Sensors

1. Connect force sensor to Pasco interface (in port “A”).

2. Open the *DataStudio* application that you will use to perform the lab.

3. With NO force applied to force sensor, press TARE button on side of force sensor. This sets the sensor to zero. This is the ONLY time you will press the TARE button.

4. Click “Setup”.

5. Click “Calibrate Sensors”.

6. Set 1st calibration point to 0 newtons, press upper “Read from sensor” button.

7. HOLDING SENSOR VERTICALLY (with hook down), hang 200g from sensor, set 2nd calibration point to 1.96 newtons, press lower “Read from sensor” button.

8. Click “OK”. Force sensor is now calibrated for the rest of your experiment. Close “Calibrate Sensors” window, close “Setup” window.

9. While still holding the force sensor still, press “Start”. Graph should now show a reading of 1.96 N. Press “Stop”.

10. Try hanging a different mass from the force sensor; press “Start” and check that it is reading correctly.