Physics 4A
Lab Exercises

De Anza College
Version 2.0

Additional equipment is required.
See the preface inside.

By David Newton

TABLE OF CONTENTS

PREFACE

The following set of lab exercises provide a starting point for the exploration of lab processes in a physics environment. The exercises are not all necessarily just one week long; some may take two weeks or more. At the instructors discretion some labs may be deleted. The order of the labs may also be changed. This booklet is designed to be used in conjunction with the "LAB SKILLS MANUAL" which must be purchased separately. It is in the LAB SKILLS MANUAL that laboratory procedure is defined. This work is only a collection of experiments, not an explanation of techniques. The experiments should be read and studied by the student before the lab commences.

The first two labs (VERNIER and DENSITY) may be performed on the same day, time allowing. There is a detailed and substantial explanation of the air track before any of the air track labs. It is imperative that this introduction be thoroughly read and studied by the student *and* instructor before any air track labs are performed. Failure to do so may result in damaging the air track equipment. A short multiple choice quiz is available for the instructor to give to students to check their having read the air track introduction. Please see David Newton to obtain this quiz.

LAB EQUIPMENT REQUIREMENTS:

Every student must bring to the lab a minimum of required equipment:

1. A **lab note book** (which may or may not be kept in the laboratory for the entire quarter). The note book must be of the size: 10" X 7 7/8", be "quadrille ruled", and either one of two style numbers: 26-151 or 26-251 or 43-475.

2. A **ruler**. A #36 "C-thru" ruler (or anything else that is better) is acceptable.

3. A **scientific calculator**. Trig and log functions required. (Statistical functions up to standard deviation are recommended)

4. A **pen and pencil**.

5. The LAB SKILLS MANUAL and this book, 4A LAB EXERCISES.

Please refer to the LAB SKILLS MANUAL for more detail about laboratory procedure.

LAB BOOK EVALUATION FORM

At your instructor's request, please tape the form below into the front inside cover of your lab book.

Physics Lab Record Evaluation

Name_________________________ Course___________ Section____

Lab Recording Skills	1	2	3	4	5	6
1. Establish Experimental Objective Devise Tentative Plan						
2. Draw Detailed Diagrams and Discuss Theory						
3. Collect and Organize Data						
4. Thoroughly Analyze Data Sample Calculations						
5. Make Good Graphs with Title Label Axes, Proper Scales & Size						
6. Discuss Results Error Analysis						
7. Compare Results with Theory Draw Valid Conclusions						
8. Compose a Readable, Sequential, Detailed, Direct-Recorded Record						

1. THE VERNIER SCALE

Equipment List:

- 3 X 5 card
- one vernier caliper
- one ruler incremented in millimeters

What you will learn:

This lab teaches how a vernier scale works and how to use it.

I. Introduction:

A vernier scale (Pierre *Vernier*, ca. 1600) can be used on any measuring device with a graduated scale. Most often a vernier scale is found on length measuring devices such as vernier calipers or micrometers. A vernier instrument increases the measuring precision beyond what it would normally be with an ordinary measuring scale like a ruler or meter stick.

II. How a vernier system works:

A vernier scale slides across a fixed main scale. **The vernier scale shown below in figure 1 is subdivided so that ten of its divisions correspond to nine divisions on the main scale.** When ten vernier divisions are compressed into the space of nine main scale divisions we say the *vernier-scale ratio* is 10:9. So the divisions on the vernier scale are not of a standard length (i.e., inches or centimeters), but the divisions on the main scale are *always* some standard length like millimeters or decimal inches. A vernier scale enables an *unambiguous* interpolation between the smallest divisions on the main scale.

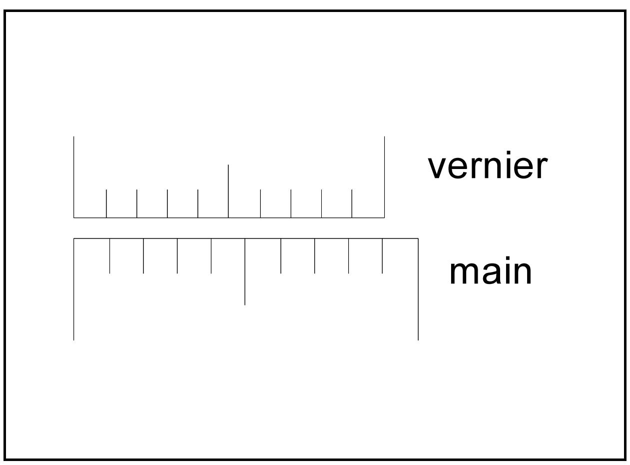

Figure 1: Ten vernier divisions in the space of nine main scale divisions, a scale ratio of 10:9.

Since the vernier scale pictured above is constructed to have ten divisions in the space of nine on the main scale, *any single division on the vernier scale is 0.1 divisions less than a division on the main scale*. Naturally, this 0.1 difference can add up over many divisions. For example, after six divisions have been spanned by *both* scales, the difference in length between the vernier and main scale would be 6 X 0.1 = 0.6 divisions.

In figure 2 below, both the vernier and main scale start evenly at the left. After a distance of six increments they differ in length by 0.6 increments as is indicated by the two dotted lines.

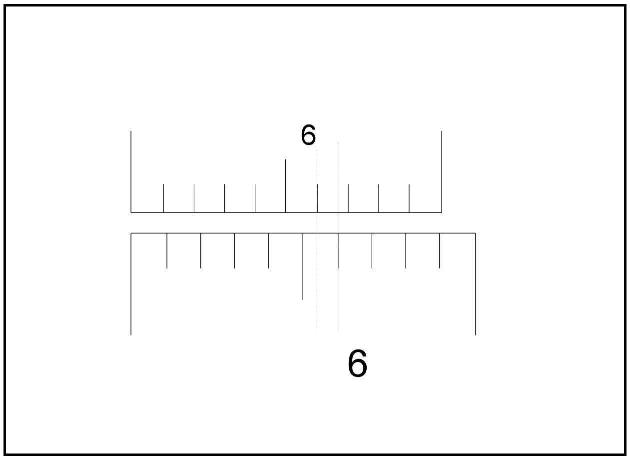

Figure 2: In the span of six divisions, the difference between the vernier and main scale is 0.6 divisions.

In practice, the **left** sides of the two scales are not matched up as above. Instead, the two left sides of each scale are *offset* by an amount corresponding to the length measured. In figure 3, the two scales are still off by 0.6 divisions as in figure 2 above, however in figure 3 the scales match up along the dotted vertical line on the right side instead of matching up on left side as in figure 2. In figure 3, we would say the two dotted vertical lines on the left side of the figure are separated by 0.6 divisions of length in the same sense that the two lines in figure 2 are separated by 0.6 divisions. Study and compare figures 2 and 3 to understand how a vernier system works.

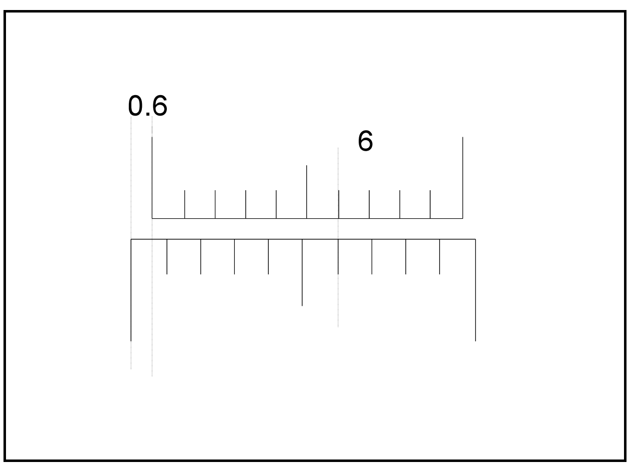

Figure 3: A length at the left has a 0.6 division difference also.

III. Measuring an object's length the vernier way:

In measuring the length of an object with vernier calipers, the first two significant figures are read from the main scale. Find where the left edge of the vernier scale crosses the main scale and record the corresponding values immediately so you don't forget them. In figure 4 on the next page, you should confirm that the first two significant figures of the measurement are 2.7 units. This information could be obtained without using a vernier; this is just standard measuring procedure. It is the third significant figure that must be obtained using the vernier scale.

In figure 4, see that the vernier and main scale divisions align where the **vernier** scale reads 0.4. Actually, in terms of the total instrument this corresponds to a value of 0.04 units, **not** 0.4. Thus, the measurement of the box's length would 2.74 units.

See that the first two numbers are read from the main scale and the third number from the vernier. Confirm the full measurement in figure 4.

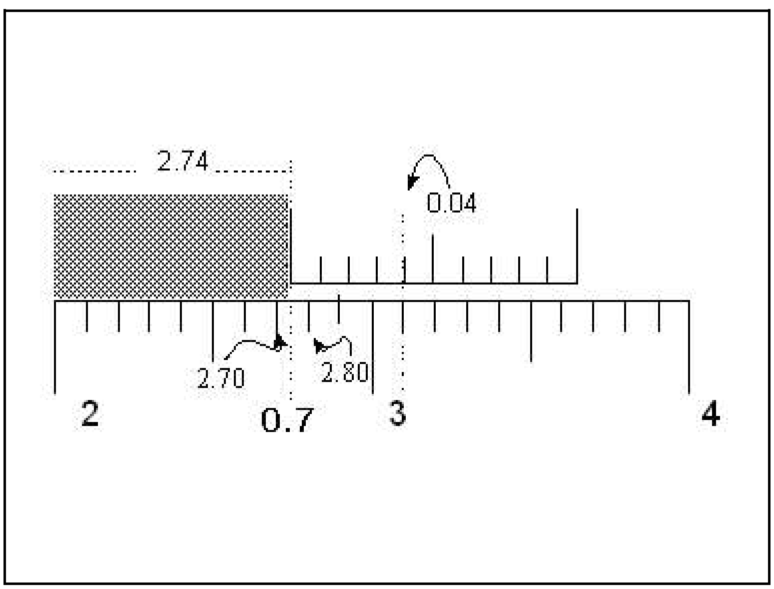

Figure 4: The box is 2.74 units long.

