

Laboratory Manual

Physics 1011/2111
Mechanics

Table of Contents

Physics 1011/2111 Labs ~ General Guidelines	3
Introduction to Statistics, Error and Measurement	5
1. The Determination of Gravitational Acceleration	11
2. Projectile Motion.....	16
3. Newton's Second Law: The Atwood Machine.....	20
4. Friction.....	27
5. The Work-Energy Theorem.....	32
6. Conservation of Linear Momentum.....	36
7. Rotational and Translational Energies	43
8. Periodic Motion and Resonance	51
Appendix A: Excel, the Basics!	57

PHYSICS 1011/2111 LABS ~ GENERAL GUIDELINES

The Physics 1011 and 2111 labs will be divided into small groups (so you will either be working with one lab partner, or, for the larger classes, in a small group). You and your lab partner(s) will work together, but you each must submit an *individual* lab report, with a discussion of the lab and interpretation of results *in your own words*.

The laboratory classroom is located in the west wing of Benton Hall, Room 331.

Laboratory attendance is mandatory and roll will be taken. At the beginning of each lab, you will sign out a lab kit and your lab instructor will check it in when you finish the lab. If you miss a lab session, it is **your** responsibility to contact the lab instructor to pick up any missed handouts or information for the following week's session. The lab instructor may allow you to make up a missed experiment, if you miss the lab for a valid medical reason. **If makeup labs are permitted, labs must be made up within a week of the original lab date. See your individual professor's syllabus for details about their rules for makeup labs.**

Always read the experiment before coming to the lab! This is really important, and will help you get the most out of the lab. Bring your calculator to lab, and take good notes when the lab instructor gives detailed information about the experiment and about what s/he expects in the lab report.

Lab reports MUST be typed. If you have trouble finding computer facilities, and don't have a computer at home, see the lab instructors or the course instructor, and we will help you find a computer to work on.

Lab reports should include your name, the name of your lab partner, the lab section (e.g., "Tuesday 12:30"), the date the experiment was performed, and the title of the experiment.

This is a recommended guideline. The lab instructor has the final say in which details to include and how to format your lab report.

You may find it useful to visit the "Lab Connection" website, which you can access via the Physics Department website: <http://www.umsl.edu/~physics/>.

The lab report itself should contain the following sections:

Purpose: State, in your own words, the purpose of the experiment.

Procedure: Describe the procedure in your own words. Describe also any novel approaches you took, difficulties you had, or interesting observations. These descriptions need to be in "scientific" style, as professionally written as if you were going to submit the lab report to a scientific journal. Writing things like "This experiment was fun" is NOT what we are looking for!

Analysis:

Data/graphs: List all data taken in the experiment, in tabular form whenever possible. Make sure that you give the units for all physical quantities. All graphs and tables should be neatly arranged and clearly labeled with titles.

Calculations: Show clearly all the calculations you performed on the data. Show all equations you used.

If calculations are used to obtain data that is plotted in the graphs, you may want to show the calculations *before* the graphs. For example, you might make some measurements, and plot the raw data. Then you might do some calculations on the raw data, and plot the results. In that case, your results section should show (1) table of original data, (2) graph of original data, (3) calculations (equations and table of calculated results), and (4) graphs of calculated results. Alternately, you might show calculated quantities in columns next to the original measurements. For each experiment, we will give a sample data table that you can copy and paste into your lab report as a guide to how to present the data. **The main point is to have the data and calculations presented clearly. You want the lab instructor to be able to clearly follow your thought process, to be able to see exactly what you measured and what you calculated.**

Questions:

Answer all the questions posed in the lab manual.

Conclusions:

What did you conclude from the experiment? What quantities were measured? Were the results of the measurements what you expected? Describe possible sources and types of error in your measurements. Tie your results back to the original purpose of the experiment.

The lab reports are due at the beginning of the following session unless stated otherwise by your lab instructor.

Graded reports will typically be handed back a week after they are turned in. End-of-semester graded lab reports will be handed back at your lecture, or can be picked up from your professor after the end of the semester.

All measurements taken in the lab should be in SI (Système Internationale) units (formerly known as MKS) units (meters, kilograms, and seconds) unless explicitly stated otherwise by your lab instructor.

Happy experimenting....And, when you get frustrated, remember that Galileo did all this **under house arrest!**

INTRODUCTION TO STATISTICS, ERROR AND MEASUREMENT
--

Throughout the semester we will be making measurements. When you do an experiment, it is important to be able to evaluate *how well you can trust your measurements*. For example, the known value of g , the acceleration due to gravity, is $\approx 9.81 \text{ m/s}^2$, (" \approx " means approximately equal to). If you make a measurement that says $g = 10.1 \text{ m/s}^2$, is that measurement "wrong"? How do you compare that measurement to the known value of g ? Suppose you measure some quantity that is *not* known? You may make a number of measurements, and get several different results. For example, suppose you measure the mass of an object three times, and get three different values, 5 kg, 4.8 kg, and 5.4 kg. Can you evaluate what the *real* mass of the object is from those measurements?

The mathematical tools we will learn in this lab will answer some of these questions. They are some of the most basic methods of statistical analysis; they will allow us to give information about our measurements in a standard, concise way, and to evaluate how "correct" our measurements are. The methods we will cover are used in all areas of science which involve taking any measurements, from popularity polls of politicians, to evaluating the results of a clinical trial, to making precise measurements of basic physical quantities.

Let's start with the basics of the different *kinds* of errors, and how to measure them.

Types of Errors

There are two types of errors encountered in experimental physics: **systematic** errors and **random** errors.

Systematic errors can be introduced

- by the design of the experiment
- by problems with the instruments you are using to take your data
- by your own biases

Consider a very simple experiment designed to measure the dimensions of a particular piece of material precisely. A systematic error could be introduced if the measuring instrument is calibrated improperly. For example, a scale might be set a little too low, so that what *reads* as "zero" is *really* "-1 kg". Everything you measure on the scale will come out one kilogram lighter than it really is. If a particular observer always tends to overestimate the size of a measurement, that would also be a systematic error, but one related to the personal characteristics of the experimenter.

Random errors are produced by unpredictable and uncontrollable variations in the experiment. These can be due to the limits of the precision of the measuring device, or due to the experimenter's inability to make the same measurement in **precisely** the same way each time. Even if systematic errors can be eliminated by good experimental design, there will always be some uncertainty due to random errors. Numerical values measured in experiments are therefore never **absolutely** precise; there is always some uncertainty.

Accuracy and Precision

The **accuracy** of a measurement describes how close the experimental result comes to the actual value. That is, it is a measure of the "correctness" of the result. For example, if two independent

experiments give the values 2.717 and 2.659 for e (the base of the natural log), the first value is said to be more accurate because the *actual* value of e is 2.718.....

The **precision** of an experiment is a measure of the *reproducibility* of the result. Suppose you measure the same thing three times. The precision would be a measure of how similar all the measurements are to each other. It is a measure of the magnitude of uncertainty in the result. Suppose one person weighs a cat, and comes up with three different masses each time: 10 kg, 12 kg, and 11 kg. Suppose another person weighs the same cat, and comes up with these three masses: 11.1 kg, 11.5 kg, and 11.3 kg. The second person's measurement would be said to be more precise. (Both people are likely to be scratched, though.)

Significant Figures

When reading the value of an experimental measurement from a calibrated scale, only a certain number of figures or digits can be obtained or read. That is, only a certain number of figures are significant. The **significant figures** (sometimes called "**significant digits**") of an experimentally measured value include all the numbers that can be read directly from the instrument scale plus one doubtful or estimated number. For example, if a ruler is graduated in millimeters (mm), you can use that ruler to estimate a length *up to one tenth of a millimeter*. For example, suppose you make a sequence of measurements of the length of some object using this ruler, and get an average value of 318.9811123 mm. The measurement is only accurate to one decimal place, so you would report the number as 319.0 ± 0.1 mm. The "zero" is shown after the decimal point because that digit is the last significant one. All the other digits are meaningless and do not convey any real information about your measurements. Also, when you are combining measurements, the most imprecise measurement is your limiting factor. You can never have more significant digits than your least accurate measurement.

Data Analysis

Percent Error and Percent Difference

How do you measure the size of an error? The object of some experiments is to measure the value of a well-known quantity, such as g . (You'll be making this measurement yourselves in next week's experiment!) The most accurate value of these quantities (measured by teams of dedicated professional scientists!!) is the value given in your textbooks and tables. In making a comparison between the results of your experiment and the accepted value measured with much more precision in specialized laboratories, you want to cite the **percent error**, a measurement of how much your measurement differs from the "official" value. The **absolute difference** between the experimental value E and the accepted value A is written $|E-A|$, where the "|" signs mean absolute value. The **fractional error** is the ratio of this **absolute difference** over the accepted value:

$$\text{Fractional error} = \frac{|E - A|}{A}$$

Usually, people convert this fractional error into a percent, and give the **percent error**:

$$\text{Percent error} = \frac{|E - A|}{A} \times 100\%.$$

Sometimes, you need to compare two equally reliable results when an accepted value is *unknown*. This comparison is the **percent difference**, which is the ratio of the **absolute difference** between experimental results E_1 and E_2 to the **average of the two values**, expressed as a percent:

$$\text{Percent difference} = \frac{|E_1 - E_2|}{\left[\frac{(E_1 + E_2)}{2}\right]} \times 100\%.$$

Mean Value

Even if systematic errors can be eliminated from an experiment, the **mean value of a set of measurements of a quantity, x , is a better estimate of the true value of x than is any single measurement**. For this reason, experiments are often repeated a number of times. If we denote $\langle x \rangle$ as the mean value, and there are N measurements x_i (where i varies from 1 to N), then $\langle x \rangle$ is defined by the following equation:

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^N x_i$$

In fact, random errors are distributed according to a Gaussian distribution, which looks like the familiar bell curve. In case you aren't familiar with it, the "Σ" symbol we just used is a capital Greek letter "sigma ". In math, it is called a summation sign. It means "add up everything to the right". So in the equation above, the sigma is a shorthand way of writing

$$\langle x \rangle = \frac{1}{N} (x_1 + x_2 + x_3 + \dots + x_N).$$

Mean Deviation

To obtain the **mean deviation** of a set of N measurements, the **absolute deviations** of $|\Delta x_i|$ are determined; that is

$$|\Delta x_i| = |x_i - \bullet x \textcircled{R}|$$

The **mean deviation** $\bullet \Delta x \textcircled{R}$ is then

$$\langle \Delta x \rangle = \frac{1}{N} \sum_{i=1}^N |\Delta x_i|$$

Example 1.1 What are the mean value and mean deviation of the set of numbers 5.42, 6.18, 5.70, 6.01, and 6.32?

Solution:

The mean is

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^N x_i = \frac{5.42 + 6.18 + 5.70 + 6.01 + 6.32}{5} = 5.926 = 5.93$$

Note that since the original measurements were only valid to two decimal places, the average can only be valid to two decimal places as well, so we round from 5.926 to 5.93.

The absolute deviations for each measurement are:

$$|\Delta x_1| = |5.42 - 5.93| = 0.51$$

$$|\Delta x_2| = |6.18 - 5.93| = 0.25$$

$$|\Delta x_3| = |5.70 - 5.93| = 0.23$$

$$|\Delta x_4| = |6.01 - 5.93| = 0.08$$

$$|\Delta x_5| = |6.32 - 5.93| = 0.39$$

Then the mean deviation is:

$$\langle \Delta x \rangle = \frac{1}{N} \sum_{i=1}^N |\Delta x_i| = \frac{0.51 + 0.25 + 0.23 + 0.08 + 0.39}{5} = 0.292 = 0.29$$

Usually, people report an experimental measurement as the mean “plus or minus” the mean deviation:

$$E = \bullet x \textcircled{\text{R}} \pm \bullet \Delta x \textcircled{\text{R}}$$

In our example, the value would be reported like this: 5.93 ± 0.29 .

Standard Deviation

Statistical theory states that the **precision** of a measurement can be determined using a quantity called the **standard deviation**, σ (called “sigma”, this is the Greek lower-case “s”). The standard deviation of a distribution of measurements is defined as follows:

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

The **standard deviation** is a measure of **spread**. If the standard deviation is *small*, then the **spread in the measured values about the mean** is *small*, and so the **precision** in the measurements is *high*. The standard deviation is always positive and has the same units as the measured values.

It can be shown, for a Gaussian distribution, that 69% of the data points will fall within one standard deviation of $\langle x \rangle$, i.e., $(\langle x \rangle - \sigma) < x_i < (\langle x \rangle + \sigma)$; 95% are within two standard deviations, and only 0.3% are farther than 3σ from $\langle x \rangle$. So, for example, if an experimental data point lies 3σ from a theoretical prediction, there is a strong chance that either the prediction is not correct or there are systematic errors which affect the experiment.

Example 1.2 What is the standard deviation of the set of numbers given in Example 1.1?

Solution:

First, find the square of the deviation of each of the numbers

$$\Delta x_1^2 = (5.42 - 5.93)^2 = 0.26$$

$$\Delta x_2^2 = (6.18 - 5.93)^2 = 0.06$$

$$\Delta x_3^2 = (5.70 - 5.93)^2 = 0.05$$

$$\Delta x_4^2 = (6.01 - 5.93)^2 = 0.01$$

$$\Delta x_5^2 = (6.32 - 5.93)^2 = 0.15$$

then

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)^2} = \sqrt{\frac{0.26 + 0.06 + 0.05 + 0.01 + 0.15}{5}} = 0.33$$

The result of our measurement of E can also be reported as:

$$E = \langle x \rangle \pm \sigma$$

Note that all these statements are valid if **only** random errors are present.

Presenting Data

Data Tables

You should always organize the experimental data which you take into data tables, in order to make the data very clear and easy to understand. The data table will generally have two or more columns which present the values of the controlled (independent) and measured (dependent) variables. The table should contain labels for the various columns, **including units and errors**. If some variables are fixed during a particular experiment, the values can be given in the title for the table or in the text; similarly, if the errors are the same for all measurements they can be included in the text or caption. Data tables are usually organized by ascending values of the independent variable.

Example 1.3 For a fixed volume, pressure is proportional to temperature for an ideal gas. A fixed amount (10 moles) of gas is placed in a container having a fixed volume of 1m^3 and the temperature

is increased from 0°C to 60°C in increments of 10°C. The pressure in Newton/m² (Pascal) is measured by an apparatus for which the pressure can be read accurately in 100 pascal units with the 10 Pascal digit estimated. The pressure was measured several times and a statistical error determined for each measurement. The independent variable (temperature) is given in the left column of the table on the next page. The measured quantity (a.k.a., the dependent variable) is given, along with the error, in the right column.

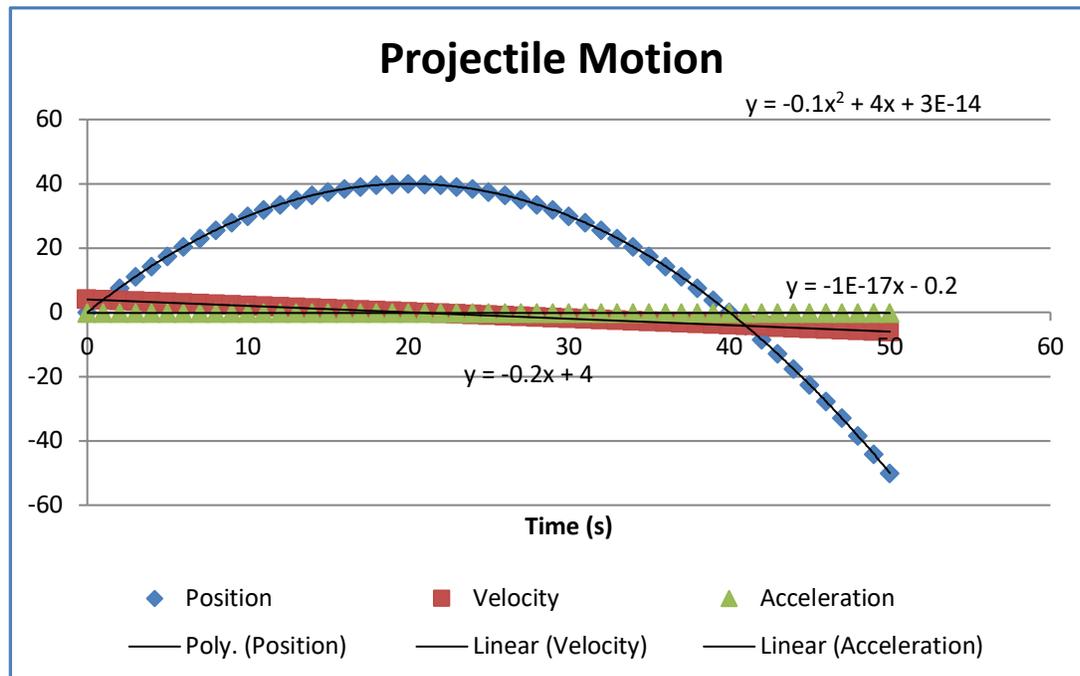
GAS PRESSURE AS A FUNCTION OF TEMPERATURE

V = 1m³; n = 10 moles

Temperature (°C)	Pressure P ± ΔP (Pascals)
0	22700 ± 20
10	23540 ± 20
20	24330 ± 40
30	25210 ± 30
40	26010 ± 30
50	26820 ± 30
60	27730 ± 50

Graphs

When you are plotting data in a graph, always make it really clear what you are plotting on each axis! Label the axes and show units. (See the Excel tutorial in the Appendix.)



EXPERIMENT 1 ~ THE DETERMINATION OF GRAVITATIONAL ACCELERATION

The first lab of the semester has three parts:

- Introduction to Statistics, Error and Measurement, which can be found on page 5.
- The actual experiment: “The Determination of Gravitational Acceleration” where you will learn how to evaluate measured data by averages and standard deviations
- A tutorial in how to plot data using Excel, which can be found in the Appendix.

There are questions on the last page of the Experiment that you will need to answer in your lab report.

You will probably want to refer back to the Introduction to Statistics, Error and Measurement, and the Excel Tutorial, later in the semester, as you work on analyzing and graphing data from more complicated experiments.

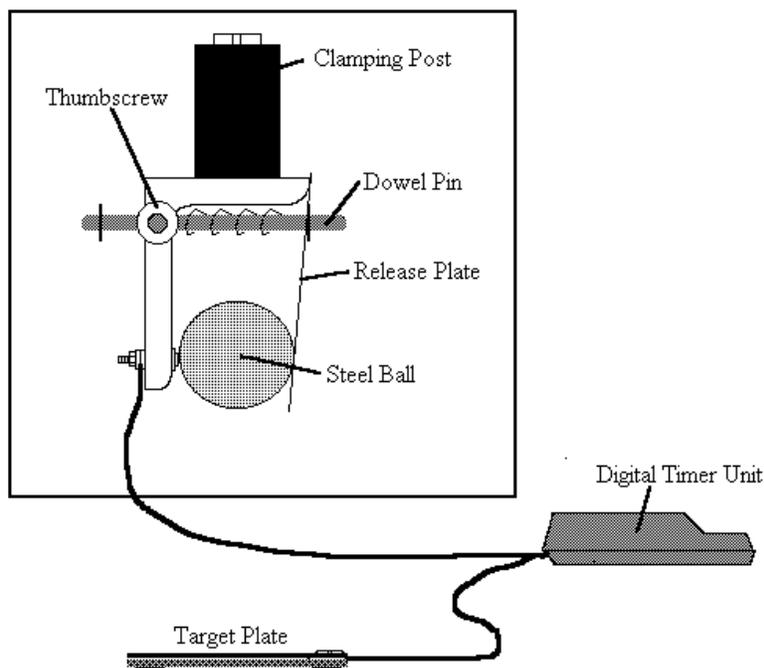
Purpose:

The purpose of this experiment is to measure the earth's gravitational acceleration from an object in free fall. You will use the equation of motion of an object in free fall, starting from rest ($v_0=0$):

$$y(t) = y_0 + v_0 t + \frac{1}{2} a t^2$$

Equipment:

Ball bearing, timer, clamping post, meter stick.



Experiment Part A:

Using the apparatus shown above, drop a ball

- 10 times, from
- 4 different heights (you pick the heights)

To clamp the ball, push in the dowel pin until the ball is tightly clamped, and then tighten the thumbscrew. To release the ball, open the thumbscrew. Be sure to reset the timer to zero before dropping the ball! The lab instructor will show you how to do all this in detail. Be careful when you measure the height: measure *from the bottom of the ball to the pressure pad*.

Collect your data at four different heights and enter the data in the tables below.

For each measured y and t , you can calculate g . Since the initial velocity v_0 is zero, the initial position is h ($y_0 = h$), and the acceleration is $-g$ ($a = -g$), you can rearrange the equation:

$$y(t) = y_0 + v_0 t + \frac{1}{2} a t^2 \tag{1}$$

to solve for g :

$$g = 2h/t^2 \tag{2}$$

You can do this with your calculator, or put the time values into Excel, and make an equation to solve for g at each value of t and y . For each height, calculate the mean value of gravity and time ($\langle g \rangle$, $\langle t \rangle$), and the standard deviation (σ_g , σ_t). Again, you can use Excel to do this.

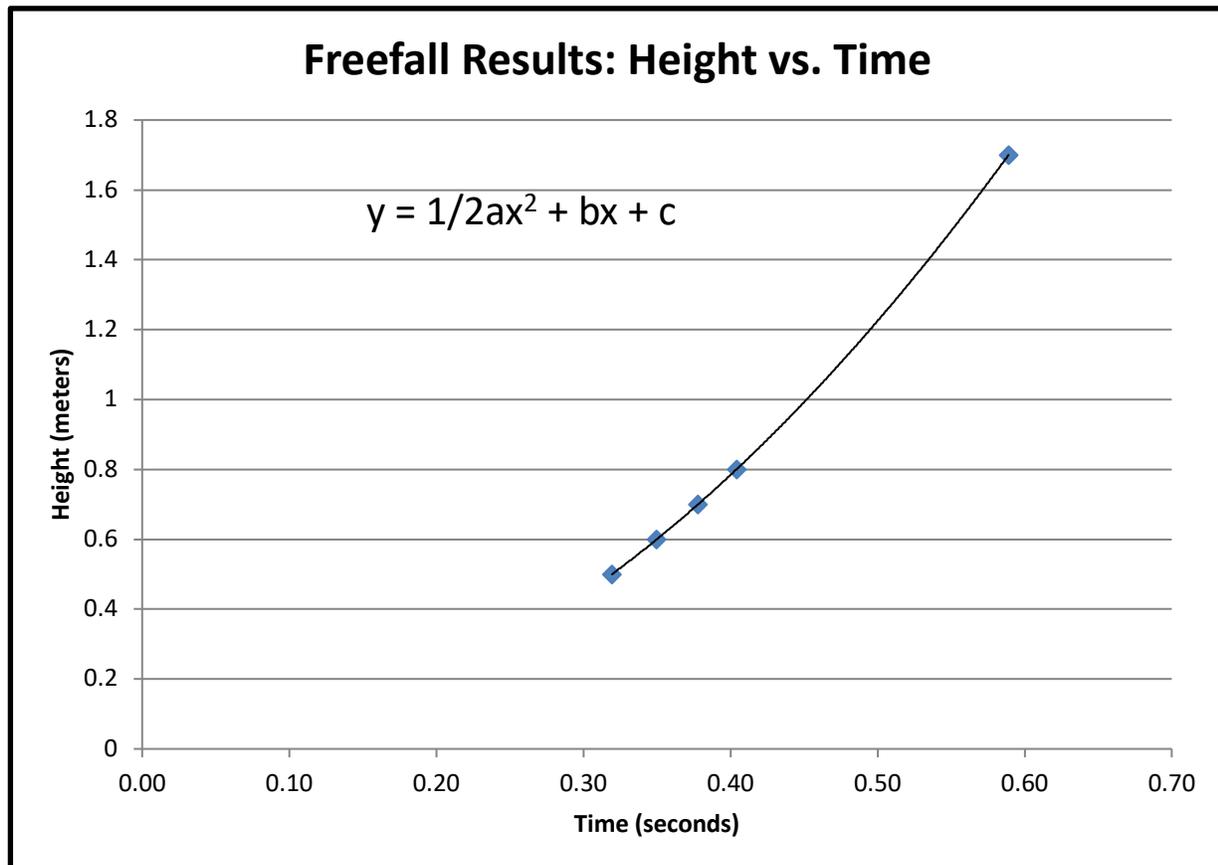
Table 1: Time and Gravity Data

Height 1: $h_1 =$		Height 2: $h_2 =$		Height 3: $h_3 =$		Height 4: $h_4 =$	
t	g	t	g	t	g	t	g
$\langle t_1 \rangle =$		$\langle t_2 \rangle =$		$\langle t_3 \rangle =$		$\langle t_4 \rangle =$	
$\sigma_{t_1} =$		$\sigma_{t_2} =$		$\sigma_{t_3} =$		$\sigma_{t_4} =$	
$\langle g_1 \rangle =$		$\langle g_2 \rangle =$		$\langle g_3 \rangle =$		$\langle g_4 \rangle =$	
$\sigma_{g_1} =$		$\sigma_{g_2} =$		$\sigma_{g_3} =$		$\sigma_{g_4} =$	

Analysis Part B:

You now have five different heights with five different average times. The plot below shows an example of a chart with height on the y axis and time on the x axis (h vs. t). Using Excel, try to recreate this plot using your own data. Use the average time you obtained for each height. Include a trend line and the polynomial equation (of order 2) for the trend line. In Appendix A you will find some helpful tutorials, if you are not familiar with Excel.

Look carefully at the trend line equation. Excel usually shows 0 as a number near 10^{-14} ; so that the equation can be reduced to $y = 1/2ax^2$. What does this value of a represent? (Hint: Compare this equation to equation 1).



Questions:

1. Discuss the sources of error in the experiment. Were there sources of random error? What were they? What about systematic error?
2. Would you expect the values of g measured at the two different heights to be the same? Why or why not?
3. Suppose you had used a metal ball of a different mass (say, ten times heavier). Would you expect the value of g to be the same, or different? Why?
4. For measuring the distance that the ball drops, we suggested that you measure from the bottom of the ball to the pressure pad, in order to get the most accurate distance. Why *shouldn't* you measure from the middle of the ball to the pressure pad? Explain.
5. Which of your values for $\langle g \rangle$ was more precise? Which was more accurate? Explain.

EXPERIMENT 2 ~ PROJECTILE MOTION

Purpose:

In this experiment, you will study projectile motion, and see how to separate the motion of a projectile into its x and y components.

Two photographs (a double exposure) using a digital camera and strobe light illumination will enable you to get a picture of the trajectory of a ball as it is tossed between you and your lab partner. One of the exposures will show you a grid from which you can calculate the ball's position; the other exposure will show you the ball's trajectory. The combined exposures will show you the ball at various instants during its trajectory superimposed on the grid. You can then compare the measured trajectory with what you would expect based on the equations discussed in class.