IV. Using the vernier calipers provided: In figure 5 below, the relation between the vernier and main scale is not one of ten in the space of nine but of twenty in the space of nineteen. This increases the precision of the instrument.

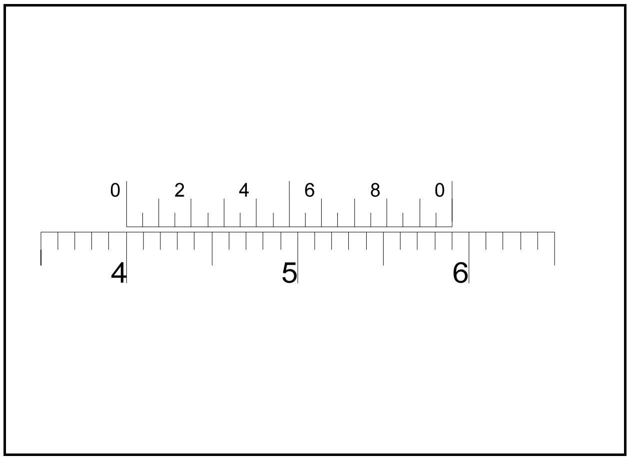

Figure 5: The calipers you will use have 20 divisions in the space of 19. The scale ratio is 20:19.

V. The absolute uncertainty of your vernier calipers: You will note a 1/20 mm (one twentieth of a millimeter) printed on the right side of the main scale. 1/20 mm corresponds to 1/200 of a centimeter or in decimals, 0.005 cm. Take this value to be the absolute uncertainty in your scale reading, although some people prefer to use 0.003 cm instead, the choice is yours. Below in figure 6, the reading to three significant figures would be 4.26 cm. But notice the two increments between the vernier and main scale are not perfectly aligned. You should interpolate the vernier scale to read to *three* decimal places. Confirm the reading to be about (4.259 ± 0.005) cm and see that it is not 4.261 cm since the left-side zero mark on the vernier scale is *closer* to the left side zero on the main scale and so the reading is *smaller* in value than 4.260.

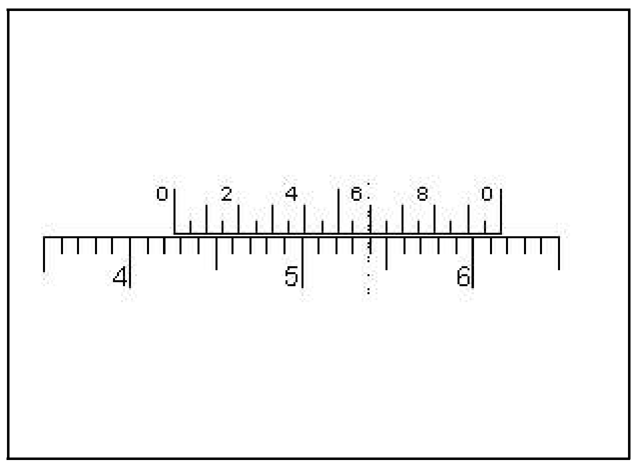

Figure 6: This value is 4.26 cm to three sig figs or 4.259 to four sig figs.

VI. Making your own vernier scale:

1. Take two 3 X 5 cards provided by your instructor.

2. Using your ruler and a sharp pencil, mark the **top** edge of one card once every centimeter starting from the left edge of the card all the way to the right side. The very left edge of this card will be the "zero". Every centimeter mark after the zero will be labelled 1, 2, 3, and so on. Write at the bottom of this card: "MAIN SCALE". Examine figure 7 for a rough idea of what you are to do.

3. Take the second card and place it before you on the lab table. At the **bottom** of this card mark an increment every *nine millimeters* starting at the left most edge. Mark ten increments only, each separated by *nine millimeters*. Label each increment with a 1, 2, 3, and so on until you reach 10. Label this card "VERNIER SCALE".

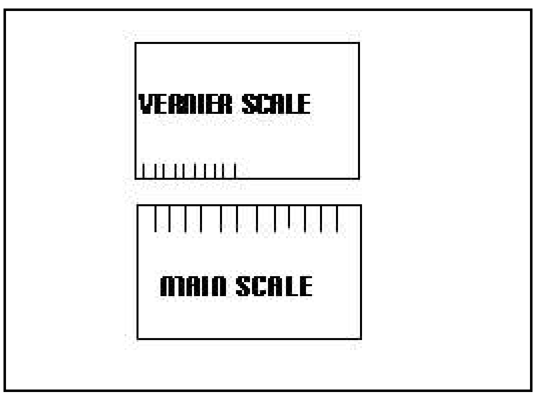

Figure 7: Your own personal vernier calculator. You should number your divisions as well.

4. You have made your first (and last?) vernier scale which will measure an interpolation of the main scale to a tenth of a centimeter (one millimeter). For one more significant figure, you could interpolate the vernier scale as well.

Use your hand made vernier to measure the two lines found below, and confirm your measurement with your ruler to the nearest millimeter. Place the left edge of your MAIN SCALE card at the left edge of the line. Then place the **left** edge of your VERNIER SCALE at the **right** edge of the line. Record the length of the line to two decimal places in centimeters (i.e., 2.34 cm).

1.))))) 2.))))))))))

The correct answers are written upside down at the bottom of this page. Measure the lines first before you look at the answers.

1. 2.

2. DENSITY AND MEASUREMENT

Equipment list:

- One aluminum block (record its number)
- Vernier Caliper (record its serial number)
- Triple beam mass balance (record the number)
- A squared brass block (optional)
- One digital balance

How to use the triple beam balance: The balance should be "zeroed" before each use. Make sure the pointing arm at the right side of the scale oscillates evenly up and down about the reference mark on its right. You should **gently** push the arm to induce the oscillations. Never take a reading without moving the arm; static friction might hold the arm in place and prevent an accurate reading.

The two larger sliding weights should each be placed securely in the notches along the balance's arm when taking a measurement. The smallest sliding weight has no notches but moves continuously along its arm; this allows a precise reading.

By examining the scale, you should confirm that the least count of the balance is 0.1 grams. You should interpolate to values less than this and since the absolute uncertainty is equal to one half the least count, a typical reading from this balance would be interpolated to the *hundredth* of a gram for a value of say, (154.23 ± 0.05) grams.

How to use the vernier calipers: The vernier calipers provided have two different scales, decimal inches and centimeters, we will use the centimeter scale only.

Before measuring an object, you should push the jaws of the caliper completely closed and confirm that the vernier measures a zero length. If it does not measure zero, a systematic error will be introduced into all your measurements and you should correct all your measurements by this amount. When measuring the length on an object, you should cinch up the jaws onto the object securely and snugly. Your vernier calipers have beveled (angled) edges at the tip of its "jaws". Use these beveled edges to take your length measurements. **Don't slide the vernier scale across the main scale unless you are pressing in the "thumb stop".** Not pressing the thumb stop increases the friction of the vernier against the main scale so the vernier will not slip when you are taking a measurement.

Theory: All matter has mass, the measure of inertia. Any object has its mass contained in a definable volume. Density (ρ) is the measure of how much mass is contained in an object's volume:

Density = Mass/Volume

$$\rho = M/V$$

Purpose: The purpose of part I is to measure the *mass* of your aluminum block three different ways and compare the values. The purpose of part I is *not* to measure the density of aluminum.

Procedure:
Part I: The Aluminum block

Attention: Aluminum is a soft metal and can easily be scratched or nicked if handled carelessly. Please be careful not to drop or bang your aluminum block, since this *may* change its dimensions and effect the accuracy of your measurements.

In this part of the lab you are to determine the mass of the aluminum block three different ways and then compare the three different calculated masses and their absolute uncertainties.

1. Measure the mass of the block on the pan balance *five different times*. Use the statistical method discussed in the LAB SKILLS MANUAL to find the most probable value and its absolute uncertainty for the mass of your block.

2. Measure the mass of the block on the digital balance. Record the absolute uncertainty as well.

3. Solving the density equation given above for mass, we see the mass of a body can be computed if we know its density and volume. Measure the volume of your block. To do this, measure the length, height, and width of your block with the vernier calipers provided. Each measurement will have an uncertainty; record the uncertainty in your lab book with the measurement. Justify the uncertainty's value. Given the density of aluminum[1] and the volume determined by computation, compute the mass of the block and its absolute uncertainty.

Analysis: Discuss how all three calculations of mass overlap when their uncertainties are considered. Discuss your confidence in the accuracy of each calculation. Which of the three mass values has the greatest precision?

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[1] Known value: D_{Al} = 2.699 g/cm^3 at room temperature.

Part II: Measuring the density of brass.

Note: Brass, like aluminum, is also soft. Please be careful not to drop or bang your brass block as it may change its dimensions.

Obtain a brass block from the lab cart. Measure its mass and volume with the greatest precision based on previous results. Calculate its density with an absolute uncertainty. Determine, if possible, what kind of brass you have. Defend your assertion.

Yellow Brass (70% Copper, 30% Zinc):

cast: 8.44 g/cm^3;
rolled: 8.56 g/cm^3;
drawn: 8.70 g/cm^3

3a. THE BEHR FREE FALL EXPERIMENT

Note: An alternative Behr free fall lab can be found at the end of this one. It is less involved and may be more approachable than the following. See your instructor to find which of the two labs you are to do.

Equipment List:

- One Behr Free Fall Apparatus and spark timer (A back-up unit is desirable).
- One two-meter stick per table.
- Masking tape.
- Red wax paper tape with Behr Free Fall data on it produced by the apparatus.

What you will do:

By a graphical method, you will find the instantaneous speed of a falling object at three different times during its flight (this is part I). Then, by a different graphical method, you will find each of those three speeds with three other graphs, one graph for each speed (parts II, III, and IV). The three speeds in part I should match the corresponding speeds found in parts II, III, and IV.

Introduction:

The Behr Free Fall apparatus produces a written record of a freely falling object's position ***at equal intervals of time***. The falling object is called the "bob". The bob falls a distance of about five or six feet. Falling from rest this would allow for a total time of flight of: $t = [2\cdot\Delta y/g]^{½} \cong 0.6$ seconds (derive and confirm this). Since the bob is in flight for about half a second, for the bob to leave a trace of its position at equal intervals of time, the intervals of time must be very short. These small time intervals are produced by a "spark timer".