Equipment:

Strobe light, digital camera and printer, 100cm X 100cm grid, black felt cover, golf ball, and flash drive (optional)

Procedure:

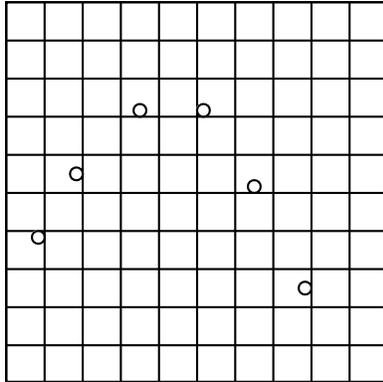
You and your lab partner should practice tossing the ball back and forth before you have the lab instructor take the photograph. Make sure that the ball's trajectory arches completely within the grid – not going above the top of the grid, and not traveling in a straight line horizontally across the grid.

Two pictures will be taken by the lab instructor. The first will be of just the grid, with the room lights on. The second photograph will be superimposed over the first, and taken with the overhead lights out and strobe light on. (If you are susceptible to light-induced seizures, please contact your TA about alternatives to this part of the experiment.) The shutter on the camera will be held open while you toss the ball in front of the grid. The photo will then show the ball's trajectory, i.e., its position at equal time intervals, (1/flash rate), superposed on the grid. The more data points you have, the better your measurement will be. The data table has spaces for 10 data points, but this is just a guideline. If you have less than this, it is OK! If you have more than this, yay you!

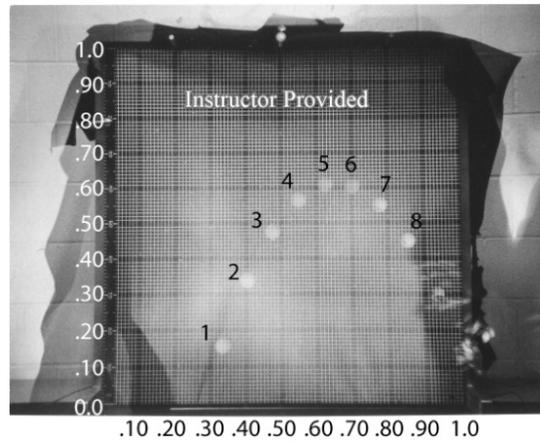
Be sure to record the flash rate from the strobe light! (It should be 14 -17 flashes/second).

The photo will be sent to the printer and a digital copy can be stored on your thumb drive to be printed in your lab report.

The two illustrations below show what the results should look like in theory (left), and an example of a real picture (right).



Theory!



Real life!

(This photo is a bit overexposed....)

Analysis:

1. Use the photo to find the x and y coordinates of the center of each image of the ball. Put the origin, (0, 0) in the lower left corner. The entire grid is 1m x 1m, with major divisions every 10cm, and further divisions every cm. Enter your measurements in the X and Y columns below. Remember to convert from centimeters to meters!

Data Table 1
Flash Rate (s^{-1}) _____

Position #	X (m)	Y (m)	V_x (m/s)	V_y (m/s)	A_x (m/s^2)	A_y (m/s^2)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

2. Calculate average speed for each data point. Remember the definitions of average speed in the x and y directions: $v_x = \Delta x / \Delta t$ and $v_y = \Delta y / \Delta t$. Calculate v_x and v_y from your recorded x and y position values. Be sure to use consecutive positions. (Why?) Enter your calculated values in the table. Remember that your Δt is 1/ (flash rate).

3. Using the definition of average acceleration and x and y components, $a_x = \Delta v_x / \Delta t$ and $a_y = \Delta v_y / \Delta t$, find a_x and a_y . Again, be sure to use consecutive speeds. Enter your calculated values in the table.

Two sets of sample calculations are shown below, to help you along: one with actual numbers, and one with equations. In the second example below, the flash rate is taken to be 15 flashes per second.

You can find an Excel spreadsheet to help with calculations at the Lab Connection website.

x	y	V_x	V_y	A_x	A_y
x_1					
x_2		$V_{x(2,1)} = \frac{x_2 - x_1}{\Delta t}$	$V_{y(2,1)} = \frac{y_2 - y_1}{\Delta t}$		
x_3	$V_{x(3,2)} = \frac{x_3 - x_2}{\Delta t}$	$V_{y(3,2)} = \frac{y_3 - y_2}{\Delta t}$	$A_{x(3,2)} = \frac{V_{x(3,2)} - V_{x(2,1)}}{\Delta t}$	$A_{y(3,2)} = \frac{V_{y(3,2)} - V_{y(2,1)}}{\Delta t}$

Position #	X (m)	Y (m)	Vx (m/s)	Vy (m/s)	Ax (m/s/s)	Ay (m/s/s)
1	0.33	0.25				
2	0.40	0.33	$(0.4-0.33)*15= 1.05$	$(0.33-0.25)*15= 1.20$		
3	0.47	0.47	$(0.47-0.4)*15= 1.05$	$(0.47-0.33)*15= 2.10$	$(1.05-1.05)*15= 0.00$	$(2.10-1.20)*15= 13.50$
4	0.55	0.57	$(0.55-0.47)*15= 1.20$	$(0.57-0.47)*15= 1.50$	$(1.20-1.05)*15= 2.25$	$(2.10-1.50)*15= 9.00$
5	0.63	0.61	$(0.63-0.55)*15= 1.20$	$(0.61-0.57)*15= 0.60$	$(1.20-1.20)*15= 0.00$	$(0.60-1.50)*15= -13.50$
6	0.70	0.60	$(0.7-0.63)*15= 1.05$	$(0.60-0.61)*15= -0.15$	$(1.05-1.20)*15= -2.25$	$(-0.15-0.60)*15= -11.25$
7	0.78	0.56	$(0.78-0.70)*15= 1.20$	$(0.56-0.60)*15= -0.60$	$(1.20-1.05)*15= 2.25$	$(-0.60-(-0.15))*15= -6.75$
8	0.86	0.45	$(0.86-0.78)*15= 1.20$	$(0.45-0.56)*15= -1.65$	$(1.20-1.20)*15= 0.00$	$(-1.65-(-0.60))*15= -15.75$

Questions:

1. Explain why the first row of calculated average speeds, and the first two rows of calculated average accelerations, are blank.
2. What forces are acting on the ball while it is in flight?
3. What value did you expect to get for a_x ? Why?
4. Calculate the average value for a_x , $\langle a_x \rangle$, and its standard deviation, for each case. Remember that the standard deviation has the same units as the number being measured (in this case, m/s^2).
5. What value did you expect to get for a_y ? Why?
6. Calculate the average and standard deviation for your value of a_y .
7. Calculate the percent error between your value of a_y (the average value you just calculated) and your predicted value of a_y (your answer to question 5).
8. Describe possible sources of random error in the experiment.
9. Describe possible sources of systematic error in the experiment.
10. Suppose you had done the experiment with ping pong balls rather than golf balls. Might you have gotten different results? Why or why not?

EXPERIMENT 3 ~ NEWTON'S SECOND LAW: THE ATWOOD MACHINE

Purpose:

To predict the acceleration of an Atwood Machine by applying Newton's 2nd Law and use the predicted acceleration to verify the equations of kinematics with constant acceleration.

Theory Part 1:

The Atwood Machine consists of a pulley of negligible mass and friction over which two masses are suspended. When the suspended masses are unequal, the system will accelerate in the direction of the larger mass.



Figure 1

move, see if it will move if you *very gently* tap the larger mass. If the system still does not move, continue adding masses and tapping the heavier mass until the system does move. Record the additional mass required to start the system moving.

In this experiment you will measure the acceleration and compare to the acceleration predicted by Newton's 2nd Law. For the purpose of this experiment, we will consider the acceleration to be constant. The system will begin at rest, at position y above the table. For Part 1, you will measure the distance y and the time t required for the system to fall to the table. The system's acceleration can then be calculated using kinematics equations.

Procedure Part 1:

Use a length of string such that, when one mass holder is on the table, the other is between 50 cm and 60 cm above the table. Make sure that one mass holder is directly in front of the meter stick.

Measure the initial mass on each holder, including the holder. Record the initial values:

m_1 _____ g

m_2 _____ g

These numbers should initially be (approximately) equal.

While gently holding the system (place your finger under the mass holder), obtain a difference of 1 gram between the sides. Let go of the mass holder to see if the system moves. If the system does not

1. With an equal total mass on each side, remove a 10 gram mass from the side farthest from the meter stick (m_2) and add it to the side in front of the meter stick, m_1 , thus making the mass difference between the two 20g.

2. Pull m_2 (the light side) down to the table and hold it in place. Read the distance of m_1 (the heavy side) above the table by sighting across the bottom of the mass holder to the meter stick.
3. Record this distance in the data table as y .
4. Release the lighter mass; the heavier mass will then fall to the table.
5. Use a stopwatch to determine the time required for the heavier mass to fall.
6. Record the time in the data table as t . Perform a total of five trials.

Return the 10g mass to m_2 , remove the 20g mass from m_2 , and add it to m_1 so that m_1 is 40 g heavier than m_2 . Repeat steps 2-6.

Add the 10g mass to m_1 from m_2 so that m_1 is 60 g heavier than m_2 . Repeat steps 2-6.

You should now have three sets of data, each having five values for y and t .

Data Part 1:

Mass required to start the system moving: _____

SET 1

Trial	y (m)	t (s)	a_y (m/s ²)
A			
B			
C			
D			
E			

$$\langle a_y \rangle = \underline{\hspace{2cm}}$$

$$\sigma_{a_y} = \underline{\hspace{2cm}}$$

SET 2

Trial	y (m)	t (s)	a_y (m/s ²)
A			
B			
C			
D			
E			

$$\langle a_y \rangle = \underline{\hspace{2cm}}$$

$$\sigma_{a_y} = \underline{\hspace{2cm}}$$

SET 3

Trial	y (m)	t (s)	a_y (m/s ²)
A			
B			
C			
D			
E			

$$\langle a_y \rangle = \underline{\hspace{2cm}}$$

$$\sigma_{a_y} = \underline{\hspace{2cm}}$$

Analysis Part 1:

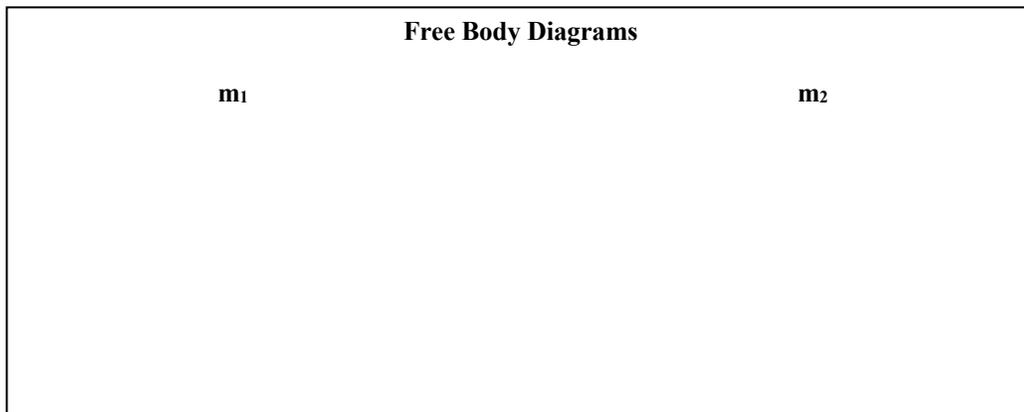
Using the equation: $y = \frac{1}{2} a_y t^2$ and the values that were obtained for y and t ; compute five values of a_y for each of the data sets. Don't forget to change y from cm to m in your equation.

Compute the average value of a_y for each of the data sets. These will be taken as the experimental values of acceleration.

Compute the standard deviation of a_y for each of the data sets.

Apply Newton's 2nd Law to an Atwood's Machine and derive a formula for the expected acceleration in terms of m_1 and m_2 . Start by making a free body diagram in the box below. The instructions following that diagram will help you find the theoretical equations for a_y .

Consider each mass as a separate object and draw a free body diagram for each. Note that all forces act in the y -direction.



Write $\sum F_y = ma_y$ for each of the masses to obtain two linear equations that include the acceleration of each mass.

$$= m_1 a_{1y}$$

$$= m_2 a_{2y}$$

Solve the resulting system of linear equations to obtain a theoretical value for a_y . Note that the masses are constrained to move together, so $a_{1y} = a_{2y} = a_y$! (Note that absolute value signs may be needed in this equation, depending on what axes you are using; see your TA or professor if you need clarification. For a good example of how this is handled in the PHYS 1011 textbook (Walker, 4th edition), see the Atwood Machine problem on page 168-169. For PHYS 2111, see Example 10-3 in the Tipler & Mosca textbook.)

Using your values for m_1 and m_2 , compute the expected acceleration for each of your three trials. These will be taken as the theoretical values of acceleration.

Theoretical Accelerations Part 1:

Set 1: $m_1 =$ _____ $m_2 =$ _____ $a_y =$ _____

Set 2: $m_1 =$ _____ $m_2 =$ _____ $a_y =$ _____

Set 3: $m_1 =$ _____ $m_2 =$ _____ $a_y =$ _____

Compute the % error between the experimental and the accepted values of acceleration. Summarize your results in the table below:

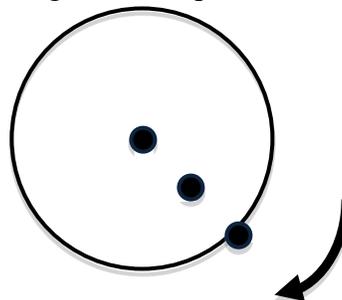
Results:

Data Set	a_y (theoretical)	a_y (experimental)	% error
#1			
#2			
#3			

Theory Part 2:

The pulley in the Atwood machine rotates. Both the rotational velocity (ω , measured in revolutions per second) and the rotational acceleration (α , measured in revolutions per second squared) can be related to the linear velocity and the linear acceleration, by the equations; $v = \omega r$ and $a = \alpha r$. Consider three points on the pulley, one at the center, one at the edge and one in-between these points. Which one travels the fastest? Remember from geometry that the circumference of a circle is $2\pi r$. So each point travels $2\pi r$ in one revolution. The point at the edge has a larger r so it rotates the fastest, even though all three points have the same rotational velocity.

All three points have same rotational velocity, but different linear velocities.



Procedure Part 2:

For this part of the lab you will use the laptop connected to your set up. Save the Data Studio file to the computer Desktop. Once you have the laptop on and the sensors plugged in, you can double click on the saved file to open the Data Studio program. If you need to find it later, the program can be found in the 'Education' folder under the programs in the start menu. To start taking measurements, click on the run button on the upper tool bar. The lab TA will provide more instruction. If you make a mistake with the program you can start over by closing the program without saving and opening it again from the Desktop.

For this experiment the spokes in the pulley act as on/off switches. The radius of the pulley is 1 inch or 0.0254 meters.

1. With an equal total mass on each side, remove a 10 gram mass from the side farthest from the meter stick (m_2) and add it to the side in front of the meter stick, m_1 , thus making the mass difference between the two 20g.
2. Pull m_2 (the light side) down to the table and hold it in place
3. On the program display click the start button.
4. Release the lighter mass; the heavier mass will then fall to the table.
5. On the computer display click the stop button.
6. Use the acceleration graph to determine α . To do this use highlight most of the points that correspond to the time it is falling (in motion). You should be able to distinguish these points from the other points by jumps or breaks in the graph. Only the highlighted points are now included in the statistical results. Record the average angular acceleration of the trial in the data table as α . Perform a total of five trials.

Return the 10g mass to m_2 , remove the 20g mass from m_2 , and add it to m_1 so that m_1 is 40 g heavier than m_2 . Repeat steps 2-6.

Add the 10g mass to m_1 from m_2 so that m_1 is 60 g heavier than m_2 . Repeat steps 2-6.

You should now have three sets of data, each having five values for α .

Data Part 2:

Radius of pulley in meters: _____

SET 1

Trail	α (rad/s ²)	a_y (m/s ²)
A		
B		
C		
D		
E		

$$\langle \alpha \rangle = \underline{\hspace{2cm}}$$

$$\langle a \rangle = \underline{\hspace{2cm}}$$

SET 2

Trail	α (rad/s ²)	a_y (m/s ²)
A		
B		
C		
D		
E		

$$\langle \alpha \rangle = \underline{\hspace{2cm}}$$

$$\langle a \rangle = \underline{\hspace{2cm}}$$

SET 3

Trail	α (rad/s ²)	a_y (m/s ²)
A		
B		
C		
D		
E		

$$\langle \alpha \rangle = \underline{\hspace{2cm}}$$

$$\langle a \rangle = \underline{\hspace{2cm}}$$

Analysis Part 2:

Using the equation $a = \alpha r$ and the values that were obtained for r and α , compute five values of a_y for each of the data sets.

Compute the average value of a_y for each of the data sets. These will be taken as the experimental values of acceleration.

Compute the % error between the experimental and the accepted values of acceleration, using the theoretical values determined in part 1. Summarize your results in the table below:

Results Part 2:

Data Set	a_y (theoretical)	a_y (experimental)	% error
#1			
#2			
#3			

Questions:

1. The pulley is not, in fact, frictionless and massless. At the beginning of the lab you found the mass difference needed to start movement of the system. How can this data be used to approximate the effect of friction?
2. What are possible sources of error in measuring the values of t and y ? What effect will these errors have on your results? Suggest a possible change to the procedure that could eliminate these errors.
3. Which data set in Part 1 produced the most accurate value of a_y ? Why? What about in part 2, which data set has the most accurate value of a_y ? Why?
4. Which data set in Part 1 produced the most precise value of a_y ? Why?
5. What value of a_y would Newton's 2nd Law predict as m_1 becomes **much larger** than m_2 ? Why would this value be expected? *Hint:* consider $\lim_{m_1 \rightarrow \infty} \frac{m_1 - m_2}{m_1 + m_2}$.

EXPERIMENT 4 ~ FRICTION

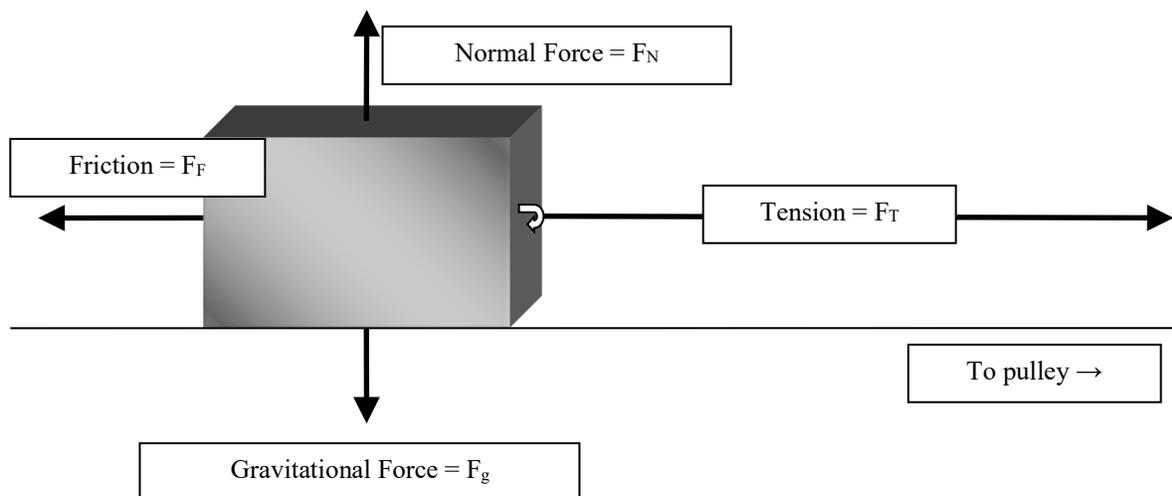
Purpose:

In this lab, you will make some basic measurements of friction. First you will measure the coefficients of **static friction** between several combinations of surfaces using a heavy block and a set of hanging masses. Next, you will measure the coefficient of **kinetic friction** between two of the combinations of surfaces you used in the static friction part of this experiment. You will also measure the **critical angle** at which some of the objects begin to slide, and compare that to the coefficients of friction you measured.

Part 1: Static Friction

Theory:

The coefficient of static friction μ_s can be measured experimentally for an object placed on a flat surface and pulled using a known force. The coefficient of static friction is related to the *Normal Force* F_N of the object on the surface, when the object *just begins to slide*. Using what we have covered in class, you can **derive this relationship** yourself!



Hint #1: The normal force F_N and the weight mg (gravitational force) are equal. Why?

Hint #2: The force of friction F_F is equivalent to the normal force F_N times the coefficient of friction μ .

Equipment:

Wooden Flat Plane
Large Steel Block + Wood Panel with Velcro
Hanging Mass Set
Pulley

Experiment:

Test two different combinations of materials; steel/wood and one other combination of materials: wood/wood, or Velcro/wood. Record the material of the block for each combination.

1. Place the block on the plane and begin adding small amounts of mass to the mass holder until the point when the block begins to slide.
2. Record the mass and material in the following data tables. Take the mass off the hanger and repeat Part 1 two more times for each combination of materials. Record all the measurements in the tables below.

Block/Ramp: _____

Block/Ramp: _____

Mass of Block (kg): _____

Mass of Block (kg): _____

Normal Force (N): _____

Normal Force (N): _____

Trial #	Mass of hanging weight (kg)	Coefficient of Static Friction (μ_s)
1		
2		
3		
Avg.		
Std.Dev		

Trial #	Mass of hanging weight (kg)	Coefficient of Static Friction (μ_s)
1		
2		
3		
Avg.		
Std.Dev		

3. Remember that in class we said that friction does not depend on surface area. You can easily test whether or not this is correct. Choose a block/ramp combination of steel/wood already tested. Place the block so that the side with the smaller surface area is in contact with the board. (Note that this is the smaller surface, not the smallest surface.)

Area of Block Face: _____

Area of Block Face: _____

Mass of Block (kg): _____

Mass of Block (kg): _____

Normal Force (N): _____

Normal Force (N): _____

Trial #	Mass of hanging weight (kg)	Coefficient of Static Friction (μ_s)
1		
2		
3		
Avg.		
Std.Dev		

Trial #	Mass of hanging weight (kg)	Coefficient of Static Friction (μ_s)
1		
2		
3		
Avg.		
Std.Dev		

Critical Angle

You learned in lecture that, for any given coefficient of static friction μ_s , an object will slide when it is placed on an incline at an angle determined by $\theta = \tan^{-1}(\mu_s)$. From your calculations of the coefficient of static friction above, calculate

Expected Critical Angle for Block/Ramp Combination 1 = _____

Expected Critical Angle for Block/Ramp Combination 2 = _____

(Note: you can use the average values of μ_s from the tables at the top of the page above to do these calculations.)

Now, remove the pulley and the added weight. Place the block on the ramp, and slowly tilt the ramp up until the block starts to slide. Measure the angle at which it begins to slide. (Hint: measure the length of the ramp and the height to which you have raised the end you are lifting. These make two sides of a right triangle. You should be able to figure out the angle from that...)

Measured Critical Angle for Block/Ramp Combination 1 = _____

Measured Critical Angle for Block/Ramp Combination 2 = _____

Part 2: Kinetic Friction

Theory:

You can calculate the coefficient of kinetic friction, μ_k using a variation of the method you used for the coefficient of static friction. For the coefficient of kinetic friction, you can use the same free body diagram as the one drawn on the first page. Now, the combination of the force of tension and the force of friction will need to add up such that the block will slide at a constant speed or with zero acceleration. Think of Newton's first and second laws when you set up this equation.

Experiment:

You can measure μ_k using a procedure similar to the one you used to measure μ_s . This time, just pick two combinations of materials. The combinations you pick for this part of the experiment **have to be combinations you already used for the static friction part of the experiment, because the point is to compare μ_s and μ_k !**

The pulley on the ramp rotates. Both the rotational velocity (ω , measured in revolutions per second) and the rotational acceleration (α , measured in revolutions per second squared) can be related to the linear velocity and the linear acceleration, by the equations; $v = \omega r$ and $a = \alpha r$. For a more detailed explanation see the previous lab. So the block and the pulley should have the same acceleration, (assuming the string is not slipping on the pulley).

Procedure Part 2:

For this part of the lab you will use the laptop connected to your set up. Save the Data Studio file to the desktop. (The .ds file can be downloaded from the Lab Connection tab on the UMSL Physics Department website.) Once you have the laptop on and the sensors plugged in you can double click on the saved file to open the Data Studio program. If you need to find it later the program can be found in the 'Education' folder under the programs in the start menu. To start taking measurements, click on the run button on the upper tool bar. The lab TA will provide more instruction. If you make a mistake with the program you can start over by closing the program without saving and opening it again from the Desktop.

For this experiment the spokes in the pulley act as on/off switches. The radius of the pulley is 1 inch or 0.0254 meters.

1. Hold the block on the plane and add the same amount of weight that you had recorded from the Procedure Part 1. For instance, if 275 g got the metal/wood started for the static friction measurement start this experiment with 275 g.
2. Start recording the data by clicking on the run button.
3. Release the block; if it doesn't move give it a flick or a tap in the right direction.
4. Stop the recording. By highlighting only the data points which indicate movement, find the average acceleration.
5. Take away 10 grams and repeat the experiment. The goal now is to try to minimize the acceleration. If taking away mass causes the system to stop moving on its own, then add weights back on to the mass holder.
6. Record the mass and material in the following data tables. Take the mass off the hanger and repeat part 1 for the next set of block/ramp material. Record all the measurements in the tables below.

Analysis:

Calculate the mean value and standard deviation of the coefficient of kinetic friction that you measured, for each set of materials.

Block/Ramp: _____

Block/Ramp: _____

Mass of Block (kg): _____

Mass of Block (kg): _____

Normal Force (N): _____

Normal Force (N): _____

Trial #	Mass of hanging weight (kg)	Coefficient of Kinetic Friction (μ_k)
1		
2		
3		
Avg.		
Std.Dev		

Trial #	Mass of hanging weight (kg)	Coefficient of Kinetic Friction (μ_k)
1		
2		
3		
Avg.		
Std.Dev		

Questions:

1. How do the values of μ_s compare to the values of μ_k ? (Of course, you can only compare them for the same pairs of materials.)
2. Is the relationship between μ_s and μ_k what you expected? Explain.
3. Of the two parts of the experiment, measurement of μ_s and measurement of μ_k , which had more sources of error? What were some of the sources of error?
4. Could μ_k or μ_s ever be greater than 1? Explain.
5. Is the coefficient of friction the same as when the block was standing on its larger (or smaller) end? Is one value within one standard deviation of the other?
6. Do your measured and calculated critical angle values agree? Would the critical angle change if the mass of the block were changed?

EXPERIMENT 5 ~ THE WORK ENERGY THEOREM

Purpose:

The objective of this experiment is to examine the conversion of work into kinetic energy, specifically work done by the force of gravity. The work-kinetic energy theorem equates the net force (gravity, friction, air resistance, etc.) acting on a particle with the kinetic energy gained or lost by that particle.