A spark timer is a high voltage mechanism that produces a spark which, as the bob falls, arcs across the bob and through a waxed paper tape making a small burn hole (a dot) in the paper. To produce the thirty or so total dots in the paper when only a total time of 0.6 seconds is allowed, sparks must be generated every one sixtieth of a second. We will assume the spark timer produces a spark *exactly* every one sixtieth of a second. **So each dot is separated by an equal interval of time.**

Although the initial speed of the bob is zero (it *does* fall from rest), the first dot produced on your paper tape is *not* created while the bob is at rest. Since the bob has to travel some distance from its rest position to where the first dot is made, the bob must have a non-zero speed when the first dot is created. We will determine this initial speed.

Since it is difficult to produce an arc through the paper, every now and then your paper tape may have a dot (or many dots) missing. When you receive your paper tape, inspect it immediately for missing dots. You should have thirty dots on your paper. Even if you are missing some dots, your paper tape may still be usable as discussed below. What really matters is that you have at least five positions each separated by equal intervals of time.

Procedure:

1. Under the direction of your instructor, obtain one red paper tape of a "run". Check the tape and replace it if there are dots missing. Be careful during the operation of the apparatus since **very high voltage** is used to create the arc that burns the wax paper tape.

2. With the masking tape provided, tape down each end of the paper tape on your lab table so that it is taut and lies flat with the light colored side facing up showing all the small burned dots.

3. Starting from the beginning of the tape where the dots are close together, draw a circle around the first dot and then every *sixth* dot after that for a total of **five** circled dots.[2] Be careful circling your dots; it is easy to miss one and that would throw all your data measurements off. **These five circled dots will be your only data points for the *entire* experiment.** Since you are not using all thirty dots produced by the apparatus, you need not have all thirty dots present on your paper tape for it to be acceptable. Your instructor may help determine if your paper tape is still acceptable with some missing dots.

4. On the paper tape, label each of the five circled dots X_0 through X_4. Where X_0 refers to the *first* dot made by the spark.

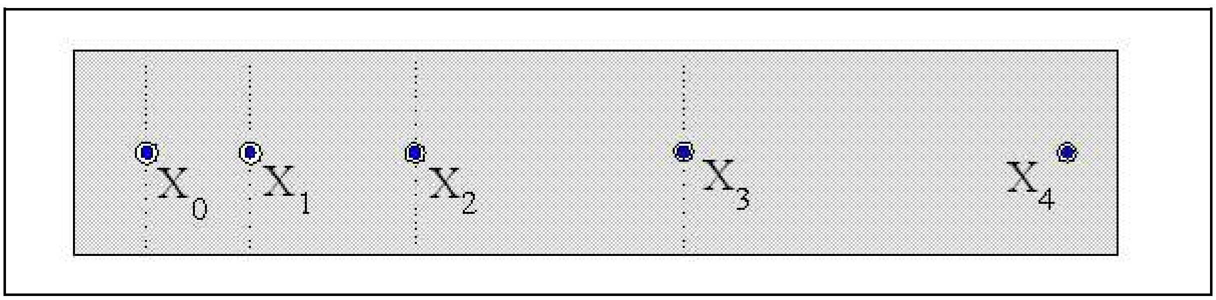

Figure 1: Circle every sixth dot for a total of five circled dots. The time interval between every sixth dot is 6 X 1/60 of a second or 1/10 of a second.

For each circled dot, draw a thin line through the dot such that the line is perpendicular to the lengthwise direction of the tape. Draw the line across the entire width of the tape (see figure 1, above).

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[2] Some instructors prefer to circle every third dot or every other dot; check with your instructor to see if you should modify any procedures.

5. **Please read this next section entirely before recording any data.**

Take your two-meter stick and place it *on edge* (to minimize parallax error) aligning it with the length of the paper tape. Place the meter stick near the dots but do not cover the dots. The meter stick should be kept parallel to the line made by all thirty dots. If no two-meter sticks are available, you will have to use a one-meter stick and move it as necessary. Do not place the meter stick at a pre-chosen position like its end edge or the one centimeter mark, doing so merely prejudices your data measurements, something to be avoided. Place the meter stick down at an arbitrary position so the position of the first dot will be the smallest value of your five positions but not some "even" or easy-to-read value.

Draw a position versus time graph *<u>while you take each data point</u>* and check to see if you have skipped any dots. Before you start taking your data, plan the scale of your graph so that it will cover at least a half page of your lab book. Relative to the meter stick, note the positions of the first and last circled dots so you can approximate the vertical axis scaling, and for the horizontal axis scaling, recall that the time interval between each circled dot is 0.1 seconds. You will know if you skipped any dots if the curve described by the data points becomes non-parabolic. **Record *<u>and graph</u>* the position of the five circled dots.** You should interpolate the measurement on your meter stick to read positions to the one hundredth of a centimeter. Write down the absolute uncertainty associated with your measurement. Let the first position be graphed at time t = 0; the first position itself should not be a zero value but should be the value you measured on your meter stick.

<u>Analysis:</u>
<u>Part I:</u> Finding instantaneous speeds from a tangent line on a position versus time graph. On your position versus time graph drawn while you took your data, use your ruler to draw an "eyeball" tangent line to the parabolic curve at each position X_0, X_2, and X_4. Measure the slope of each of your three straight lines. Interpret the physical meaning of each line.

<u>Part II:</u> Finding the instantaneous speed V_0 at the initial position X_0 and calculating g.

The following method is important to understand as it forms the basis for the analysis of parts II, III, and IV.

The goal of this analysis is to show a limit process by graphical methods and, by *extrapolating* the graph, to find an instantaneous speed. In this part we will also determine the value of *g* from the graph.

We know the definition of instantaneous speed as a limit:

$$v_{inst} = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t}$$

If we plot **average speeds** on the y-axis and corresponding **time intervals** on the x-axis, then it is possible to see that the average speed approaches an instantaneous speed as the time intervals approach zero. On the graph the time intervals approach zero as the data points approach the vertical axis. Understand that this kind of graph is *not* the classic *instantaneous* speed versus time graph that is typically discussed in kinematics; the graph we will use is an *average* speed versus a time *interval*. Study the graph on the next page to help understand this.

As an example, a sample data/calculation table for a hypothetical Behr Free Fall experiment is given on the next page. The acceleration that produced this data is not equal to *g* and the time interval between dots is 0.5 seconds not 0.1, but the calculations used are identical to those needed in constructing your graphs. These calculations would be used to find the initial instantaneous speed V_0 at the position X_0. When you graph $\overline{V}_{ij}$ versus Δt_{ij} (you will have four data points to graph from *five* measured positions) a linear relation should be observed.

From the table, you should observe that the first average speed is calculated between the first two circled dots at positions 2.25 and 2.53 cm. Since the time interval between these positions is half a second, the average speed is:

$$\overline{V}_{01} = (X_1 - X_0)/\Delta t_{01} = (2.53-2.25)/0.5 = 0.56 \text{ cm/s}$$

You should confirm the other calculations in the table to test your understanding. Your graph is a graph of $\overline{V}_{ij}$ versus Δt_{ij}. Notice that in calculating the different average speeds the position of the dot where we want to find the instantaneous speed is always part of the calculation. Notice also that the average speeds increase as the position between the dots increases and the time interval between the dots increases; this is natural since the bob *is* speeding up as it falls - its average speed is increasing.

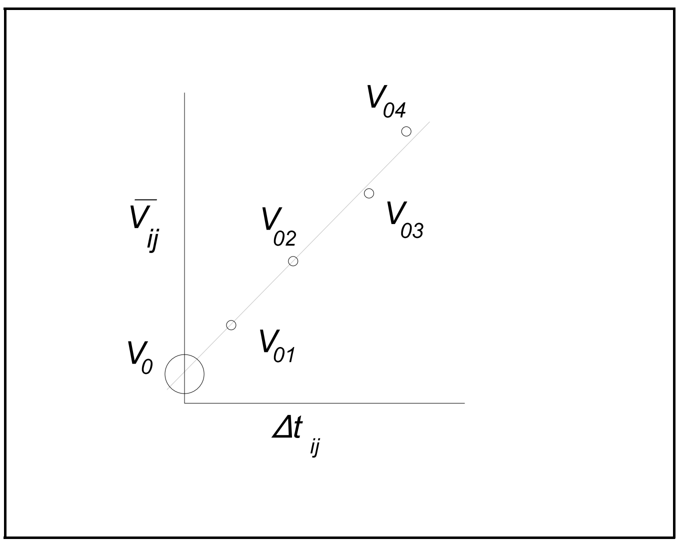
To further aid your understanding, the next data point in the graph would be calculated as follows:

$$\overline{V}_{02} = (X_2 - X_0)/\Delta t_{02} = (3.35-2.25)/1.0 = 1.10 \text{ cm/s}$$

Sample data/calculation table.

X_i (cm)	t_i (s)	$\overline{V}_{ij}$ (cm/s)	Δt_{ij} (s)
2.25	0.0	----	----
2.53	0.5	V_{01} = 0.56	0.5
3.35	1.0	V_{02} = 1.10	1.0
4.73	1.5	V_{03} = 1.65	1.5
6.65	2.0	V_{04} = 2.20	2.0

From your graph determine the initial speed of the bob, V_0, at the first position X_0. Also from the slope of your graph calculate *g* (see the theory section below). Compare your calculated value of *g* with the known value using a discrepancy test.



Plot the average speed versus the time interval to get a straight line.

<u>Theory exercise:</u> Using kinematics, show that $\overline{V}$ versus Δt is linear. As part of the derivation of your equation, show how the slope of this graph is related to the acceleration of the falling body. Interpret the physical meaning of the y-intercept.

Part III: **Finding the instantaneous speed of the bob at its final position.** Repeat the methods of part II to find the instantaneous speed V_4 at the position X_4. To find the instantaneous speed at the final position, hold the final position constant while varying the other position and time values.

Part IV: **Find the instantaneous speed V_2 of the bob at the time midpoint t_2 at the position X_2.** Again use the methods previously developed. In this part however, as you shrink your time intervals *no* positions are held constant. Think symmetry, and see if you can figure it out.

Part V: Compare the three instantaneous speeds found in part I to those found in parts II, III, and IV. Also, can you calculate *g* from the graphs in parts III and IV? Error analysis has been ignored, how could you apply it meaningfully to this experiment?

Part VI: **Show mathematically (i.e., algebraically with no numbers) that the average speed over a time interval is equal to the instantaneous speed at the *midpoint* of that time interval if the acceleration is constant.** Confirm this principle by taking the average speed $(V_0 + V_4)/2$ and comparing the result to the instantaneous speed value V_2 at the time midpoint as calculated in Part I *and* Part IV.

3b. THE BEHR FREE FALL EXPERIMENT

Equipment List:

- One Behr Free Fall Apparatus and spark timer (A back-up unit is desirable).
- One two-meter stick per table.
- Masking tape.
- Red wax paper tape with Behr Free Fall data on it produced by the apparatus.

Procedure:

In this lab you will draw two graphs. The first graph will be a position versus time graph for *all* the dots on your wax tape. Remember, each individual dot is separated by 1/60th of a second. You will then draw a tangent line to every fifth dot for a total of five tangent lines. You will measure the slope of each tangent line. Recall, in this case, a tangent line represents the instantaneous speed of the bob at that point where the tangent line is drawn.

For the second graph, using the slope of each tangent line from the first graph, plot the instantaneous speed of the bob as a function of time. This graph will have five data points on it. From kinematics we know the slope of this graph is equal to the acceleration of the bob.

Analysis and Conclusion:

Take the value of g to be 9.81 m/s^2 and compare your slope value to this accepted value using uncertainties and/or a discrepancy test. Discuss sources of systematic uncertainties in your results and how they could be eliminated.

4. INTRODUCTION TO THE AIR TRACK

I. What is an air track?

An air track is an experimental apparatus that allows the study of motion with minimal interference by frictional forces. To see a typical air track setup, look at the diagram at the bottom of page 26.

By allowing the air track gliders to move on a cushion of air, frictional effects are reduced. A blower adjusted to the correct output level forces air inside a piece of aluminum extrusion. The high air pressure inside the track forces air out of the track through small holes drilled into the upper surface of the track. The air track glider rides on this surface of air.

To make effective use of eliminating friction from our experiments we need to measure speeds with great accuracy. This is accomplished with the use of "photogates". Combined with these sophisticated timing devices, low friction air tracks enable the experimenter to make high accuracy confirmations of fundamental motion studies.

Before you start experimenting with the air track, you must learn how to avoid damaging them. The tracks are made of aluminum which is a soft metal and easily scratched, nicked, and damaged if not handled carefully. Any irregularity in the track surface will increase frictional effects and reduce the accuracy of your results. Please be considerate of our equipment, take care not to damage these tracks as they are expensive and must last the De Anza physics department a long time.

II. How to avoid abusing the air tracks:

1. ***Never*** **place a glider on a track unless there is air blowing out through the track's holes.** ***Never*** slide a glider along the track unless there is air blowing out through the small air track holes. Before putting the glider on the track, feel the air blowing out of the track with your hand. The glider must slide on a layer of air and must never slide touching the aluminum track. Contact between the glider and track will scratch and ruin the track's surface.

2. Remove and replace the track from the storage rack **slowly** with great care making sure the track does not collide with other objects. The track is long so that removing and replacing it is a **two person** procedure where each person is in charge of one end of the track to ensure it hits nothing. Hitting the track will throw it out of alignment. These tracks are straight to within 0.02 millimeters over their entire length. Deviations from this tolerance will reduce the accuracy of your results.

3. ***Never*** put any kind of tape on the track or glider. Do not write on the glider with pen or pencil. It is also a good idea not to excessively touch the track with your hands since finger oil will eventually gum up the track's surface.

4. ***Never* push down on a glider.** On or off the air track, pushing downward on a glider may bend the delicate sides of the glider. The angle between the sides of the glider *must* match the ninety degree angle of the track surface.

III. Preparing the air track, glider(s), and photogates for an experiment:

A. Preparing the air track.

1. Carefully remove the air track from its cradle on the storage cart and place it on your lab bench. **This is a two person job!**

2. You will also need the following items:

Necessary items for the air track: one air blower box one blower box power cord one flexible air hose two "end pieces" for each end of the track one flat plastic accessory box

3. Connect the air blower hose to the track and the blower; connect the power cord to the blower. Turn on the blower to a level of about 2 units to allow the track to warm up.

4. In the accessory box you will find four thumb screws used to mount the two end pieces on the air track. Mount the end pieces on the track. Remember these must be taken off when you are done. 5. Also from the accessory box, remove two end reflectors (they are flat and U-shaped) and insert a rubber band tautly in each one. Insert each end reflector in the end piece you already mounted on the air track. Insert the end reflector in the top hole of the end piece.

B. Preparing the glider. The plastic box has many items for the glider. These items can be added to one side or the other of the glider or the top of the glider. There are also weights provided to increase the mass of your glider. For the correct balance, weights should always be added evenly to both sides of the glider. Your lab experiment equipment list will tell you exactly what accessories are needed for a given lab. You always need at least one glider (see your experiment equipment list) and the accessory box from above.

You will always need an accessory in the top of the glider to act as a "flag" (see below, section IV). The flag triggers the photogate. Typically the flag will be one of the cylindrical plugs found in the accessory box. You will also need an accessory inserted into both ends of the glider. Often this will be a cylindrical plug with a flat end on it (two of these are in one accessory box). Insert one of these cylindrical plugs with a flat end in each end of the glider. Use the upper of the two holes in the glider end to insert the cylindrical plug. The flat end on the glider should be oriented vertically so that it will push against the rubber-band reflector on the end of the air track.

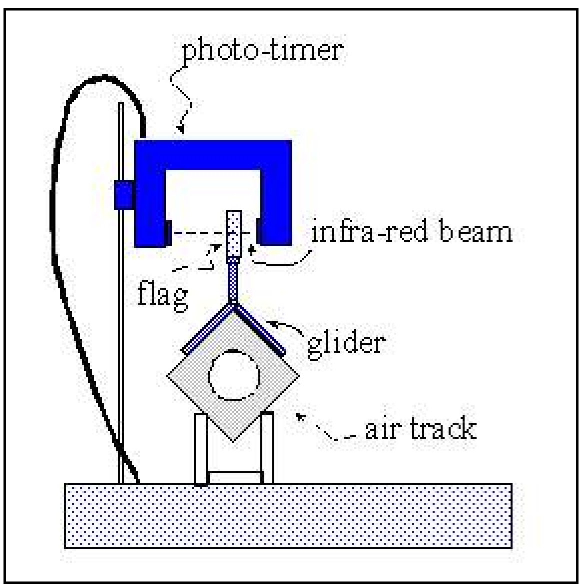
You are asked to **hold the glider in your hand when adding accessories to it** and not add accessories while the glider is on the lab bench, or the air track, to prevent having the sides of the glider bent from pushing down on it while it rests on a hard surface. Your hand holding the glider will "give" when pushing an accessory into the glider and therefore the sides of the glider will not be bent or damaged.

C. Preparing the photogate timers. You will need at least one photogate timer (see your experiment equipment list). You will also need a power cord for the photogate. The power cord will have a transformer end that plugs into the power outlet; you may also need an adaptor to plug the transformer into the lab bench power strips. The photogate timer is turned on by turning the slide switch to gate, pulse, or pendulum mode. To correctly position the photogate see sections IV and V below.

Note: When finished with your experiment, the "break-down" of the apparatus is the reverse of the above. Make sure you take the glider off the track ***before*** you turn off the air blower.

IV. How to adjust the air track and photogates for optimum accuracy in measurements:

1. **Photogate placement.** For accurate results the photogates must be correctly placed. See the diagram below and notice how close one side of the photogate is to the glider. This eliminates so-called parallax error. The glider has a "**flag**" that triggers the timer.



The correct position of the photogate and cart.
End View

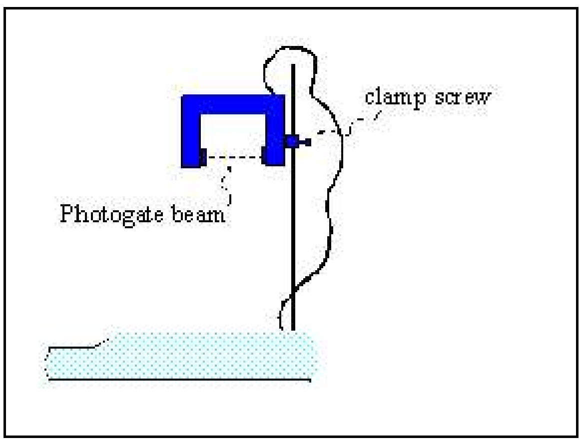
A flag is an object placed on the top of the glider that interrupts the photogate beam and activates the timer.
Use a cylindrical plug on the top of your glider as a flag. Using the cylindrical plug means that the cross sectional length the beam senses is independent of the rotation of the cylinder. This is important so you don't have to worry about the rotational position of the flag affecting your measurements.

2. Blower output level. The blower output may be too low *or* too high. If the blower output level is too low then the glider may scrape the track and damage could result. If the blower output level is too high, the glider may be blown one way or the other and your results will be less accurate. **It is better to have the blower output too high than too low!** Note that the air output through the small holes is higher near the blower input end of the track and air output is lower at the end of the track far from the blower input.

Make sure air output is high enough to keep the glider from scraping the track at the end of the track farthest away from the blower input. **A blower output level of at least 2.5 is correct when one unweighted glider is on the track.** You will have to increase the output level when two gliders are used or when a more massive glider is on the track. As long as a glider does not noticeably slow down from a gentle push, the output level is high enough.

3. **How to level the air track.** Unless your experiment involves tilting the track for an inclined plane experiment, you must make sure your track is level. Place one glider near the center of the track. If the track is level, the glider will drift back and forth randomly but will not pick up much speed traveling either to the left or to the right. The track is leveled at one end only using the adjusting screws found on its long "foot". Leveling may take time, be patient.