Theory:

In physics, mechanical work is the amount of energy transferred by a force. Like energy, it is a scalar quantity, with SI units of joules. The term work was first coined in the 1830s by the French mathematician Gaspard-Gustave Coriolis.

According to the work-energy theorem if an external force acts upon an object, causing its kinetic energy to change from KE_1 to KE_2 , then the mechanical work (W) is given by

$$W = \Delta KE = KE_2 - KE_1 = \frac{1}{2} m \Delta(v^2)$$

where m is the mass of the object and v is the object's speed.

The mechanical work applied to an object can be calculated from the scalar multiplication of the applied force (F) and the displacement of the object parallel to the force. This is given by the dot product of F and the total displacement vector d ,

$$W = \vec{F} \cdot \vec{d} = Fd \cos \theta.$$

The techniques for calculating work can also be applied to the calculation of potential energy. If a certain force depends only on the distance between the two participating objects (force of gravity), then the energy released by changing the distance between them is defined as the potential energy, and the amount of potential energy lost equals minus the work done by the force,

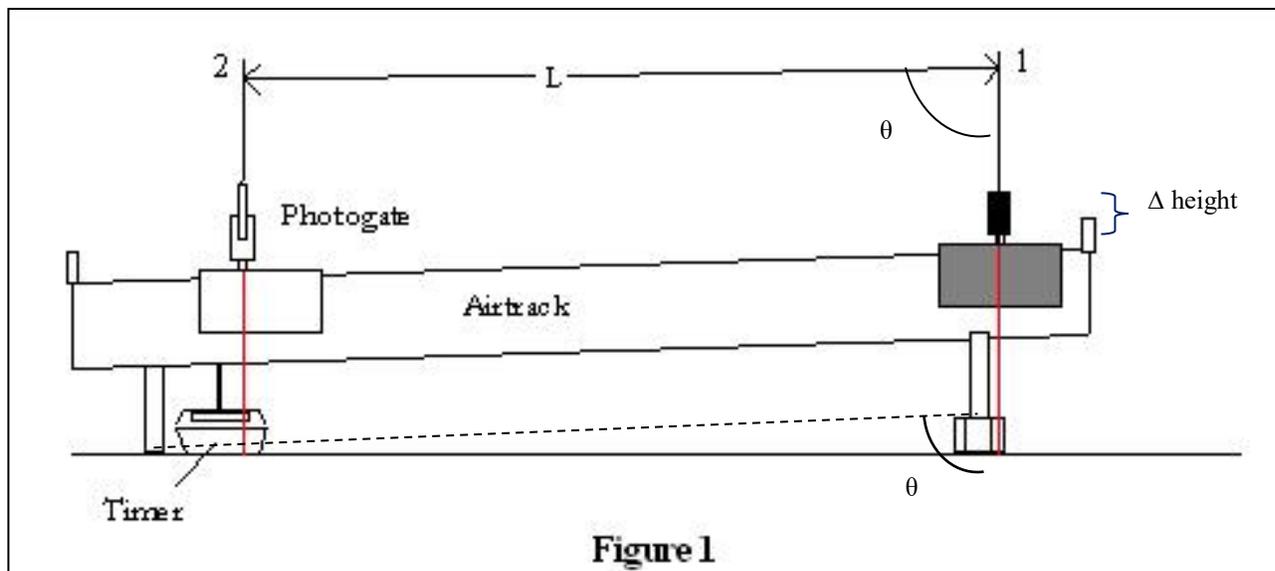
$$\Delta PE = -W = mg(h_f - h_o).$$

By using a nearly frictionless set up such as the air track and glider we can reduce the amount of friction that is parallel to the motion. Therefore what we hope to measure is a result of only the gravitational force.

Experimental Procedure:

Use the block to prop one end of the air track up as shown in figure 1. Place the photo gate near the lower leg of the track.

By using trigonometry, similar triangles, you can calculate the angle theta (as indicated in the diagram) that your air track makes with the vertical line. (HINT: You can measure the height of the block (adjacent) and the distance between the air track's feet (opposite) then use trig.)



Measure or record the following quantities for your air cart and air track setup.

Mass m of your air cart:	$m = \underline{\hspace{2cm}}$ kg
Distance L (=s) from release point to photo gate:	$L = \underline{\hspace{2cm}}$ m
Angle θ of your air track:	$\theta = \underline{\hspace{2cm}}$ °

The photo gate is to be set to measure the amount of time the sensor is blocked.

Q1. When sending the air cart through the photo gate, what will the distance traveled be? What is its change in height?

For this part of the lab you will use the laptop connected to your set up. Save the Data Studio file to the desktop. The .ds file can be downloaded from the Physics lab site at:

<http://www.umsl.edu/~physics/Lab%20Connection/Mechanics%20Lab/index.html>. Once you have the laptop on and the sensors plugged in you can double click on the saved file to open the Data Studio program. If you need to find it later the program can be found in the 'Education' folder under the programs in the start menu. To start taking measurements, click on the run button on the upper tool bar. The lab TA will provide more instruction. If you make a mistake

with the program you can start over by closing the program without saving and opening it again from the Desktop.

1. Start Data Studio program for the first measurement.
2. Release the air cart from somewhere near the top of the ramp. Record the velocity in Table 1 below.

Repeat the steps 1 and 2 two more times with two 50 g additional weights for each trial.

Table 1

Mass (kg)	Velocity (m/s)	Acceleration (m/s ²)
m=		
+100=		
+200=		

Determine the acceleration of your air cart from your measurements above. Indicate what equations you used to determine this acceleration. (HINT: Think kinematics: Kinematics can be solved as long as you know three variables; which three do you know from this experiment? You don't know t !)

Determine what Newton's 2nd law predicts for the acceleration due to gravity down the frictionless incline:

$$a_x = \frac{F_{\text{net},x}}{m}$$

Note that this acceleration is not equal to g !

Q2. How do your measured and your calculated answers for the acceleration compare? State any causes of error and your percent difference between the two values. Is your percent difference acceptable?

Q3.

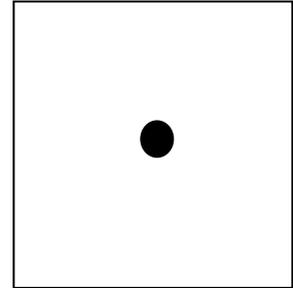
Analysis: Work Energy

- a. Calculate the work done using the change in kinetic energy for each trial.
- b. Calculate the work done by the forces on the air cart using $W = FL \cos(\theta)$ for each trial.
- c. Draw a free body diagram showing all forces acting on the air cart, including the extra force that may be causing a discrepancy between your numbers. Please also state what

the culprit might be and along with your percent error. Remember that the answer to a source of error is not always air resistance. In other words, neglect air resistance even in your answers.

Additional Questions:

4. In the space to the right, draw the free body s diagram for an object of mass 15kg in free fall near the surface of earth. Label all forces. The work done by a force F on an object traveling a distance d is given by $W = Fd \cos (\theta)$. The angle θ is the angle between F and d . What is the angle θ between F and d for the falling object? Calculate the work done on this object by F after it has fallen a distance of 6.8m.



5. If you observed any discrepancies between your two answers (i.e., between $W = \Delta KE = KE_f - KE_o$ and $W = FL \cos (\theta)$) explain where they might have come from. Did you calculate your theoretical work to be greater or less than your experimental measurement (ΔKE) of the work done? If your value for ΔKE is less than your theoretical work, what might have caused this discrepancy?
6. Did the acceleration of the cart change when you added mass? Why? Did your energy change when you added mass? When did you observe the most energy (i.e. what mass)?

EXPERIMENT 6 ~ CONSERVATION OF LINEAR MOMENTUM

Purpose:

The purpose of this experiment is to reproduce a simple experiment demonstrating the Conservation of Linear Momentum.

Theory:

The momentum p of an object is the product of its mass and its velocity:

$$p = mv.$$

Momentum is a vector quantity, since it comes from velocity (a vector) multiplied by mass (a scalar). The law of conservation of momentum states that the total momentum of all bodies within an isolated system,

$$P_{\text{total}} = p_1 + p_2 + \dots,$$

is constant. That is, if the total momentum has some initial value p_i , then, whatever happens later, the final value of the total momentum p_f must equal the initial value. So we can write the law of conservation of momentum like this:

$$p_f = p_i$$

Conservation of momentum is usually studied in problems that involve collisions. In this experiment, you'll look at collisions between two gliders on an air track. You will measure the final momentum of an initially stationary glider, struck by another glider which is initially moving. You'll do this experiment for two different types of collisions, elastic and inelastic. Elastic collisions are ones where kinetic energy is conserved (the objects bounce off each other without losing any energy). Inelastic collisions (e.g., if the objects get stuck together) do not conserve kinetic energy. The kinetic energy of an object is defined as

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

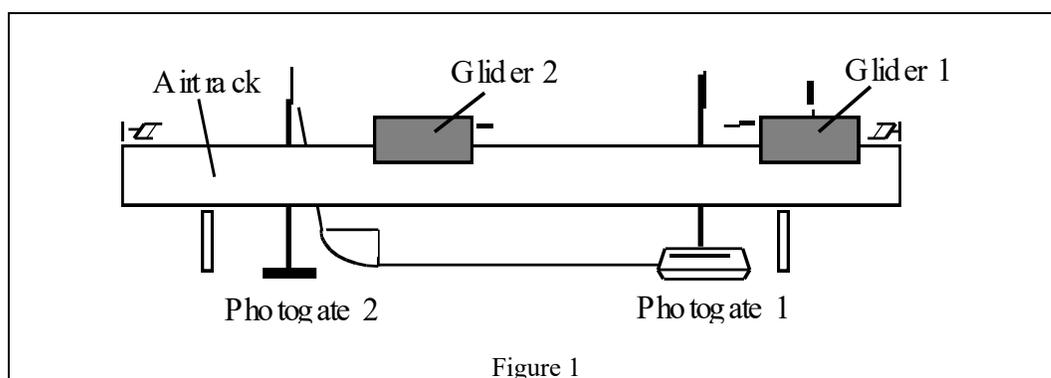
where m is the object's mass and v is its velocity. Kinetic energy is not a vector: it's a scalar, and its units are Joules (J).

Part I: Inelastic Collisions

Equipment:

Before you begin this experiment, you have to make sure the air track is level. First, turn the air supply on. Place a glider in the middle of the track with no initial velocity. Adjust the leveling screws until the glider remains in its initial position, not accelerating in either direction. The glider may oscillate slightly about its position. This movement is caused by air currents from the air holes in the track and should be considered normal.

Figure 1 illustrates the experimental method used for observation of inelastic collisions. Glider 2, fitted with a Velcro impact pad (to make the gliders stick together!), will be positioned at rest between Photo gate 1 and Photo gate 2. Glider 1 will be fitted with a measurement flag and a needle.



Experiment:

For this part of the lab you will use the laptop connected to your set up. Save the Data Studio file to the desktop. The .ds file can be downloaded from the Physics lab site at:

<http://www.umsl.edu/~physics/Lab%20Connection/Mechanics%20Lab/index.html>. Once you have the laptop on and the sensors plugged in you can double click on the saved file to open the Data Studio program. If you need to find it later the program can be found in the 'Education' folder under the programs in the start menu. To start taking measurements, click on the run button on the upper tool bar. The lab TA will provide more instruction. If you make a mistake with the program you can start over by closing the program without saving and opening it again from the Desktop.

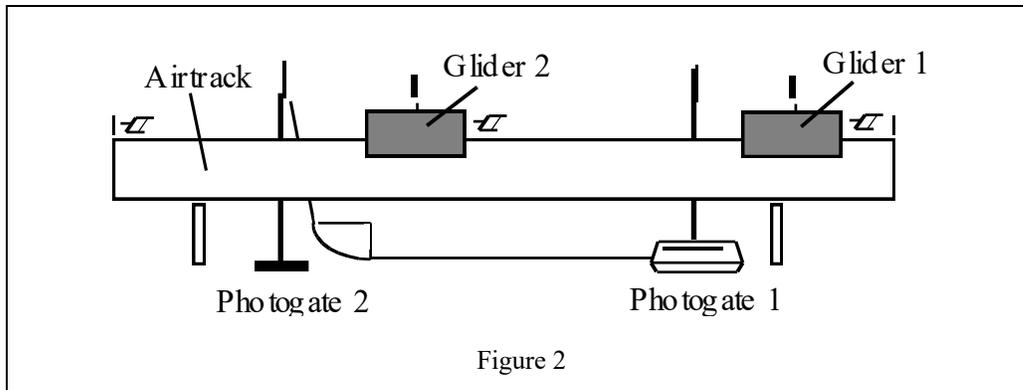
Start recording the data for the first measurement.

- Give Glider 1 a push. As it passes through Photo gate 1, a time interval (the "before" time) will be measured. The velocity and momentum of Glider 1 can be computed from time data measured and the mass of the glider.
- Once Glider 1 strikes Glider 2, the two should stick together. The resulting momentum of the coupled Gliders 1 and 2 can be computed from their total masses and the velocity measured at Photo gate 2 (the "after" time). Once the gliders have stuck together, you can treat them as a single object. Since the recorder is measuring time, the velocity recorded is automatically computed using the 2.5 cm flag width (Δx).
- Do this experiment a few times, and record your data.