V. Understanding the photogate timer:



The Photogate

A narrow infra-red beam is emitted from the arm close to the vertical positioning pole. This beam strikes a detector in the opposite end of the arm away from the vertical positioning pole. A timer circuit is connected to the detector that allows four types of timing modes to be used. When the beam is blocked a red LED (**L**ight **E**mitting **D**iode) lights up on the top of the photogate arm.

Be careful not to over tighten the clamp screws on the photogate arm and notice the small metal lever switch (the memory switch) on the photogate timer cannot be turned in the left and right direction but up and down only.

The four timing modes:

1. Gate Mode: Use this mode to calculate speeds. The timer is activated when the beam is blocked. When the beam is unblocked the timer switches off. If you know the length, L, of an object (e.g. your glider's flag) and the time it takes for the object to go through the photogate then you can compute the average speed of the object as it passes through the photogate. Note, in reality you must not use the "physical" length of the object but the so-called "effective" length, L_{eff}, of the object. See the **effective length** section found below for more details.

2. Pulse Mode: Use this mode to calculate the time one object moves between *two* different photogates placed some distance apart (a second accessory photogate is necessary). Timing begins when the beam is first blocked and continues after the beam is unblocked; timing terminates when the beam is blocked again a second time at the second photogate.

3. Pendulum Mode: Use this mode to calculate the period of one full oscillation. The timer starts when the beam is first interrupted and the timer continues through one more interruption and then finally stops on the third interruption.

4. Manual Stopwatch: In **Pulse** mode the START/STOP button makes the timer act as a conventional stopwatch. In **Gate** mode the timer starts when the START/STOP button is pressed and the timer stops as soon as the button is released.

Memory switch: Each timer has a memory switch to allow the recall of a previously timed value. When you recall the stored time, the time displayed is the **sum** of both events. Therefore you must subtract the two displayed times to find the time of the stored event. Typically, leave the memory switch in the "off" position.

Resolution switch: The slide switch on the front panel enables the user to set the "resolution" of the timer to 1 mS (mS = 10^{-3} seconds) or to 0.1 mS. In both cases the timer is accurate to 1 percent of its readout. **The difference between the two settings is that on the 1 mS setting a maximum time interval of 20 seconds can be measured whereas on the 0.1 mS setting only a time interval of 2 seconds can be measured**. Not remembering this can lead to many frustrating measurement errors. Unless otherwise told, leave the switch on the 1 mS setting.

VI. Finding the effective length of the flag and calculating its speed: Although it sounds odd, the physical length of the flag you use on the glider is not *exactly* equal to the length that the beam senses with the photogate! The length the beam senses is called the "effective length", L_{eff}, and can be measured with the following procedure.

A. With the glider off the track and ***held in your hand***, gently place a cylinder into the top of the glider. This cylinder is your flag. Remember, don't push down hard on the glider or you may bend its sides.

B. **Make sure the blower is turned on so the glider does not touch the track when placed on it.**

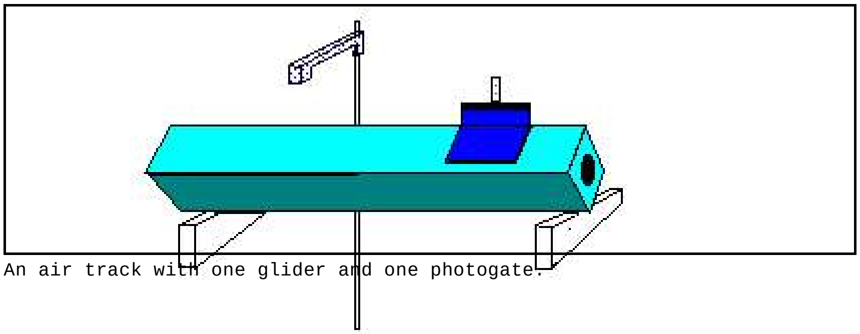
C. Place the glider on the track near a photogate timer switched to **GATE** mode. Make sure the photogate is correctly positioned as described above in section IV.

D. Adjust the vertical height of the photogate so only the cylinder on the glider will trigger the photogate. Move the glider in and out of the photogate. See that as soon as the flag on your glider blocks the photogate the red LED on the top of the photogate arm lights up. Use this red LED as the indicator of when the flag first blocks the photogate.

E. You are now ready to measure the effective length of the flag. Make sure the timer is not running. Slowly move the glider into the photogate until the red LED goes on. Record in your lab book the position the front edge of the glider makes with the ruler on the track ***just*** when the glider triggers the photogate. Continue to move the glider through the photogate until the red LED goes off. When the red LED shuts off, record the new position of the glider's front edge with respect to the air track's ruler. The difference between your two recorded positions is the effective length of your flag, L_{eff}; the value should be about 1 cm, you should have the value to one decimal place. Make sure this length is clearly recorded in your lab book. All speed calculations are made using this length.

F. Calculating the speed of a glider in an experiment. Now that you know the effective length of the flag, you can calculate the average speed of the glider as it moves through the photogate by dividing the effective length of the flag, L_{eff}, by the time the flag keeps the timer activated, Δt.

$$V_{glider} = \frac{\Delta L_{eff}}{\Delta t}$$



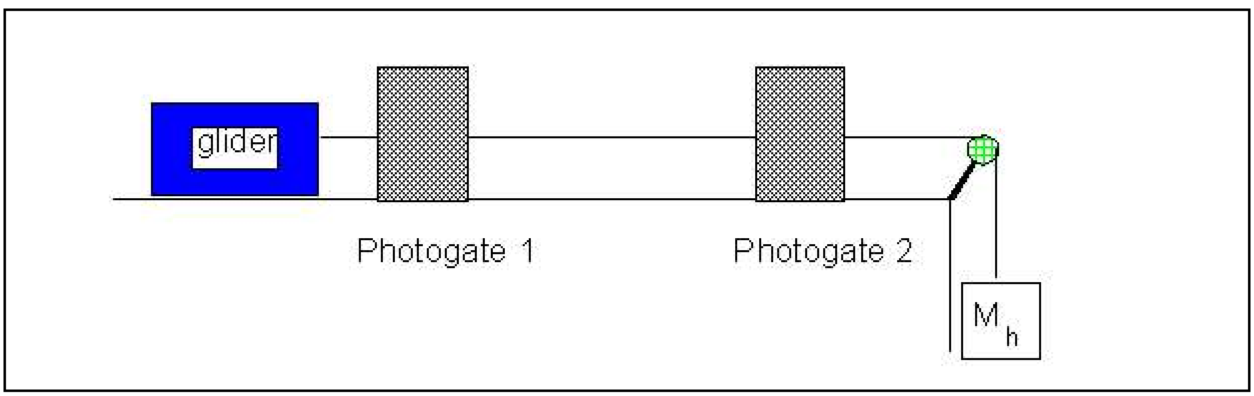
An air track with one glider and one photogate.

5. NEWTON'S SECOND LAW AND THE AIR TRACK

Equipment List:
- One air track, blower, blower hose and power cord
- One digital photogate and one accessory photogate
- One glider
- One flat plastic accessory box
- String
- Electronic Pan Balance

Introduction:

In this experiment we examine the acceleration of a mass, *m* (the air track glider), under the influence of a tension force due to the weight of a hanging mass, M_h. We assume that the *only* horizontal force acting on the glider is the tension force from the string. For this to be true, the track must be level and friction should be negligible. Remember, it is the force from the tension in the string connecting the two masses that accelerates the glider, not the weight of the hanging mass itself.



Your setup will look like this.

Theory:

1. Using Newton's Laws, derive an expression for the acceleration of the glider in terms of the mass of the glider and the mass of the hanging weight.

2. Using kinematics, derive an expression for the acceleration given an initial and final velocity, and the distance over which the velocity changes.

Procedure:

1. Following the methods from the INTRODUCTION TO THE AIR TRACK section, set up your air track and prepare one glider and two photogates for your experiment. From your accessory box, take the pulley and connect it to the end of the track that does not have the blower hose in it.

2. Set the two photogates apart by a distance of about 60 or 70 centimeters. Measure precisely (interpolating to the *hundredth* of a centimeter) the distance between the two photogates by using the front edge of the glider as it triggers each photogate as a reference mark. Record your uncertainties and compute the distance between the photogates. By using uncertainty propagation, compute the absolute uncertainty in the distance (the distance is found by a *subtraction*) between the two photogates.

3. Using the methods detailed in your air track introduction, compute the "effective length" of the flag on your glider. Do this for each photogate. Do not assume the effective length of the flag is the same for the two photogates. Again, by uncertainty propagation, find the absolute uncertainty in the effective length. **Set your timer resolution to 0.1 mS.**

4. Connect the glider to the hanging weight (found in your accessory box) with the string provided.

5. For your first run, use the hanging weight with about seven grams. Confirm the mass of the hanging weight and the mass of the glider (with all attachments in place) on the balance provided. Ignore the mass of the string. Record the absolute uncertainty of each mass using the method of an absolute uncertainty obtained from a digital readout (if you use the electronic pan balance).

6. On the air track with blower on, hold the glider by hand completely clear of the first photogate. Record this initial position for repeat trials. Let the glider go and allow it to accelerate moving through each photogate. Record the two times by using the memory switch and subtracting one displayed time from the other (which time should be bigger?). Record the absolute uncertainty in the time using the digital readout method. Take care not to let you glider bounce back through a photogate as this could change your time readout. Your first run is now complete. Repeat this procedure for a total of five runs. For each run you should let the glider go from the same initial position. You should have five time values for each of the two photogates.

Analysis:

You now have the data to compare your theoretical acceleration, a_t, to the calculated acceleration, a_c. The theoretical value is obtained from the measurement of the two masses and the known value of g (let $g = 9.80$ m/s^2 *exactly* so that $\delta_a g = 0$). The calculated acceleration is obtained from the distance between the two photogates, the times and effective lengths.

You should derive the absolute uncertainties of each acceleration by the uncertainty propagation methods.

Repeat the above for a different hanging weight value varying the distance between the two photogates. What effect would varying the distance between the photogates have on the absolute uncertainty in the calculated acceleration?

State each acceleration with an absolute uncertainty. Do the most probable ranges of the two accelerations (a_t and a_c) overlap? If so, then on the basis of your experiment, the values are equal; if not, speculate as to why this is so. Would you expect a_c to be larger or smaller than a_t based on the presence of systematic uncertainties?

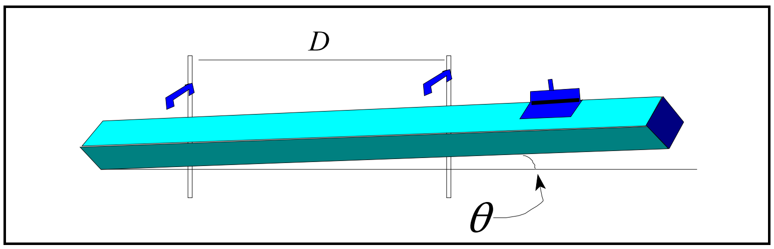
Conclusion:

Discuss the presence of systematic uncertainties and any ways in which these errors may be eliminated.

6. THE AIR TRACK AS AN INCLINED PLANE

Equipment List:

- One air track, blower, blower hose and power cord
- One digital photogate and one accessory photogate
- One glider
- Five different riser blocks
- One flat plastic accessory box
- One meter stick



Your setup should look like this.

Introduction:

You will calculate the acceleration of a body on an inclined, near-frictionless plane (the glider on the air track). From this acceleration you can figure the angle of the inclined plane. You will then compare this calculated angle to your actual measurement of the angle and see how close the two results are using a discrepancy test.

Theory:

Derive an equation that gives the angle of an inclined plane, θ, as a function of the acceleration of a body down the plane and g.

Also, from kinematics derive an equation that yields the acceleration of a body given its initial and final speeds and the distance between the points where it has those speeds. You will need this equation to calculate the acceleration of the glider along the track.

Procedure:

1. Set up your air track equipment following the procedures in the INTRODUCTION TO THE AIR TRACK. Remember, you need not
worry about leveling your air track since this experiment uses the air track as an inclined plane.

2. Using some combination of the small riser blocks provided, raise the end of the air track that has one foot only (the other end has two feet) about one centimeter.

3. Experiment to determine good placement of the photogates when one end of the track is elevated. Place the two photogates as far apart as possible. Measure the distance between the two photogates. To measure this distance, use the leading edge of the glider and record the position of the glider as it triggers each photogate. To see if the photogate has been triggered, check the red LED on the top of the photogate arm. Subtract the position of the glider at each photogate and you will have the distance between the two photogates.

4. For your runs, have the timer set to **GATE** mode, and have the resolution switch set to 0.1 mS (use the 0.1 mS setting only if the time the glider is between the photogates is less than two seconds). The memory switch should be turned on so that the small red LED next to the switch is lit. The number on the LCD display is always the time measured *in seconds*.

5. Release your glider and let it accelerate moving through both photogates. Record the time for each photogate. The first photogate time is read directly from the LCD display on the timer. The second time is found by *subtracting* the first time displayed from the time displayed after the MEMORY READ switch is pushed. Understand on a physical basis which time should be smaller. Make sure the glider doesn't bounce back through the second photogate for a second time; this may change your time readings.

6. Repeat the same procedure for a total of **five** trials. This will allow you to calculate five accelerations which, in principle, should all be the same. Of course, due to random fluctuations the accelerations won't be identical. Apply the statistical method to calculate an average acceleration with an absolute uncertainty.

7. From the above acceleration, compute the angle of the incline.

8. Now calculate the angle of the plane. Use right triangle trigonometry to calculate the angle as a function of the arctangent (or arcsine if appropriate) of two measured sides. It is for you to figure what two sides need to be measured.

Analysis: Compare your two angles using a discrepancy test.

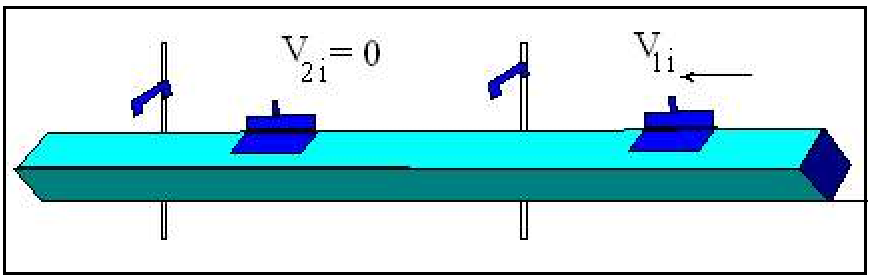
Optional Graphical Analysis

Repeat steps 3-7 for four more angles for a total of five different angles and 25 timing runs. Calculate g from the slope of a straight line graph that relates the angle θ to your calculated acceleration. Your graph will have five data points.

Conclusion: Discuss methods that would minimize the discrepancy calculated above. Which angle would you expect to be larger most of the time due to systematic errors? See if you can discover any systematic errors and suggest ways in which they could be eliminated or at least minimized. At the discretion of your instructor, hand in an **abstract** written by you and your partner. The structure of an abstract is discussed in your lab skills manual.

7. KINETIC ENERGY AND CONSERVED QUANTITIES

Equipment List:
- One air track, blower, blower hose and power cord
- One digital photogate and one accessory photogate
- One Pasco counter-timer (optional)
- Two gliders
- One flat plastic accessory box
- One set of riser blocks (if enough time is allowed)
- Digital Pan Balance



Glider 2 is initially at rest and closer to photogate 2.

Introduction:

In this lab we examine the kinetic energy of two bodies before and after they collide in two different types of collisions:

1. An *elastic* collision: The bodies bounce away from one another with no energy loss.

2. **A totally *inelastic* collision:** The bodies stick together after the collision.

You will calculate the kinetic energy of each body before and after each type of collision and compare the *total* kinetic energy of both bodies before and after the collisions ($KE_{total} = KE_1 + KE_2$).

If the total kinetic energy remains unchanged after the collision, then we say the kinetic energy is "conserved". In this experiment you will test whether kinetic energy is conserved in the two types of collisions discussed above.

Procedure:

1. Experiment to determine appropriate placement of the photogates. Measure the distance using the glider as a reference. Place your two photogates about fifty centimeters apart or even closer if you can still take accurate measurements. You should explain the advantage of having the photogates as close together as possible.

2. Prepare your two gliders for an elastic collision (i.e., they will bounce apart) by placing one rubber band bumper on each glider so that the sides of each glider that touch during the collision meet with bumpers. The other end of each glider should have cylinders put into them so that the gliders are balanced. Increase the mass of one glider (call it glider 2) by slipping one weight (from your accessory box) onto the post found on each of its two sides; one weight on each side. Measure the mass of each glider complete with all accessories on the digital pan balance. Measure the effective length of each glider through each photogate.

3. Place glider 2 at rest between the two photogates but close to the second photogate. Place the other glider (glider 1) outside the two photogates and prepare to launch glider 1 through the first photogate so that it collides with glider 2 *before* either glider goes back (or forward) through a photogate. When the collision occurs, make sure glider 2 is initially at rest so that you know the initial speed of glider 2 is zero.

You will have three time measurements from your photogates. The first time will yield the initial speed of glider 1. The other two times will allow you to calculate the speeds of both gliders after the collision. With just the LED photogate timer and one accessory photogate, this may require some practice. The times will have to be recorded and quickly erased for new times. You may opt to use a Pasco counter-timer with an accessory photogate for greater accuracy, check with your instructor. Best of all would be the Pasco counter-timer with *two* accessory photogates plug into the back of the counter with no LED photogate timer. This method is the easiest way, but if the lab has too many people, there may not be enough accessory photogate timers so everyone can have two.

4. From the effective length measurements and the photogate measurements as well as the measurements of the mass of each glider, calculate the total initial kinetic energy and compare that value to the total final kinetic energy after the collision. Determine within experimental error whether the two values, the total initial and final kinetic energies, are equal. That is, does the total initial kinetic energy equal the total final kinetic energy? On the basis of your experiment, is kinetic energy conserved in this type of collision?

5. Repeat the above procedures varying certain parameters. For example:
   - A. Make both gliders equally massive (the result is surprising and not trivial to correctly explain).
   - B. Make glider 1 more massive than glider 2. Categorize your results as a function of different initial speeds of glider 1.

6. **Totally inelastic collisions.** Prepare your gliders so that they do not bounce away from one another after the collision but so that they stick together after the collision. To do this, remove the rubber band bumpers from each glider and replace with the needle and wax cylinders described below.

In your accessory box, one of your cylinders has a cork on one end. Carefully remove this cork and see the needle. **The cork exists to protect you from stabbing yourself or someone else (the teacher?) with the needle. Please leave the cork on the needle when you are not using this cylinder to avoid puncturing yourself.**

Another cylinder in your box has some ear wax in one end. Together, the needle and the wax cylinders allow two gliders to stick together when they collide. It doesn't matter which glider has which type of cylinder.

7. With the needle and wax cylinders, repeat the relevant procedures from above to examine the values of the total kinetic energy before the collision to the total kinetic energy after the collision. From the basis of your experimental results, conclude whether the total kinetic energy of both gliders is a conserved quantity in this type of collision. If not, why not? Is the initial energy greater or less than the final energy? What happens to the missing energy?

<u>Other energy experiments:</u>

1. Energy conservation: Using the riser blocks, raise the single footed end of your air track so that it becomes an inclined plane. Using one glider and two photogates, measure the change in the kinetic energy of the glider as it accelerates down the track. Experimentally relate this increase in kinetic energy to the decrease in gravitational energy within the glider-earth system. You will need to measure the change in the vertical height of the glider at the two positions of each photogate as well as some other parameter left for you to determine.

2. **The work done by friction:** Level your track. Put your two photogates as far from one another as possible. Launch one glider through the first photogate. If the track is perfectly level and there is no friction, the glider should have the same speed through the first photogate as it has through the second photogate. Calculate the kinetic energy of the glider at each of the two photogates and compare the initial and final values. If the two kinetic energies are not equal, then by the work-energy theorem, the change in the kinetic energy must equal the work done on the glider by the friction force.

Compute the coefficient of kinetic friction between the glider and the air track. You may need to measure other values to accomplish this. Work out the theory first then you will need to know what to measure. Repeat for different glider masses to see if the coefficient of kinetic friction is independent of the mass of the glider (should it be?). Also, repeat the experiment for different initial glider speeds and see if the coefficient changes with these different speeds.

3. **The energy loss in an end reflection:** You only need one photogate and one glider for this one. Put the photogate near one end of a leveled air track. The track end and glider should both have rubber band bumpers attached to them. With the photogate close to the bumper (but not too close!), calculate the kinetic energy of the glider after the reflection and compare it to the kinetic energy before the reflection. Discover how the energy loss due to an end reflection is a function of the incident speed of the glider. Would you expect the energy loss to be constant, linear, or a power curve as a function of incident speed? A graph would help you see this.

8. CENTRIPETAL ACCELERATION

Equipment list:

- Circular motion apparatus
- Pan Balances
- Weight sets
- String (the string is stored by wrapping it around the "vertical pointer")
- Counter-timers

Purpose:

In this lab you will calculate a centripetal acceleration and confirm the value of the force necessary to cause this acceleration.

Theory:

Any body undergoing circular motion must be accelerating even if it is moving at constant speed since the direction of its velocity vector is continuously changing. Since acceleration is a vector it has a magnitude and a direction. It can be shown[3] that the magnitude of the centripetal acceleration is v^2/r, where r is the radius of the circle the body is moving in, and v is the body's speed. The direction of the acceleration vector at any instant is always toward the center of the circle.

By Newton's 2nd Law, any body that is accelerating *necessarily* has a non-zero net force acting on it. In circular motion, the net force is often called the centripetal force, but it is important to understand that the centripetal force is the name of the *net force* acting on a body and *always* represents the vector sum of "real" forces acting on the body. The centripetal force is not itself a single, "real" force but the name given to the net force acting on a body causing it to move in a circle.

Leave at least one page in your theory section for further derivations.

Introduction:

This lab is performed in two parts. In the first part a "bob" undergoes circular motion when spun by hand (see the diagram on page 2). By knowing the radius of the bob's circular path and the time it takes to complete one revolution, you can compute the magnitude of the centripetal acceleration of the bob, a_c.

In the second part of the lab, in a non-accelerating static situation, you will measure a force equivalent in magnitude (but not conceptually equivalent!) to the net force required to make the bob accelerate in the first part. This force is the weight of a hanging mass, $W_{hanging}$.

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[3] See Tipler's Physics, 3rd edition, pages 65-67.

The analysis consists of comparing $W_{hanging}$ to $M_{bob} \cdot a_c$. These two values should be equal.

Note: The following paragraph is an in-depth explanation of why $W_{hanging}$ is equal to $M_{bob} \cdot a_c$.

To see that the magnitude of the static force measured in the second part of the lab is equal to the mass of the bob multiplied by the resultant acceleration of the bob in the first part of the lab, see that the spring is stretched by the same amount in both the dynamic and static parts, and see that if a spring is stretched by the same amount in any case, then the same magnitude of force is acting on it. However in the dynamic part of the lab (part 1), the spring exerts an inward force on the bob to keep the bob accelerating and this *is the only horizontal force acting on the bob*. By Newton's 3rd Law then, the bob exerts a force *back* on the spring outward thereby stretching the spring. In the second part of the lab (part 2), there are no accelerations, the bob is in static equilibrium. The hanging weight pulls out on the bob via the connecting string (note: the tension in the connecting string is only equal to the hanging weight since there is no acceleration) and the spring pulls inward on the bob. Since the acceleration of the bob is zero, the net force acting on the bob is zero, so the force of the hanging weight on the bob is equal in magnitude to the force of the spring on the bob.

Procedure:

Part 1. The dynamic part.

Preparation: Setting the radius of the circle. With the spring not attached to the bob, allow the bob to freely hang without moving. Position the vertical pointer underneath the bob so the rod and bob match exactly. You now have set the radius of the circle. Measure the radius and record its value. You might have to move the horizontal position of the counter-weight and bob assembly in addition to the vertical pointer to achieve the correct alignment. Re-attach the spring to the bob. Use the leveling screws on the base of the apparatus to level the platform. You are now ready to "run" the dynamic part of the experiment.

The setup for part 1. It is important the string holding up the bob be kept absolutely vertical while spinning.

Running part 1.

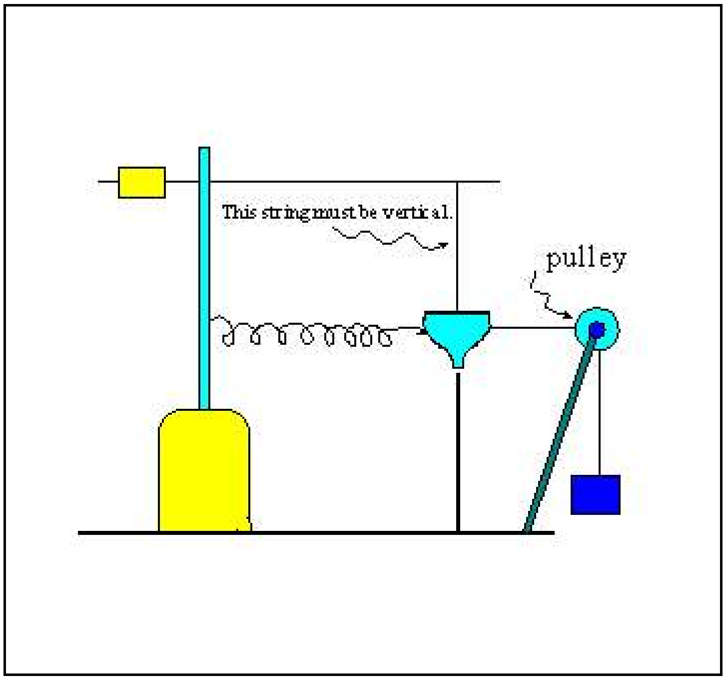
Practice rotating the bob (while the spring is attached to it) by turning the vertical shaft. Make absolutely certain that the bob is swinging directly over the pointer at all times. If the bob is not directly over the pointer as it swings in its circle, then the string holding up the bob will have a horizontal component. The horizontal component of the string's tension force will alter the spring's force on the bob and your results will be inaccurate. Position your hand near the bottom of the shaft where it is roughened for a good grip. You must rotate the shaft and therefore the bob at a constant speed. You can check to see if you are doing this because if you turn the shaft at the "correct" speed then the bob will always be just over the vertical pointer. You may have to hold on to the bottom section of the whole apparatus to keep it from turning with the bob.

When you have gained confidence in turning the shaft at constant speed, have your lab partner use the counter-timer to time at least fifty total rotations. Call this time the total time, T_{total}. You now have the necessary data to calculate the centripetal acceleration of the bob.

Record all your measured values in the data section of your lab book.

In the theory section of your lab book (you *do* have the space, right?), derive an equation for the centripetal acceleration, a_c, in terms of the radius of the circle you measured and the total time of all fifty turns. Your final equation should be a function of r and T_{total} only, no speed v! Hint: the circumference of a circle is $2\pi r$ and the speed of a body moving in a circle is $2\pi r/t$, where t is time for *one* revolution. Use your final equation to find the numerical value of a_c in your calculation section.

Part 2. The static part.
Leave the spring attached to the bob. As shown in the diagram at the right, place an amount of mass on the hanger that stretches the spring so that the bob moves over the vertical pointer. The value of the hanging mass's weight (include the hanger!) is equal in magnitude to the force that was required to make the bob accelerate in part 1. This equivalence is actually far from obvious but is worth some effort on the student's part to fully explain it.



Your setup for the static part.

Part 3. The last thing to do is to measure the mass of the bob. From Newton's 2nd Law, to equate the net force and the acceleration of a body, the mass of the body must be known. A question to answer is whether you should measure the mass of the spring as well as the bob.

You should repeat the above procedure for one more radii. Switch jobs with your partner. Compare your two values, $W_{hanging}$ and $M_{bob} \cdot a_c$, and discuss the results including the uncertainties. If your agreement is reasonable you are ready to go on and complete the lab.

Analysis:

With this equation in mind, take five sets of data varying in radius and period. Knowing the equation that relates the radius and the period, construct a graph with the appropriate axis that gives a straight line whose slope can be related to the mass of the bob. Use linear regression to find the best slope and calculate the mass of the bob with an uncertainty. Compare the mass of the bob to its measured value found earlier. Use a full uncertainty analysis.

Questions to consider.

Speculate on possible sources of systematic errors that could be eliminated in future labs.

In terms of systematic errors, would you expect $W_{hanging}$ or $M_{bob} \cdot a_c$ to be consistently larger? If you can think of a reason, explain why.

What is the experimental value of using fifty total rotations rather than just one or ten? What type of error does this technique minimize?

In the dynamic part of the lab, if the string tension force on the bob has a horizontal component pulling out on the bob, will this make the spring force on the bob larger than it should be or smaller than it should be? How would this change if the string tension force had a horizontal component pulling in on the bob? (Remember, there should be *no* horizontal component of the string tension force.)

9. SIMPLE HARMONIC MOTION (WITH AN AIRTRACK)

Equipment List:

- Air track and accessories
- digital balance
- weight set and hangers

Introduction; This lab involves a graphical analysis of data taken during the simple harmonic motion of a glider when under the action of a spring's restoring force.

Theory: By examining the forces acting on the glider and using Newton's second law, a solution of the resulting differential equation is obtained with the condition that the angular frequency, ω, of the oscillating mass, m, is:

$$\omega = [k/m]^{1/2}$$

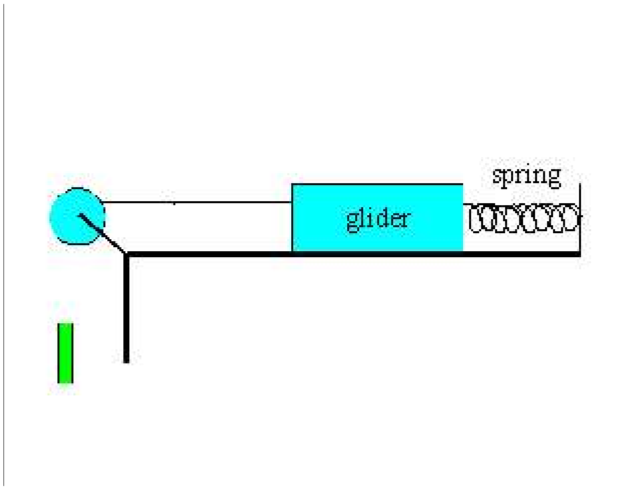
where k is the stiffness coefficient of the spring.

Since the period of the oscillation is defined as $T \equiv 1/f$ and the angular frequency is defined as $\omega = 2\pi f$, the relation between the period, the mass, and the stiffness can be found. Do this.

Note: Your photogate timer should be set for a 1ms resolution. Also, don't use the small hanging weight set found in the accessory box, use the weight and hanger set provided.

Procedure:

Refer to the diagram below for the set up.



Take sufficient data to analyze the relation between T and m. Use this data to draw a graph and find the stiffness of the spring k. Your graph should be linear but the relation between T and m is *not* linear. Construct the axes of your graph such that a linear graph will result. Relate the slope of the line to the value of k. Find the correct axes *before* you begin your data taking so that you can draw a rough graph while you take the data, point for point. This technique will help to see if your axes are indeed correct and if your data yields a straight line. Measure the slope of the graph and determine k.

More: Perform a linear regression for the value of k and a full uncertainty analysis for the absolute uncertainty in k. Include error bars on your data in the graph. Use the computer to draw a quality graph and tape the graph in your lab book.

10. SIMPLE HARMONIC MOTION (NO AIR TRACK)

Equipment List:

- An ample supply of string and scissors to cut it.
- Hanger and weight sets
- Photogate timers
- Connecting rod assemblies to form an "L" shape over the lab bench

Introduction:

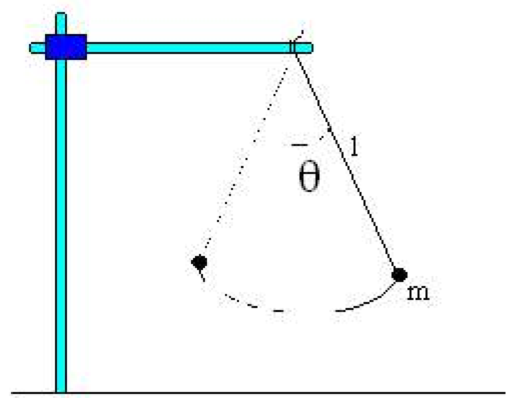
In this lab a simple pendulum is investigated in terms of its periodic motion. The parameters involved are the length of the pendulum, *l*, the period of one oscillation, T, and the mass of the "bob", *m*. These three parameters are related by an equation derived from Newton's laws.

Theory:

Derive the simple pendulum equation that relates the period of one oscillation to the length of the string. Make the necessary approximations. Examine the theoretical dependence of the period on the mass of the bob, on the length of the string, and on the amplitude of the swing, θ.

Procedure:

1. Construct the apparatus approximately as shown to the right. All that matters is that you get something that does not "sway" as the bob moves back and forth; you need a stable platform.



2. With one and only mass, measure the dependence of the length of the string on the period of the motion. This means you must take several runs (the more the better) with a single length of string, then change the length and perform some more runs. Take data for at least five different lengths.

Analysis:

1. Graph the length versus the period for your data such that the resulting curve is a straight line. Which variable should be on the x axis?

2. Perform a linear regression to find the value of *g* from your data. Include an absolute uncertainty for your measurement found from the statistical methods of linear regression.

3. Compare your calculated value of *g* with the expected value, 9.81 m/s^2.

More:

1. Investigate the dependence of the period of the pendulum on the amplitude of the swing.

2. Investigate the dependence of the period of the pendulum on the mass of the bob.

11. SIMPLE HARMONIC MOTION AND A VERTICAL SPRING

Equipment List:

- Vertical spring apparatus
- Weight sets and hangers
- Timers

Introduction:

This lab examines the relationship between the period of the oscillation of a vertical spring and the mass of the hanging bob. As well, the stiffness of the spring must be determined.

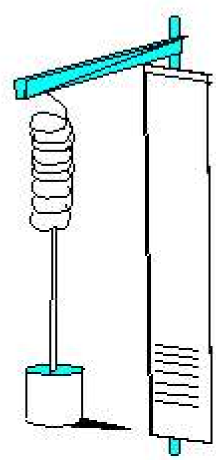
Theory:

From Newton's Laws derive a formula that relates the period of the motion of the mass on a spring to the mass of the hanging weight and the stiffness of the spring.

Procedure:

Finding the stiffness of the spring (method 1):

1. Set up the apparatus as shown in the diagram to the right.



2. Increase the mass of the hanging weight and measure the resultant change in the position of the pointer against the mirrored background ruler provided with the apparatus. Use the mirror qualities of the ruler to align the actual pointer to the image of the pointer in the mirror. by

moving your head back and forth and up and down you can align the two images. When these two images are aligned, parallax error has been minimized.

Will this reduce the systematic uncertainty or the random uncertainty in the measurements taken with the ruler?

3. Construct a graph where, from your examination of the theoretical formula already derived, will yield a straight line. From the same formula, relate the stiffness of the spring to the slope of the graph. Use linear regression.

Finding the stiffness of the spring (method 2):

1. Measure the period for at least five different masses. That's five periods for five masses.

Graph the results as a linear function. Perform a linear regression on the data and find the value of the stiffness of the spring with an uncertainty.

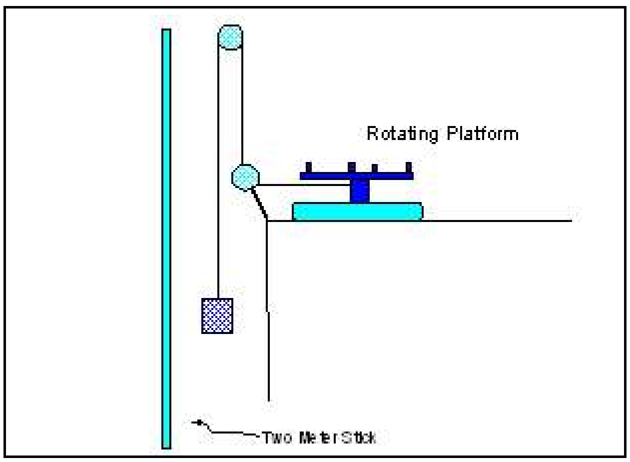
Analysis:

With uncertainties in both values, compare the stiffness of the spring in terms of a confidence level.

12. ENERGY CONSERVATION AND MOMENT OF INERTIA

Equipment List:

- The "rotating platform", its disk, and hoop
- Pulleys and long rods
- One hanging weight set
- String
- One Pasco counter-timer and two-meter sticks
- Electronic pan balance
- Vernier Calipers



Ignore the rotational inertia of the pulley, but don't forget to include the increasing kinetic energy of the hanging mass as it falls.

Introduction: Given an appropriately defined and isolated system, the total energy of that system will remain unchanged; this is an expression of *energy conservation*. When rotational velocities are involved in some process, we must expand the concept of kinetic energy and now distinguish between two forms of kinetic energy, linear and rotational.

Let the rotational kinetic energy be defined as follows:

$$RKE \equiv \tfrac{1}{2} I \cdot \omega^2$$

Where I is called the "moment of inertia" or "rotational inertia" of the body and ω is the body's angular velocity.

Conceptually, the moment of inertia of a body describes its resistance to having its angular velocity changed; it is analogous to "linear" inertia in describing how a body resists having its linear velocity changed. The rotational inertia of a body depends on its mass and how its mass is distributed relative to the axis of rotation.

Thus, we now expand the work-energy theorem to include these two forms of kinetic energy.

$$W_{ext} = \Delta KE + \Delta RKE + \Delta U$$

In this experiment, we will use this equation to solve for the moment of inertia of various bodies, some with known theoretical values allowing a check of your experimental technique, and some bodies with unknown rotational inertia values.

Theory:

Consider the diagram of your apparatus shown on page 46, define the correct system, invoke energy conservation, and solve the work-energy theorem for the moment of inertia of the rotating body.

As the hanging weight falls, the rotating platform starts to spin. The gravitational potential energy between the earth and hanging mass decreases and the linear kinetic energy of the hanging weight and the rotational kinetic energy of the rotating platform both increase. The total energy is conserved if there is no work done by friction to decrease the system's energy.

Clearly define all the values that need to be measured experimentally.

Procedure:

1. Set up your apparatus as shown.

2. Let the hanging mass fall from rest so its linear velocity is initially zero and the angular velocity of the rotating platform is initially zero.

3. From kinematics, derive an expression for the final velocity of the mass after it has fallen from rest through a vertical distance you measure with the meter stick during a time measured by the counter-timer.

4. Perform your first run with the rotating platform alone (don't use the hoop or the disk) so you can calculate the moment of inertia of the rotating platform. There is no theoretical value for the moment of inertia of the rotating platform since it is irregular in shape, so its rotational inertia must be determined empirically. This must be done before the moment of inertia of the other objects can be calculated.

5. Calculate the moment of inertia of the rotating platform.

6. You will need to measure the radius of the drum of the rotating platform. Use the vernier calipers.

7. Now run the experiment with the disk on the rotating platform and then with the hoop on the rotating platform. Calculate the moment of inertia of the hoop and disk. Compare your calculated values to the theoretical values.

8. Run the experiment with *both* the hoop and disk on the rotating platform and confirm that the moment of inertia of the sum of the two is equal to the moment of inertia of each added separately.

9. Time allowing, try some other object and calculate its moment of inertia. See if you can estimate its values by reasoning and approximations before you actually calculate it.

A refinement: See if the systematic error introduced by the bearing friction of the rotating platform's drum can be eliminated by first measuring this friction value and then subtracting it from your calculations.