Part II: Elastic Collisions

Equipment:

Figure 2 illustrates the experimental method used for observation of elastic collisions. In this part of the experiment, you'll observe the momenta (plural of momentum!) of a pair of gliders before and after an elastic collision. Keep the photo gates in the same positions as in the first part of the experiment. Remove the Velcro pads from the gliders. Attach rubber bumpers to Gliders 1 and 2, and then position Glider 2 at rest between Photo gate 1 and Photo gate 2. Both Gliders 1 and 2 will be equipped with vertically positioned-measurement flags.



Experiment:

Clear the previous data runs. Make sure that Glider 2 (the one that is going to be hit) is placed between the two photo gates. Glider 1 should be outside the photo gates (see Figure 2). The first time measurement ("time before") will be made by giving Glider 1 a push. Push it gently (we'll explain why in a moment). As Glider 1 passes through Photo gate 1, a time interval will be measured. The initial velocity, momentum and kinetic energy of Glider 1 can be computed from the velocity measured, and from the mass of Glider 1.

→ Now, this is why you want to push Glider 1 gently. You want it to hit Glider 2 so that Glider 2 will start moving, but Glider 1 will stop moving. Think of a situation where one pool ball hits another and then stops – but the second ball, the one that was hit, starts moving. That's what you want to do with the gliders. Basically you are transferring all the kinetic energy of Glider 1 to Glider 2! ←

The second velocity you will measure is the velocity of Glider 2 as it passes through the second photo gate. This is our "time after". The momentum and kinetic energy of Glider 2 can be computed from the velocity measured, and from the mass of Glider 2.

Data and Calculations:

$$m_1 = \text{ ______ kg}$$

$$m_2 = \text{ ______ kg}$$

Equation for initial and final momentum:

$$(mv)_o =$$

$$(mv)_f =$$

Equation for initial and final kinetic energy:

$$KE_o =$$

$$KE_f =$$

V (m/s) =d/t		mv (Kg m/s) (momentum)		$\frac{1}{2}mv^2$ (J) (kinetic energy)	
Before	After	Before	After	Before	After

Analysis:

Part I: Inelastic collisions

1. For each run of your inelastic collision experiment, calculate the percent difference between the initial momentum and the final momentum. Does your data indicate conservation of momentum?
2. For run of your inelastic collision experiment, calculate the percent difference between the initial energy and the final energy. Does your data indicate conservation of energy?
3. List some possible source of error in this part of the experiment. Are these sources of error random or systematic?

mv (kg m/s) (momentum)		% difference	$\frac{1}{2}mv^2$ (J) (kinetic energy)		% difference
Before	After		Before	After	

Part II: Elastic collisions

1. For each run of your elastic collision experiment, calculate the percent difference between the initial momentum and the final momentum. Does your data indicate conservation of momentum? Is the “before” velocity of Glider 1 equal to the “after” velocity of Glider 2? Why or why not?

2. For run of your elastic collision experiment, calculate the percent difference between the initial energy and the final energy. Does your data indicate conservation of energy?

3. List some possible source of error in this part of the experiment. Are these sources of error random or systematic?

mV (kg m/s) (momentum)		% difference	$\frac{1}{2}mv^2$ (J) (kinetic energy)		% difference
Before	After		Before	After	

EXPERIMENT 7 ~ ROTATIONAL AND TRANSLATIONAL ENERGIES

Purpose:

The objective of this experiment is to examine the conversion of gravitational potential energy to different types of energy: translational, rotational, and "internal" kinetic energy.

Theory:

Energy In: If an object of mass m slides or rolls down a total vertical distance Δh along an inclined plane, its gravitational energy decreases by $U=mg(\Delta h)$ during its downward trip. The lost gravitational potential energy is converted into other types of energy, such as kinetic energy.

Note that if the object is traveling a distance L along the inclined plane, the total vertical distance it covers is $\Delta h=L \sin \theta$, where θ is the angle of the incline. Draw a sketch to convince yourself that this is true!

Velocity Out: Given the time Δt to traverse a small interval Δd at the end of its trip, you can get a very rough estimate of the object's final velocity: $v=\Delta d/\Delta t$.

Kinetic Energy: An object of mass m will have a translational kinetic energy of

$$K_t = \frac{1}{2}mv^2 \quad (1)$$

If the object is a ball or a cylinder, it will also have rotational kinetic energy!! Remember that

$$K_r = \frac{1}{2}I\omega^2 = \frac{1}{2}I\frac{v^2}{r^2} \quad (2)$$

where r is the radius and I is the moment of inertia. The moment of inertia of an object depends on its shape and other properties, like whether it is solid or hollow. (See Table 9.1 in the textbook!) For a solid cylinder of radius r , the moment of inertia is

$$I = \frac{1}{2}mr^2 \quad (3)$$

and so, if you substitute Eq. (3) into Eq. (2), you can show that the rotational kinetic energy will be

$$K_r = \frac{1}{4}mv^2. \quad (4)$$

(Do the calculations yourself to make sure you agree!) For a hollow cylinder of radius r , the moment of inertia is

$$I = mr^2 \quad (5)$$

and substituting Eq. (5) into Eq. (2), the rotational kinetic energy becomes

$$K_r = \frac{1}{2}mv^2. \quad (6)$$

Again, check the algebra yourself to make sure you agree.

Other Energy: You might think that, due to conservation of energy the initial potential energy should be converted completely into kinetic energy, which includes both rotational and translational energy. So, since

$$E_{initial} = E_{final} \quad (7)$$

you could write

$$U = K_t + K_r. \quad (8)$$

But that's not quite true! Not all the initial potential energy is transformed into kinetic energy. Some of it is lost in other ways, to "non-conservative forces" like friction and drag (air resistance). So really,

$$U = K_t + K_r + \Delta E \quad (9)$$

where ΔE is this "extra" energy.

Equipment:

The experimental setup is diagrammed in Figures 1 and 2, and consists of an elevated air track, photo gate timer, and a removable ramp for the rolling object measurements.

You'll do measurements with three different objects: a glider (which will only have K_t), and two types of cylinder (solid and hollow). The cylinders will have both K_t and K_r .

Use time in tab labeled time in gate. For the glider, the photo gate should be at the level of the flag. For the cylinders, the photo gate should be at a height as close as possible to the diameter of the cylinder (so that the distance that is crossing the photo gate is equal to the diameter of the cylinder).

Experiment:

Glider:

Determine the mass of the glider.

Determine the total change in glider height Δh from its release at the top of the ramp to when it crosses the center point of the photo gate. The glider is going to travel a total distance L as shown in the figure below. You want to determine the height when it starts (point 1) and its height when it reaches the photo gate (point 2). These are the vertical heights shown by the red lines in the figure. The difference between these heights is Δh .

Measure the time interval for the glider to pass through the photo gate. Do this for 5 trials. Record the data in the table below.

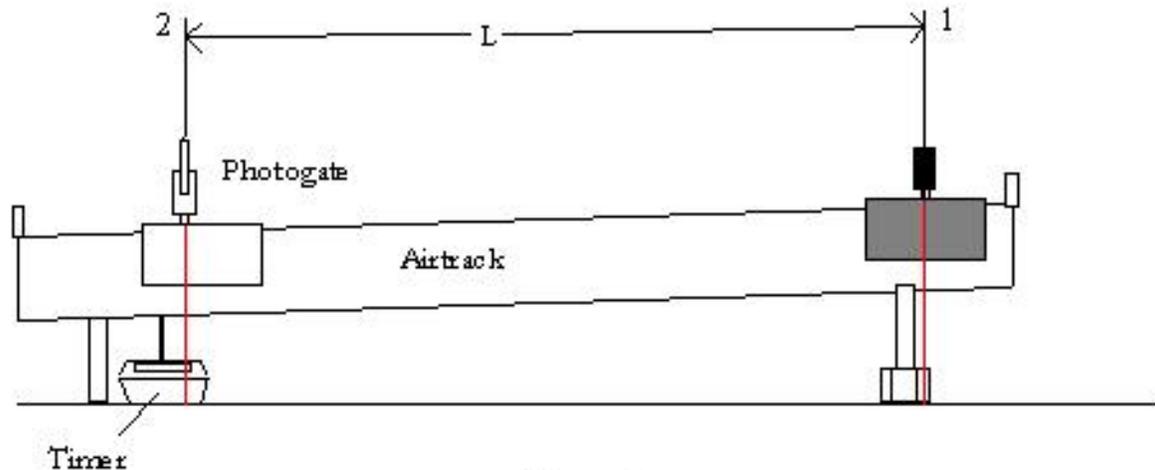


Figure 1

Solid cylinder:

Determine the mass of the solid cylinder.

Determine the total change in the cylinder's height Δh from its release at the top of the ramp to when it crosses the center point of the photo gate. Use the same procedure as for the glider to do this, measuring the height at the top of the ramp and the height at the bottom of the ramp, and taking their difference.

Measure the time interval for the solid cylinder to cross the photo gate. Do this for 5 trials. Record the data in the table below.

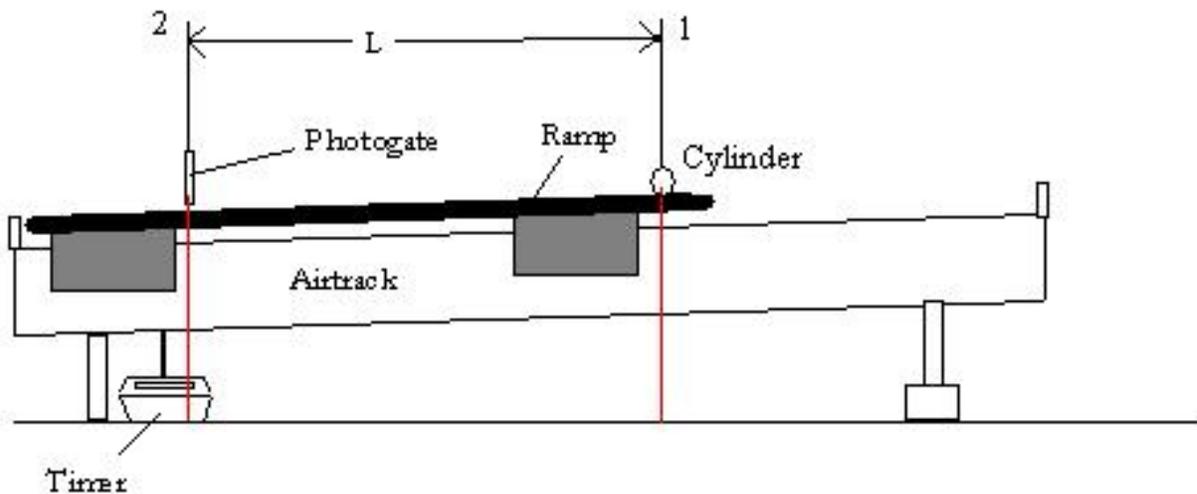


Figure 2

Hollow cylinder:

→ Use the time between Gates for this part of the experiment. (From what you know about how the photo gate timers work, can you figure out why? Hint: Think about how the photo gate is triggered, and about what the hollow cylinder's cross section looks like compared to the cross section of the solid cylinder. This affects which diameter you need to use for the hollow cylinder!)
←

Determine the mass of the hollow cylinder.

Determine the total change in the cylinder's height Δh from its release at the top of the ramp to when it crosses the center point of the photo gate. Use the same procedure as for the glider to do this, measuring the height at the top of the ramp and the height at the bottom of the ramp, and taking their difference.

Measure the time interval for the hollow cylinder to cross the photo gate. Do this for 5 trials. Record the data in the table on the next page.

Analysis Part I:

Glider:

Length of object passing through photo gate (glider flag) $d =$ (m)

$\Delta h =$ (m) mass = (kg)

t (s)

$$t_{\text{avg}} =$$

$$\sigma_t =$$

$$v = d/t_{\text{avg}} =$$

Solid cylinder:

Length of object passing through photo gate (cylinder diameter) $d =$ (m)

$\Delta h =$ (m) mass = (kg)

t (s)

$$t_{\text{avg}} =$$

$$\sigma_t =$$

$$v = d/t_{\text{avg}} =$$

Hollow cylinder:

Length of object passing through photo gate (cylinder diameter) $d =$ (m)

$\Delta h =$ (m) mass = (kg)

t (s)

$$t_{\text{avg}} =$$

$$\sigma_t =$$

$$v = d/t_{\text{avg}} =$$

Analysis Part II:

Now you have the height and final velocity for each of the objects, and you can calculate the changes in their energies using the equations derived in the “Theory” section above.

Glider:

Potential energy lost:

$$U \text{ (formula) =}$$

Translational kinetic energy gained:

$$K_t \text{ (formula) =}$$

$$\% \text{ of initial potential energy =}$$

Additional loss of energy due to friction:

$$\Delta E = U - K_t =$$

$$\% \text{ of initial potential energy =}$$

Solid Cylinder:

Potential energy lost:

$$U \text{ (formula) =}$$

Translational kinetic energy gained:

$$K_t \text{ (formula) =}$$

$$\% \text{ of initial potential energy =}$$

Rotational kinetic energy gained:

$$K_r \text{ (formula) =}$$

$$\% \text{ of initial potential energy =}$$

Total kinetic energy:

$$K_{\text{tot}} = K_t + K_r =$$

$$\% \text{ of initial potential energy =}$$

Additional loss of energy due to friction:

$$\Delta E = U - K_{\text{tot}} =$$

$$\% \text{ of initial energy =}$$

Hollow Cylinder:

Potential energy lost:

$$U \text{ (formula) =}$$

Translational kinetic energy gained:

$$K_t \text{ (formula) =}$$

$$\% \text{ of initial energy =}$$

Rotational kinetic energy gained:

$$K_r \text{ (formula) =}$$

$$\% \text{ of initial energy =}$$

Total kinetic energy:

$$K_{\text{tot}} = K_t + K_r =$$

$$\% \text{ of initial energy =}$$

Additional loss of energy due to friction:

$$\Delta E = U - K_{\text{tot}} =$$

$$\% \text{ of initial energy =}$$

Once you have completed your calculations you can check your work by downloading the Excel spreadsheet from:

<http://www.umsl.edu/~physics/Lab%20Connection/Mechanics%20Lab/index.html>

Questions:

1. For the glider, are U and K_t equal? Should they be equal? If there is a difference between them, what might be the cause of the difference?
2. For the solid cylinder, is there any mechanical energy lost to friction?
3. For the hollow cylinder, is there any mechanical energy lost to friction?
4. For which of the three objects is ΔE the largest? Can you give any hypothesis as to why?
5. Which object showed the most efficient conversion of gravitational potential energy to translational kinetic energy? Why?
6. Which object showed the most efficient conversion of gravitational potential energy to rotational kinetic energy? Why?
7. Which object showed the least efficient conversion of gravitational potential energy to total kinetic energy? Why?
8. List some sources of error in the experiment. What types of error are they?
9. Do you always need to measure the mass of two objects in order to compare their energies? Explain why or why not?
10. For the glider part of the experiment, we used an air track. Why? Suppose you had the glider just sliding down the incline? What would have been different? How might that have affected your energy calculations?

EXPERIMENT 8 ~ PERIODIC MOTION AND RESONANCE

Purpose:

The purpose of this experiment is to reproduce a simple experiment demonstrating the natural resonance frequency of a mechanical system and compare experimental vs. theoretical results.

Theory:

The motion of a particle or a system of particles is periodic (also called oscillatory, or harmonic) if it repeats itself in equal time intervals. Some examples of periodic motion are the swinging motion of a pendulum, the vibration of atoms in a solid lattice, or the vibration of the strings on a harp. The path of an oscillating particle can often be described by sine and cosine functions. Sines and cosines are “harmonic” functions; therefore the oscillation of the particle is called harmonic motion. If the turning points of the motion are equally spaced about the origin (meaning that the equilibrium position is at the origin), the motion of the particle is called simple harmonic motion. For simple harmonic motion, the particle's position as a function of time takes the following form:

$$x = A \cos (\omega t + \phi).$$

The constant A is the amplitude of the motion. It is the distance between the equilibrium position and the turning points (maximum, minimum) of the motion. The equilibrium position is the point at which no net force acts on the oscillator. The constant ω is the angular frequency and ϕ is the phase constant of the motion. The phase constant determines at what time the particle reaches its maximum displacement. Angular frequency and linear frequency are related by the expression

$$\omega = 2\pi f.$$

Frequency, f , is the repetition rate of the motion and its reciprocal is the period, T , the amount of time it takes the system to complete one cycle. If the oscillator is the pendulum on a clock, the period can be measured directly by noting the amount of time it takes the pendulum to swing from one end of its path to the other and then return to its original position. If, however, the oscillator is the vibrating string on a musical instrument, the period is too small to measure with the eye alone. This is the case in this experiment. The frequency of the oscillator will be read from the digital frequency meter of a function generator.

The simple harmonic oscillator for this experiment consists of a mass attached to an ideal, mass less spring which obeys Hooke's Law. The other end of the spring is held in a fixed position. If the mass is initially in the equilibrium position, no motion occurs. If, however, we perturb the system by displacing the mass to one side or the other of its equilibrium position, the restoring force of the spring acts to return the mass to the equilibrium position. Inertia causes the

mass to overshoot the equilibrium position and oscillatory motion results. If there were no friction, this motion would continue forever.

Using the above equation and Newton's Second Law we can derive an expression for ω in term of the mass, m , and the spring constant, k :

$$\omega = \sqrt{\frac{k}{m}}$$

We can rewrite this as

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Notice that the frequency does not depend on the amplitude! This means that the time for one complete oscillation does not depend on how far the mass travels from equilibrium. The independence of frequency on oscillation amplitude holds only if the restoring force is strictly linear (meaning that it follows Hooke's Law).

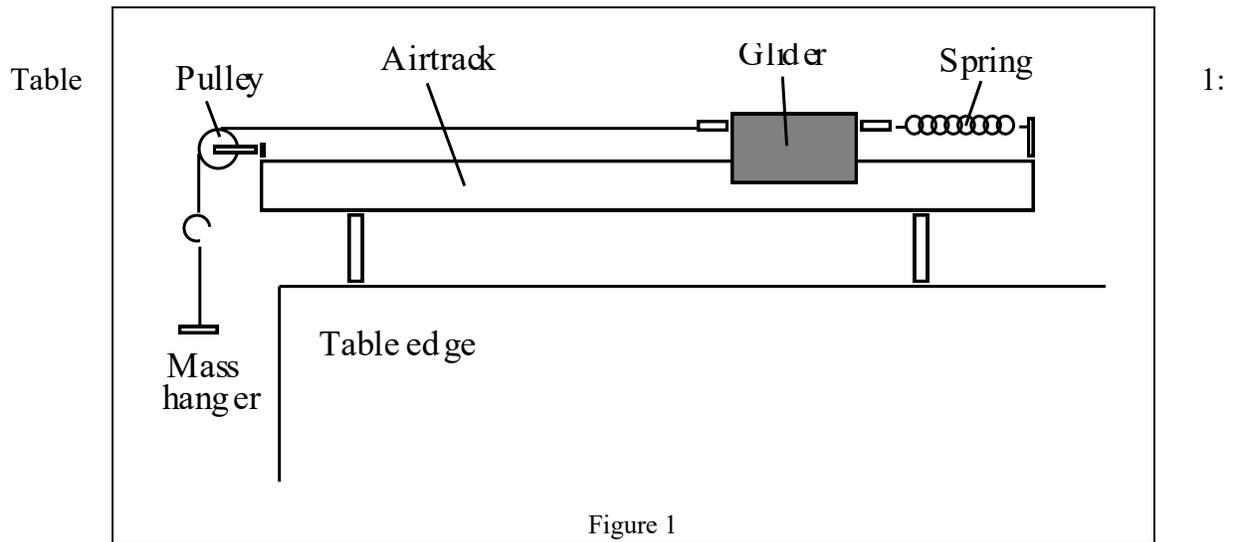
We have ignored the force of friction when deriving the above equation. Friction is present (though minimized by the fact that we are using an air track). For this experiment, we will also add a driving force to balance the force of friction and maintain the oscillations. A driving force is needed to begin the oscillations and to cancel frictional effects. If no driving force were present the amplitude of oscillation would gradually decrease to zero because of friction. (Oscillations that die down to zero because of "damping" force like friction are called damped harmonic motion.)

In this experiment, we will look at a phenomenon called resonance. When the frequency of the driving force is equal to the natural frequency of the oscillator, you will observe the largest displacement of the mass from its equilibrium position. Resonance has been attained, and this frequency is called the resonant frequency.

Experiment:

Part I - Determination of the spring constant k

Arrange the equipment as shown in Figure 1. Turn on the air source to maximum, and then load the mass hanger with different masses. Record each mass you use, and the elongation (displacement) caused by that mass, in Table 1. Be sure to include the mass of the hanger. Compute the force caused by the mass (i.e., mg) and enter that in Table 1 as well. To measure the displacement, first record the equilibrium position of the spring, and then the stretched position. The displacement is the difference between these two values. Be careful not to displace the spring more than 3 or 4 cm from its equilibrium position or you will deform the spring and change its spring constant!



Equilibrium position: _____

Mass	Stretched position	Displacement	Force

Plot a graph of Force (y-axis) vs. Elongation (x-axis), from data Table 1; label this as graph 1. From the data and graph, determine the spring constant, k , of the spring. Ideally the curve fitted to this data should be a straight line; k is simply the slope of this curve. (Look at Hooke's law and you will see why this makes sense.) To make your life easy, you can calculate the slope by fitting a line to the data using Excel.

Spring constant k : _____

Part II Determination of experimental resonance

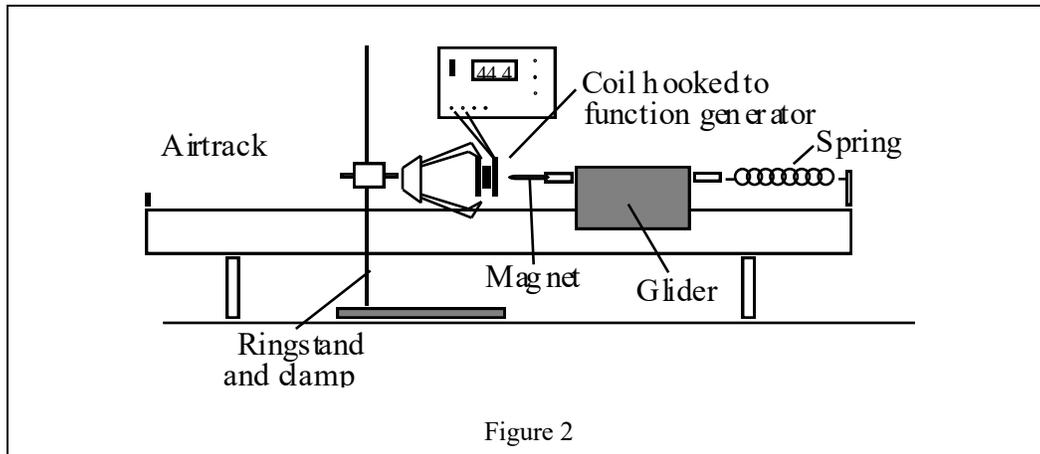


Figure 2

The setup for this part of the experiment is shown in Figure 2. The driving force is a sinusoidal electronic function generator (driving a power amplifier) with a digital frequency meter to provide the readout of the driving frequency. The output of the function generator produces a varying electric current in the coil, which in turn produces a varying magnetic field. This varying magnetic field attracts and repels a permanent magnet/glider assembly that is attached to a spring. The other end of the spring is fixed to the air track. The spring constant, k , and the mass of the magnet/glider will be measured directly. The natural frequency of the system will be estimated by supplying a driving frequency and observing resonance of the system.

Note: When you make your measurements, please don't make pencil or pen marks on the air track assembly!!

1. Turn on the air supply to maximum air pressure, stabilize the glider with your hand, and with all other instruments turned off record the equilibrium position of the glider. Now you can turn on the other instruments. Before taking any data, use the frequency adjustment control to scan through a range of driving frequencies (1Hz to 15 Hz) and observe the changes in the glider / magnet movements on the air track. Resonance of this mechanical system occurs at a frequency where the greatest linear displacement of the glider/magnet is observed. Locate this resonance point by "tuning" the frequency generator until this phenomenon is observed.

Once you have an idea of how resonance occurs in this system, you can start recording data in Table 2. Gradually change the frequency of the drive, and record the amplitude of the motion for each frequency. For the purpose of our experiment we will assume that the excitation signal and subsequent motion of the magnet/glider assembly are symmetrical about the equilibrium point. For each frequency, measure the distance the glider moves in one direction; this distance is the amplitude that you should record and record in Table 2. In order to get a good measurement of the resonant frequency, you need to take about 10 (or more) data points be taken at frequency values slightly greater than the resonant frequency, and 10 (or more) points at frequency values slightly less than the resonant frequency. Of course, you won't know the exact resonance frequency until you finish the experiment, so you will have to make the best guess you can (from your initial "scanning" of the driving frequencies), and then pick frequencies above and below your guessed value.

How do you measure the maximum displacement? The glider is oscillating too fast for you to read the maximum displacement by eye. A good trick is the “index card method” for determining displacement of the glider is suggested in order to improve accuracy. This method requires that you slide an index card along the air track, moving it close to the glider. Find the position of the card where the glider is just about to hit it every time it oscillates. The difference between this position and the equilibrium point gives the amplitude of the motion.

Don't forget to record the mass of the glider + magnet. You'll need this for your calculations later.

Table 2:

Mass of glider and magnet: _____

Equilibrium position (same as in Table 1): _____

Frequency	Card Position	Amplitude

Continued on next page.....

APPENDIX A: EXCEL, THE BASICS!

Note: This tutorial was originally written for Excel 2003. There are a few additional instructions for the Excel 2007 (and later) versions. As it does not fit all versions of Excel, see the Excel help files or ask a lab instructor if you need additional help.

We are going to walk through a few steps to practice (or learn) some important features in Excel. We are going to:

- define some Excel terminology
- learn how to enter data into a spreadsheet
- learn how to calculate mean and standard deviation from the data
- learn how to enter equations into a spreadsheet
- learn how to graph the data in the spreadsheet
- learn how to analyze the data based on the graph

First, the terminology:

When you create a new spreadsheet in Excel, a page will show up with a grid on it. To the left of the grid, there are numbers designating which rows and to the top of the grid, there are capital letters designating columns. Each box is referred to as a 'Cell' and we will consider the upper left cell to be the home cell. So, if you move 4 cells down and 3 cells to the right you would be in cell D5. Cell designations will be important when using equations.

Entering data:

The first task will be to type in some information. All you have to do for this is select a cell and start typing! A good thing to do first is to set up column headers. Simply go to cell 'A1' and type 'L1', cell 'B1' and type 'L2', cell 'C1' and type 'L2-L1'. You can move between cells either by clicking on the new cell where you want to enter information, or by hitting the tab key or up/down/left/right arrows.

Now it is time to enter some data. Type your measurements of l_1 into one column, and l_2 into the next column.

Now, we want to calculate the difference between the two measurements, in order to calculate the length. Excel will do this for you! Select cell C2. Type the following:

=B2-A2

Notice that as you type "B2", cell B2 is highlighted, and as you type "A2", cell "A2" is highlighted! Also notice that as you type in the cell, the equation appears in the formula bar at the top. Now, hit enter, and the difference between the values in cells B2 and A2 will appear...in cell C2!

Now, you want to calculate the difference for each of your pairs of measurements. You could repeat the method we just described, for every row of your data, a very tedious method, but

Excel does have way to speed up this process. The first step to unlock this secret is to select cell C2. Then hit “control C” on the keyboard to select this cell. (You are actually selecting the equation associated with the cell.) Now select cells C2 through C10 (or however many rows of data you have), and hit “control V” on the keyboard. You have just pasted the equation into all the rows! Each cell in column C now contains the difference between the corresponding rows in column B and column A!

What about calculating the average (mean) and standard deviation? Do this by hand, with your calculator (you can do that at home). It is annoying and tedious, but we want you to do it ... just this once. The easier way is with Excel, of course. Suppose you want to put the average value of your measured lengths in cell C11 (or whatever is your first empty cell in column C). Select this cell. Now type this:

```
=AVERAGE(C2:C10)
```

and hit Enter. The average (mean) of cells C2 through C10 will appear in cell C11! (Another trick: instead of typing “C2:C10”, you can select cells C2 through C10, and the cell numbers will automatically appear in your equation!)

What about the standard deviation? Select the cell where you want the standard deviation to appear. Go up to the formula bar, and type:

```
=STDEV(C2:C10)
```

Now hit Enter, and the standard deviation of the numbers in cells C2 through C10 will appear!

You may want to set up your data tables so that they display the correct number of significant digits. To do this, select the cells you want to change. Right click on the selection, and choose ‘Format Cells’. Under the ‘Number’ tab, choose ‘number’, and choose the number of decimal places you want to keep.

Also, you can set up your table with borders. Again, select all the cells you want to put a border around. Right click in the selection, and choose the ‘border’ tab. Click the ‘outline’ and and ‘inside’ buttons, then ok.

Practice Creating a Graph (Using Pretend Data):

Now, let’s do something a bit more complicated. Let’s enter some “pretend” data. Suppose a ball is rolling down an inclined plane. You measure its position at various different time points. Suppose you measure time from 0 seconds to 50 seconds, in increments of 1 second. Let’s enter that data in column D. First, set up column headers. Go to cell D1 and enter “Time”. Go to cell E1 and enter “Position”. Go to cell F1 and enter “Velocity”. Go to cell G1 and enter “Acceleration”.

There are 2 ways to enter the time data. The obvious one would be to go to cell 'D2' and type 0, then cell 'D3' and type 1, etc... Again, a very tedious method, especially at the end of a long day when you want to go home! Again, Excel does have way to speed up things up. Enter 0

in 'D2' and 1 in 'D3'. Next highlight cells 'D2' and 'D3' (do this by clicking on one cell and dragging over to the other). Once you have selected the two cells, let go of the mouse buttons. You will notice in the lower right corner of cell 'B4' there is a small black square. Move the mouse over this square and you will notice that your cursor changes from a white thick plus sign to a black thin plus sign. Once the cursor changes to this black plus sign you can click and drag straight down about 50 cells. You should notice to the right of the mouse a box with a number in it appears. This number represents the value that Excel will enter into the cell for you. When you see that number reach 50, you can let go of the mouse and, like magic, all the cells will be filled with the values you would have otherwise had to type in yourself. This process is known as **autofilling**.

Now, let's work with an equation. Just like what we did for the length data before, to enter an equation, you simply have to choose a cell and hit the '=' key. This tells Excel that you want to use an equation in that cell. The equation you are typing will appear in the function bar as you type it in the cell.

Go to cell 'E2' and hit the '=' key. After the '=' you are free to enter any equation into the cell. For our purposes, we will use the equation $-.1*t^2+4*t$, where '^' designates the use of a power. This equation may seem strange, but you will see it in class in a few days. It shows **how position changes as a function of time for something that is moving at a constant acceleration**. Since our times are in column D, the equation we need, in terms that Excel will understand, is

$$=-0.1*D2^2+4*D2$$

Now hit Enter, and a number will appear in cell E2. Excel has taken the value in cell 'D2' and entered it into your equation. Does the value that showed up make sense? Check it with a calculator.

Now that you have your equation, you can manually type it into each cell or you can use the method for autofilling described before. The only difference is that this time you will not select multiple cells. The reason you selected multiple cells in the previous step was so that Excel could **determine the pattern of the values you wanted**. This time, you have an equation in cell E2, which *already* specifies a pattern. Simply click on the cell with the equation, move the mouse over to the lower right corner and click and drag until you will fill all the cells you have times for.

Do the same thing in column F (velocity) with the equation starting with $'=-.2*D2+4'$ in cell 'F2', and autofill the data into the rest of the columns.

Do the same thing in column G (acceleration) with the equation starting with $'=-.2'$ in cell 'G2' and autofill the data into the rest of the columns.

The 'manual' method of making a scatter plot of data (Vista version):

First, select any blank cell on the Excel spreadsheet to which you want to add a graph. Next, select the "Insert" tab near the top left of the Excel window. A row of new options will appear just below the tabs row. Near the middle of the row of options, you'll see a box labeled "Scatter". Select this and a drop down menu should appear with various scatter graph options. Select the "Scatter with

only Markers" option (The options aren't labeled by name, but the associated picture looks like graphed polka dots. You can check the option by scrolling over the pictures and letting your mouse cursor sit for a second or two). After selecting the desired plot, a blank rectangle will pop up over some of your Excel worksheet, and a new row of options will appear just below the row of tabs.

The blank rectangle will house your plot, but to do so you'll need to first select your data. Select from the options row, "Select Data". A pop-up window "Select Data Source" will appear. Under the section labeled "Legend Entries (Series)" you'll have the choice to "Add", "Edit", "Remove", and two series ordering buttons (up and down arrows). Since no data was selected before opening "Select Data", no series will appear under "Legend Entries (Series)" (this is how the 'manual' method contrasts to the 'automatic' method).

To add a data series, select the "Add" button. A new pop-up window will appear, "Edit Series". Here, you can label your series by clicking in the blank space under "Series name:". Now you can enter what data you want to plot along your x axis and what data you want along your y axis. Your y values should always be your **dependent** variable while your x values should be the **independent** variable. In our case, time is the independent variable. Position, velocity, etc. are CALCULATED FROM TIME, and therefore they are dependent variables ("dependent" on time).

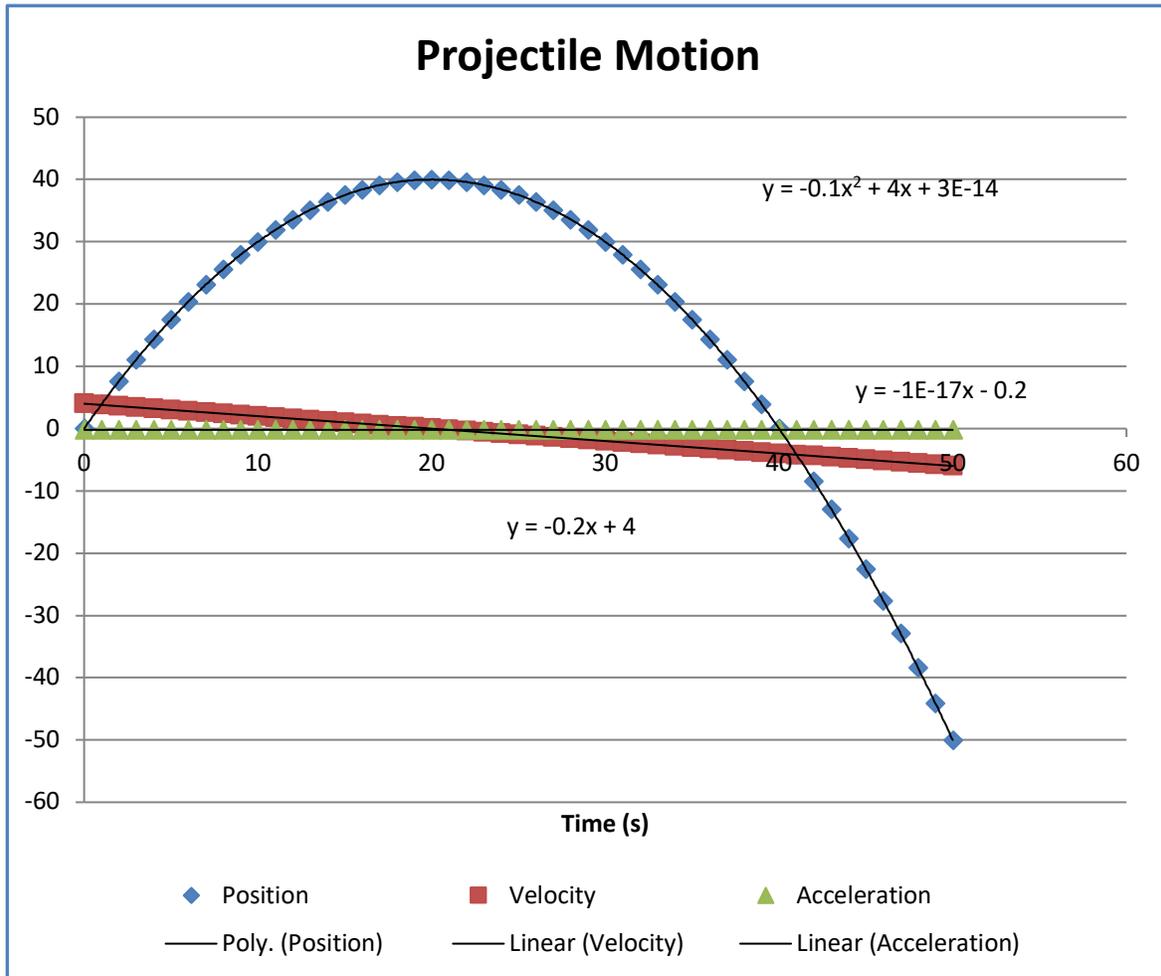
To choose the time column as the for the x axis, select the white space under "**Series X values:**". After clicking in the white box, you need to select the data from your spreadsheet. Simply click on the first value you want plotted and drag down to the last (select all 50 of your time values). When you let go of the mouse button the appropriate code will be entered into the box for you. (Excel won't know what to do if you select multiple rows or columns, so it may fuss at you). Once your desired row OR column is selected, you'll notice that the white space under "Series X values:" is filled in. Next do the same procedure for the box next to '**Y Values:**' To do so, select the white space under "Series Y values:". Delete{1} from this space. Now, you may click and drag over a row OR column on your worksheet which you want to plot along the y-axis, for example, position data. The white space under "series Y values:" will be filled in after you've made your selection, which SHOULD mean you are done selecting some data. Click the "OK" button on the "Edit Series" pop-up window to return to the "Select Data Source" window. Notice that the series you just selected from the worksheet is now under "Legend Entries (Series)".

We now want to add more series to the graph, one for time vs. velocity, and another for time vs. acceleration. To do this simply, **right-click on the chart and select 'Source Data' from the menu**. This will bring up the window we saw in the previous steps. You can rename or select alternative data for a series you have created by selecting your series first and then selecting "Edit". *Make sure you are on the series tab*. Next add a new series and follow the same procedure to add the next columns. Your graph should end up with 3 series on it (i.e., 3 data plots). **An example of what the graph should look like is shown on the following page.**

The 'automatic' method of making a scatter plot of data (2007 version):

First, make sure the cell above each column of data is labeled (for example: above time values, make the cell just above the time data cells say "Time (*you insert appropriate units here*)". Then, with your x-axis values on the left side of your data table (this should be the time values for this example 'experiment'), select ALL columns of data you'd like to plot. The rows to the right of the

time column should be position, velocity, and acceleration for this example. Now, while this data table is selected, click the "Insert" tab near the top left corner of the Excel window. Look for the "Scatter" button near the middle of the row of options. Then select the polka dots of data picture which should represent "Scatter with only Markers". Once you have selected this plot type, a graph should appear over your worksheet with your data series automatically plotted. And that's it besides adding a label for your x-axis and a plot title.



To add axis labels and a chart title (2007 Version):

First select your graph by clicking somewhere in the white space around the legend. Next, select the "Layout" tab. Near the mid left of the options row, the "Chart Title" option will allow you to input a chart title, and the "Axis Titles" option will allow you to input horizontal and vertical axis titles. Once you've selected your desired title(s), you can edit them by clicking on them in your graph.

Our final task, before you get to go home, is to add **trendlines** to the data. Trendlines are useful because they allow us to figure out an equation for data if we do not already know it.

To add a trendline, **right-click on any one of the data points** from the data set you want to add a trendline to. To add a trendline to the position data, right-click on any one of the position data points and a drop-down menu should appear. Select '**Add Trendline**' from the list and a dialog box will appear. The screen that comes up should have a number of boxes with different types of equations you can fit to the data. Depending on which series you clicked on you will have to select the correct type of equation to fit to the data (parabola for position, straight line for velocity and acceleration). Once you have made this selection, click on the '**Options**' tab at the top. Check the box next to '**Display equation on chart**' so that you can actually see the equation Excel used to make the trendline. Click "ok", and your graph should now have a trendline on it with a handy equation.

One more trick you can use is to add error bars to your data. To do this, click on any point in the data set you are interested in. Go to the Format menu, and click "Selected Data Series". A menu will appear where you can select the error bars you want to add. This way you can plot data points and show their standard deviation on the same plot. Your plots should look something like the previous graph: