Physics 6A Lab Manual

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Introduction

PURPOSE

The laws of physics are based on experimental and observational facts. Laboratory work is therefore an important part of a course in general physics, helping you develop skill in fundamental scientific measurements and increasing your understanding of the physical concepts. It is profitable for you to experience the difficulties of making quantitative measurements in the real world and to learn how to record and process experimental data. For these reasons, successful completion of laboratory work is required of every student.

PREPARATION

Read the assigned experiment in the manual before coming to the laboratory. Since each experiment must be finished during the lab session, familiarity with the underlying theory and procedure will prove helpful in speeding up your work. Although you may leave when the required work is complete, there are often "additional credit" assignments at the end of each write-up. The most common reason for not finishing the additional credit portion is failure to read the manual before coming to lab. We dislike testing you, but if your TA suspects that you have not read the manual ahead of time, he or she may ask you a few simple questions about the experiment. If you cannot answer satisfactorily, you may lose mills (see below).

RESPONSIBILITY AND SAFETY

Laboratories are equipped at great expense. You must therefore exercise care in the use of equipment. Each experiment in the lab manual lists the apparatus required. At the beginning of each laboratory period check that you have everything and that it is in good condition. Thereafter, you are responsible for all damaged and missing articles. At the end of each period put your place in order and check the apparatus. By following this procedure you will relieve yourself of any blame for the misdeeds of other students, and you will aid the instructor materially in keeping the laboratory in order.

The laboratory benches are only for material necessary for work. Food, clothing, and other personal belongings not immediately needed should be placed elsewhere. A cluttered, messy laboratory bench invites accidents. Most accidents can be prevented by care and foresight. If an accident does occur, or if someone is injured, the accident should be reported immediately. Clean up any broken glass or spilled fluids.

FREEDOM

You are allowed some freedom in this laboratory to arrange your work according to your own taste. The only requirement is that you complete each experiment and report the results clearly in your lab manual. We have supplied detailed instructions to help you finish the experiments, especially the first few. However, if you know a better way of performing the lab (and in particular, a different way of arranging your calculations or graphing), feel free to improvise. Ask your TA if you are in doubt.

LAB GRADE

Each experiment is designed to be completed within the laboratory session. Your TA will check off your lab manual and computer screen at the end of the session. There are no reports to submit. The lab grade accounts for approximately 15% of your course total. Basically, 12 points (12%) are awarded for satisfactorily completing the assignments, filling in your lab manual, and/or displaying the computer screen with the completed work. Thus, we expect every student who attends all labs and follows instructions to receive these 12 points. If the TA finds your work on a particular experiment unsatisfactory or incomplete, he or she will inform you. You will then have the option of redoing the experiment or completing it to your TA's satisfaction. In general, if you work on the lab diligently during the allocated two hours, you will receive full credit even if you do not finish the experiment.

Another two points (2%) will be divided into tenths of a point, called "mills" (1 point = 10 mills). For most labs, you will have an opportunity to earn several mills by answering questions related to the experiment, displaying computer skills, reporting or printing results clearly in your lab manual, or performing some "additional credit" work. When you have earned 20 mills, two more points will be added to your lab grade. Please note that these 20 mills are additional credit, not "extra credit". Not all students may be able to finish the additional credit portion of the experiment.

The one final point (1%), divided into ten mills, will be awarded at the discretion of your TA. He or she may award you 0 to 10 mills at the end of the course for special ingenuity or truly superior work. We expect these "TA mills" to be given to only a few students in any section. (Occasionally, the "TA mills" are used by the course instructor to balance grading differences among TAs.)

If you miss an experiment without excuse, you will lose two of the 15 points. (See below for the policy on missing labs.) Be sure to check with your TA about making up the computer skills; you may be responsible for them in a later lab. Most of the first 12 points of your lab grade is based on work reported in your manual, which you must therefore bring to each session. Your TA may make surprise checks of your manual periodically during the quarter and award mills for complete, easy-to-read results. If you forget to bring your manual, then record the experimental data on separate sheets of paper, and copy them into the manual later. However, if the TA finds that your manual is incomplete, you will lose mills.

In summary:

Lab grade =	(12.0 points)
	− (2.0 points each for any missing labs)
	+ (up to 2.0 points earned in mills of "additional credit")
	+ (up to 1.0 point earned in "TA mills")
Maximum score =	15.0 points

Typically, most students receive a lab grade between 13.5 and 14.5 points, with the few poorest students (who attend every lab) getting grades in the 12s and the few best students getting grades in the high 14s or 15.0. There may be a couple of students who miss one or two labs without excuse and receive grades lower than 12.0.

How the lab score is used in determining a student's final course grade is at the discretion of the individual instructor. However, very roughly, for many instructors a lab score of 12.0 represents approximately B− work, and a score of 15.0 is A+ work, with 14.0 around the B+/A− borderline.

POLICY ON MISSING EXPERIMENTS

1. In the Physics 6 series, each experiment is worth two points (out of 15 maximum points). If you miss an experiment without excuse, you will lose these two points.

2. The equipment for each experiment is set up only during the assigned week; you cannot complete an experiment later in the quarter. You may make up no more than one experiment per quarter by attending another section during the same week and receiving permission from the TA of the substitute section. If the TA agrees to let you complete the experiment in that section, have him or her sign off your lab work at the end of the section and record your score. Show this signature/note to your own TA.

3. (At your option) If you miss a lab but subsequently obtain the data from a partner who performed the experiment, and if you complete your own analysis with that data, then you will receive one of the two points. This option may be used only once per quarter.

4. A written, verifiable medical, athletic, or religious excuse may be used for only one experiment per quarter. Your other lab scores will be averaged without penalty, but you will lose any mills that might have been earned for the missed lab.

5. If you miss three or more lab sessions during the quarter for any reason, your course grade will be Incomplete, and you will need to make up these experiments in another quarter. (Note that certain experiments occupy two sessions. If you miss any three sessions, you get an Incomplete.)

Heart Rate Meter

APPARATUS

- Computer and Pasco interface
- Heart rate sensor

INTRODUCTION

This is a short experiment designed to introduce you to computer acquisition of data and the Pasco Science Workshop with its Capstone control program. It is not solely a physics experiment, but also an exercise to acquaint you with the equipment that will be used for "real" labs. If you are already familiar with computers, then this experiment will probably take less than an hour; if not, you should use any remaining time to practice with the computer.

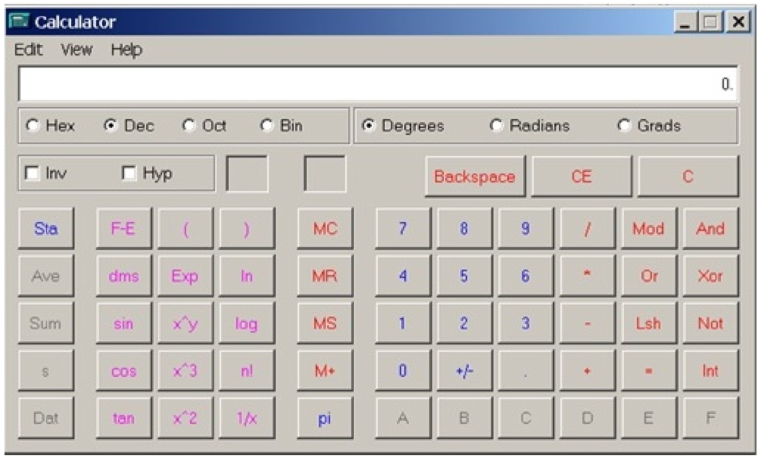
COMPUTER EXPERIMENTS

Many experiments in the Physics 6A lab series utilize a desktop computer to acquire and analyze data. Most students entering UCLA are already familiar with the basic Windows operations of clicking and dragging with a mouse, pulling down menus, scrolling and resizing windows, and so forth. If you are not familiar with these operations, then consider this experiment a practice session.

It is likely that the computer has already been turned on when you enter the lab. If not, when you turn it on, it will take a minute or two for the system to "boot up". In the entire Physics 6 lab series, two basic programs are used: Capstone (which controls an interface box to which various experimental sensors can be connected) and the spreadsheet program Microsoft Excel (which allows you to analyze and graph data). After the computer is booted up, you should see shortcut icons for these two programs on the desktop.

SCIENTIFIC CALCULATOR

You may also have occasion to use an on-screen calculator while working on experiments. Bring up the calculator by clicking on the "Start" menu, go to "Programs", then to "Accessories", and finally to "Calculator". When the calculator is displayed, pull down the "View" menu to "Scientific", so that the type of calculator on the screen changes to scientific. If you have any difficulty bringing up the scientific calculator, ask your TA for assistance. You should be able to access the scientific calculator quickly at any time during the next three quarters of labs.



THE PASCO INTERFACE

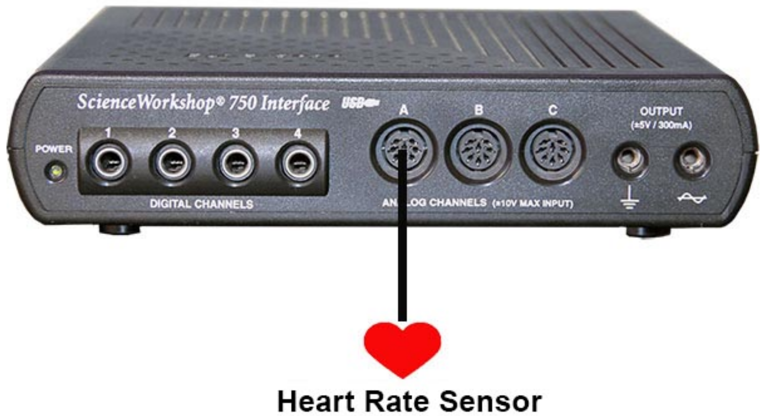
The Pasco Science Workshop system consists of an interface box controlled by the Capstone computer program, and a variety of different sensors that can measure distances and velocities by echo ranging (via a sonic ranger) or by motion of a smart pulley; as well as by voltage, heart rate, temperature, pressure, light intensity, magnetic fields, and many other physical quantities. Newer interfaces plug into a USB port of the computer, and have inputs for four digital channels and three analog channels. The interface can measure several quantities simultaneously and also has a built-in signal generator which can be controlled to produce 0 – 5 volt signals of DC, AC, and several other different wave forms. The software with the interface permits you to display and analyze the results in a number of different forms: digital meter, analog meter, graph, table, oscilloscope, and so forth.

PROCEDURE

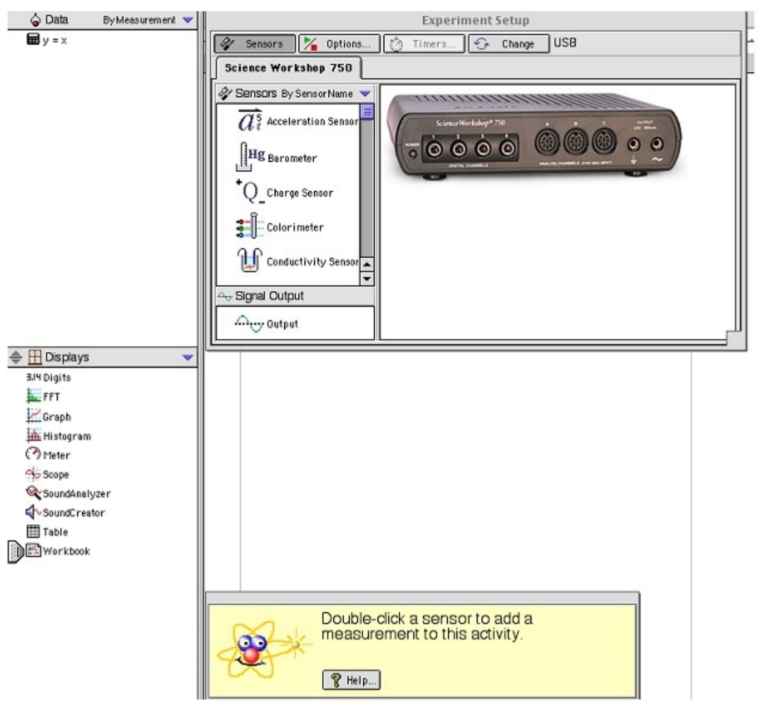
The terms in bold lettering below are basic computer operations with which you will need to be familiar by the end of this first experiment. If you have any difficulty with these operations, ask your TA; perhaps your lab partner can also help you. The partner less familiar with computers should perform most of the operations for this experiment. For the remaining experiments in the Physics 6 lab series, each partner should plan on performing half of the computer operations and half of the experimental setups and adjustments. Your TA has been instructed to intervene if he or she notices one partner doing a disproportionate share of either task.

The heart rate sensor consists of a small box with a multiple pin connector and a clip that attaches onto your ear lobe. The sensor measures the flow of blood through the lobe. As the heart forces blood through the vessels in the ear lobe, the light transmittance of the lobe is changed. The sensor monitors this light with a phototransistor.

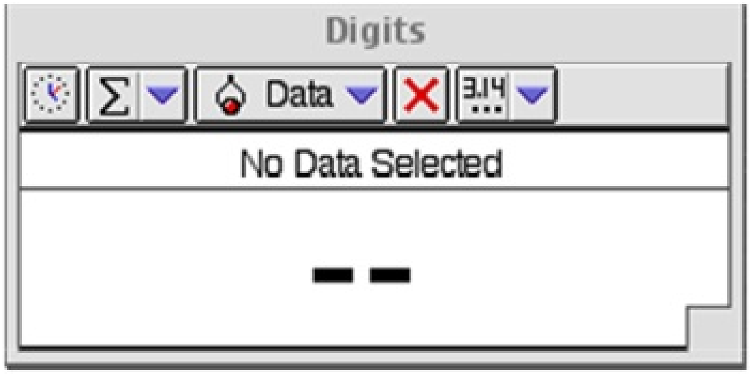
1. Plug the heart rate sensor into analog channel A, and turn on the signal interface.



2. On the computer screen, **double-click** on the PASCO Capstone icon to bring up the program. The illustration below shows the screen when Capstone is first loaded.



3. **Click** on the "Graph & Digits" option. Then **click** the "Hardware setup" button to display the interface. **Click** on Channel A of the interface and choose "Heart Rate Sensor". Next, **click** the red thumbtack button above the interface to bring both windows into view. Your screen should look like the image below.



4. On the y-axis of the graph, **click** the "Select Measurement" button and select "Heart Rate (beats/min)". Above the graph, **click** on the "Select Measurement" button in the digits box and choose "Heart Rate (beats/min)".

5. You are now ready to check your heart rate. Clip the heart sensor to your ear lobe. (The newer sensor boxes also show your heart rate with an LED display on the sensor box.) **Click** "Record" on the bottom tool bar. Observe the data for about one minute, and then **click** "Stop". You should see your resting heart rate (55 – 70 beats per minute for a typical person). The figure changes slightly every few seconds. If you do not see a clear, reasonable rate, try repositioning the ear clip or attaching it to your other ear. As a last resort, ask your TA for help.

6. To see the sensor voltage produced by your heartbeat, **click** on "Heart Rate" on the y-axis of the graph and select "Voltage (V)". You will see the voltage output data of the heart rate meter as a series of pulses. If there are too many pulses that it looks messy, try zooming in by clicking and dragging on the numbers on the x-axis of the graph

7. Whenever you **click** "Record" in Capstone, your previous recordings are no longer displayed. However, if you wish to see them again, **click** on "Data Summary" to see all recordings. You can view them again by dragging them to the desired graph or table or you can drag them to the display icons on the right side of the screen.

8. When the graph and digits windows are positioned clearly on the screen, and you have some clear data for your heart rate and sensor voltage, ask your TA to check you off. Congratulations! You have now finished the first experiment.

ADDITIONAL CREDIT: RAISING AND LOWERING YOUR HEART RATE (2 mills)

Throughout the lab sessions, you will have opportunities to earn "mills", or tenths of a point, which are added to your final lab score. You can earn up to 20 mills, or two points. This additional credit assignment is worth two mills, but first, be sure you and your lab partner are both familiar with the Windows computer operations described above.

The objective of this section is to raise your heart rate to a moderately high value by exercising, and then to produce a graph of heart rate as a function of time as the heart relaxes back to its resting mode. Before proceeding with the instructions below, be sure you have clicked "Stop" if the machine is still monitoring your heartbeat.

The sensor will not record an accurate heart rate when you are moving around. You will need to take off the sensor, exercise, and then hook yourself back up. Raise your heart rate to 140 beats per minute or higher by doing jumping jacks in position, or by going out and running around the building. <u>Do not perform the exercise if you have a health problem. Have your lab partner or another volunteer do it.</u> After exercising, reattach the sensor, and click “Record” to record your heart rate as a function of time. Remain as still as possible while the recording is made — say, for five minutes (or 300 seconds). Click “Stop” when you are finished.

Your graph should show a relatively smooth, decreasing heart rate from 140 beats per minute down toward your resting rate. If you do not obtain a smooth graph, get some more exercise and try again. Try to remain more still while recording, reposition the ear clip, or attach it to your other ear until you get a nice result. If the appearance of the graph is satisfactory, you can show this graph to your TA to collect two mills.

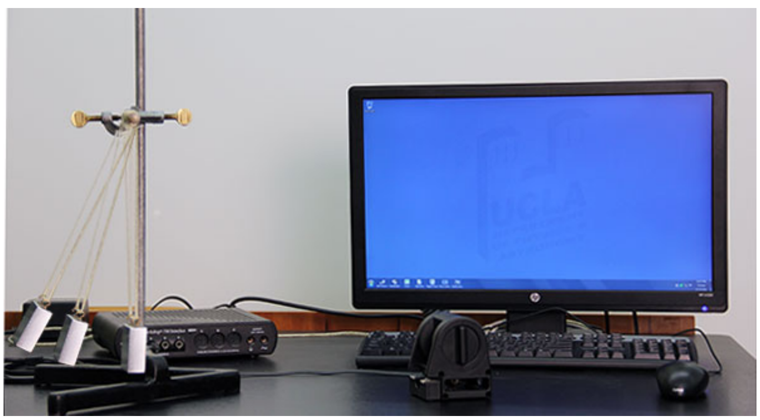
Kinematics

APPARATUS

- Computer and Pasco interface
- Motion sensor (sonic ranger)
- Air track, glider with reflector, block to tilt track
- Calipers to measure thickness of block
- Pendulum arrangement

INTRODUCTION

In this experiment, you will produce position, velocity, and acceleration graphs of your own movements, as well as that of a glider on an air track, using a motion sensor. A motion sensor (sometimes called a sonic ranger) measures the distances to objects by repeated reflection of ultrasonic sound pulses. The software included with this device takes the first and second derivatives of the position measurements to calculate the velocity and acceleration, respectively.



To determine distances, the motion sensor emits and receives ultrasound pulses at a frequency of approximately 50 kHz. Since the speed of ultrasound in air at room temperature is known, the software calculates these distances by measuring the time required for the pulse to reflect from an object and return to the sensor. This process is similar to how a bat "sees" using ultrasound, as well as how a Polaroid autofocus camera determines the distance to an object in order to focus properly.

The ultrasonic sound emitted by the motion sensor spreads about 15° off axis. Keep this in mind as you design your experiments. The sensor does not work for objects closer than 0.4 meters. (Some of the newer motion sensors have adjustable width beams and will measure objects as close as 15 centimeters.)

The clicking noise made by the motion sensor is not ultrasound, but a by-product of the mechanism that produces the ultrasound. Most people cannot hear the frequencies emitted by the sensor. If you place your ear near the device, however, you may be able to "feel" the pressure pulse of sound against your eardrum.

INITIAL SETUP

1. Turn on the signal interface and computer, plug the motion sensor into the interface (inserting the yellow-banded plug into digital channel 1 and the other plug into digital channel 2), and call up Capstone.

2. Choose "Table & Graph", then under Hardware Setup, click on channel 1 of the interface. Choose "Motion Sensor II".

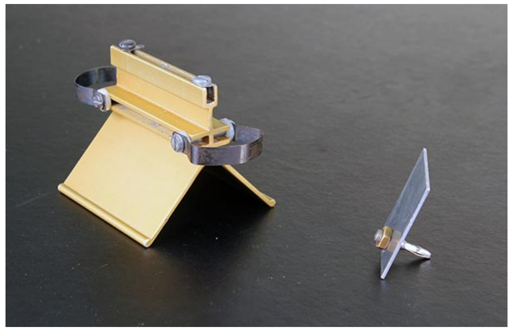
3. Click "Select Measurement" on the y-axis of the graph and choose "Position (m)". There is a tool at the top of the graph that says "Add new plot area to the Graph display". Click on this tool twice to display a total of three graphs.

4. For the second graph, set "Velocity (m/s)" on the y-axis. For the third graph, set "Acceleration (m/s^2)" on the y-axis.

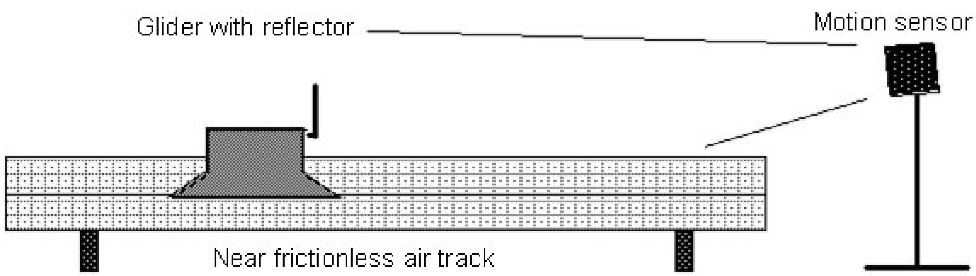
5. Click "Record" to activate the motion sensor. You should hear a series of rapid clicks. Test out the motion sensor by holding a book facing, and approximately 0.5 meter away from, the sensor. (The sensor does not measure distances closer than 0.4 meter.) Move the book to a distance of 1.5 meters from the sensor and then back to 0.5 meter, click "Stop", and observe the graph. You may want to click the "Scale axes to show all data" button at the left end of the tool bar above the graphs. If you do not obtain a clean trace, try again, being careful to keep the book directly in front of the sensor.

PROCEDURE

1. Turn on the air track and level it by adjusting the leveling screw such that a glider on the track has no apparent tendency to move in either direction. Since air tracks are often bowed in the middle, place the glider at several different positions on the track to verify that it is as level as possible. Attach a reflector to the glider.



Arrange the sensor so it points slightly downward and can follow the glider along the entire length of track, as shown below. Place your eye at the position you want the sensor to point. Look into its reflective face, and adjust the sensor until you see your reflected image. The sensor is now directed at your eye position.



Tilt the end of the track up by placing the small block under the leveling screw. Give the glider a small hand push up the track. The glider should slow as it moves up, stop momentarily before reaching the top end, and then coast back down the track. After experimenting with several trials, predict the position, velocity, and acceleration of the glider as it moves along the track.

Now set your computer to produce all three graphs aligned vertically. Record the motion of the glider moving up, slowing, stopping, and moving back down.

Practice the attitude that you are going to make the experiment work well and produce a good position graph. If your initial graphs are not clean, adjust the position and direction of the motion sensor, adjust the tilt of the reflector on the glider, etc., until you get a good data set. (Your acceleration graph may still look ragged.) When you have a graph with clean data on the screen, compare this with your predictions. You can print it out to keep for your records.

2. Use the Vernier caliper (see instructions below) to measure the height h of the block which tilts the track, and use the ruler built into the track to measure the distance D along the track between the track supports. The sine of the tilt angle α is equal to h/D; knowledge of h and D allows you to determine α. As the glider moves along the track, Newton's Second Law predicts that its acceleration should be constant and equal in magnitude to $g \sin \alpha$. Calculate the value of this acceleration. This is your theoretical prediction for the acceleration of the cart.

3. Acceleration graphs often look ragged, as small errors accumulate when the software takes

the second derivative of the position data. We will use the method of linear regression to determine the the acceleration of the cart. Notice the linearly increasing portion of your velocity graph. Select this region of interest by first clicking on the velocity graph then clicking on the "Highlight range of points in active data" tool. A rectangle will appear. Drag and extend this rectangle over the linearly increasing portion of your data. Click inside the rectangle to highlight the data.

4. Click the drop-down arrow of the "Apply selected curve fits to active..." tool and choose "Linear". Click this tool again to bring up a display box. You should see a best-fit line appear on top your selected data and a box should pop up that tells you the slope and y-intercept of this best-fit line. The slope of this line is your experimentally measured acceleration of the cart. Write this value down for your analysis.

5. Another way to measure the acceleration is by looking at the acceleration graph. In general your graph should be flat (and possibly a a bit ragged). We want to find the average of these data points. To do this, select the data points of interest using the "Highlight range of points in active data" tool. Click the "Display selected statistics for active..." tool. This will display the mean value of the points you selected. Compare this to the value you obtained by making a best-fit line.

   Note: By default, Capstone gives only one digit of precision for acceleration measurements and calculations performed using them. You can increase this precision as follows: Open "Data Summary" from the left hand panel and select the name of the measurement in question. In this case, you would select "Acceleration (m/s^2)" . Next click the blue gear icon (settings), open the "Numerical Format" dropdown menu, and modify the "Number of Decimal Places" as desired.

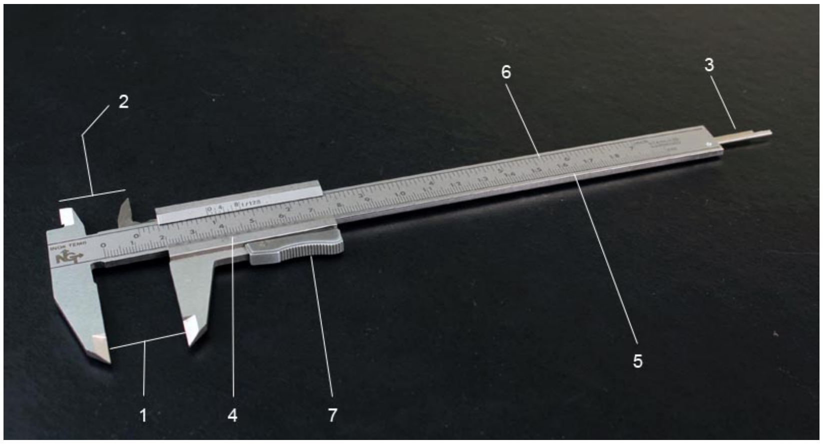
6. Calculate the percentage error between the experimental results a_{exp} obtained in steps 4 and 5, and the theoretical value a_{th} determined in step 2:

   percentage error $= (100\%) \times (\mid a_{\text{exp}} - a_{\text{th}} \mid) / a_{\text{th}}$.

   The absolute value is taken because we are not interested in the sign of the difference. Typical experimental accuracies in an undergraduate lab range from $3-5\%$, although some quantities can be measured much more accurately (and some much less!).

VERNIER CALIPER

The **Vernier caliper** is designed to provide a highly precise measurement of length. The numbers in parentheses refer to those found in the figure below.



The **outside jaws** (1) are used to measure around the exterior of an object. The **inside jaws** (2) are used to measure inside the holes of an object. The **depth gauge** (3) is used to measure the depth of holes.

The **Vernier** (4) is used to divide further the **metric scale** (5) or the **English scale** (6) down to 0.01 centimeter or 1/128 inch, respectively. Its operation is described in detail below.

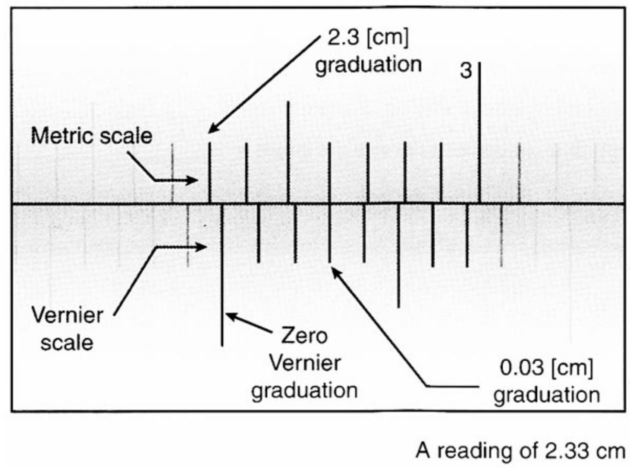
The **thumbwheel** (7) is used to open and close the jaws.

The **locking screw** (8) is used to lock the jaws in position.

The **Vernier** is a device used for estimating fractional parts of distances between two adjacent divisions on a **scale**. The **Vernier scale** subdivides each **main scale** division into as many parts as there are divisions on the scale.

The **Vernier** and **main scales** are placed in contact with each other. The **main scale** is read to the nearest number of whole divisions, while the zero on the **Vernier scale** serves as the index (i.e., the line on the extreme left). One should then estimate the fractional part of the **main scale** reading as a check of the more accurate reading to be made with the aid of the **Vernier scale**.

The **metric scale** is divided into tenths of a centimeter (i.e., millimeters). The **Vernier scale** is divided into 10 divisions, thus representing hundredths of a centimeter. At any given setting, the marks on the **Vernier** and **main scales** coincide at only one point. The mark on the **Vernier scale** which coincides most closely with a corresponding mark on the **main scale** represents the Vernier reading. The figure below should help clarify this.



DATA

This section is to help you organize your data and guide you through the calculation.

1. Mean value of acceleration = ______________________________

   Slope of velocity graph (best-fit line) = ______________________________

Always record units with your results.

CALCULATIONS

2. $g \sin\alpha$ = ______________________________

3. Percentage error for mean value of acceleration = __________

   Percentage error for slope of velocity graph (best-fit line) = __________

QUESTIONS

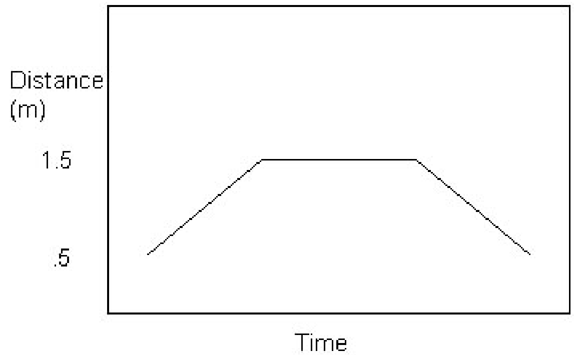
a. What does calculus tell us about the relationship between the position and velocity graphs?

b. Suppose you were able to arrange the motion sensor to measure and plot the position, velocity, and acceleration of a ball thrown vertically upward into the air. Neglecting air resistance, how would these graphs compare with those of the glider experiment? Elucidate any differences.

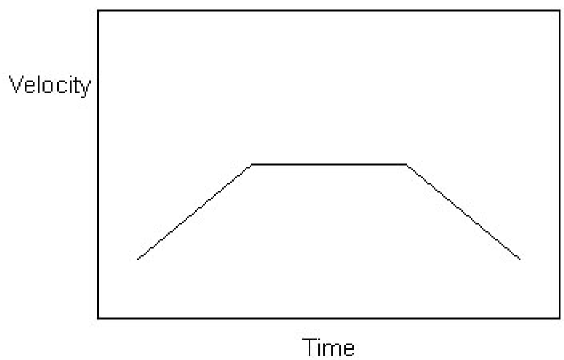
ADDITIONAL CREDIT: Kinematics Graphs (3 mills)

In the steps below, you will need to move in a straight line away from the motion sensor for a distance of roughly 2 meters. Begin by removing any objects that may hamper your motion or otherwise reflect the signal from the sensor. Arrange the computer monitor so you can see the screen while traveling backward, and be sure your path is clear.

1. While holding a book facing the sensor, move in such a way that you qualitatively reproduce the position-versus-time graph pictured below. (That is, move in such a way that you produce a computer graph shaped roughly like the one below. However, don't worry about getting any of the numbers to match up – we're only interested in reproducing the shape here.)



2. Now move in such a way that you produce a computer graph described qualitatively by the velocity-versus-time graph shown below. You may find the velocity graph more difficult to reproduce than the position graph. Have each lab partner attempt the motion a few times, and display the best result. If you are not able to obtain the approximate shape, ask your TA to demonstrate, and try to repeat the motion.



ADDITIONAL CREDIT: PENDULUM MOTION (3 mills)

Arrange the motion sensor to track a swinging pendulum. For a pendulum bob, use a block with a flat side facing the sensor. Set the pendulum into motion with small-amplitude oscillations (so the pendulum swings only a few inches), carefully positioning and aligning the sensor so it tracks this motion and produces smooth curves. Display a graph showing position, velocity, and acceleration. Be prepared to discuss which mathematical function describes each graph, as well as how the graphs are related, and ask the TA to check your work.

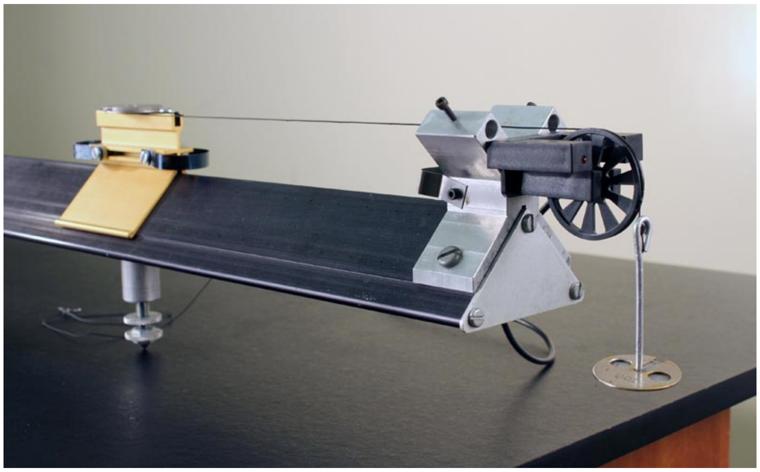
Note: It is very common for students doing this experiment to position the motion sensor in such a way that the pendulum is out of view of the motion sensor for at least part of the motion. As stated above, the pendulum should move in a *smooth* curve – if your curve is mostly smooth but has spikes or bumps at the uppermost or lowermost points, then you likely need to reposition the sensor.

Newton's Second Law

APPARATUS

Shown in the picture below:

- Air track, smart-pulley mount, and smart pulley
- Small glider
- Mass holder for gliders
- 5-gram mass hanger and three 5-gram disks



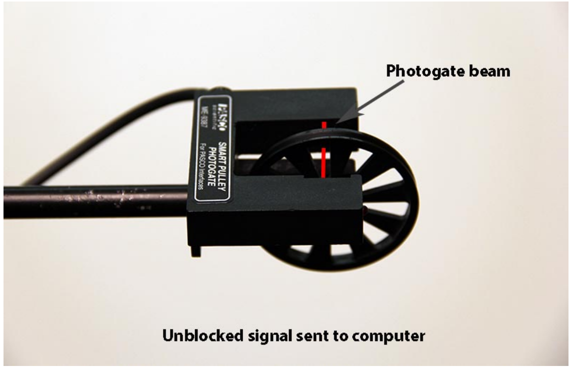
Not shown in the picture above:

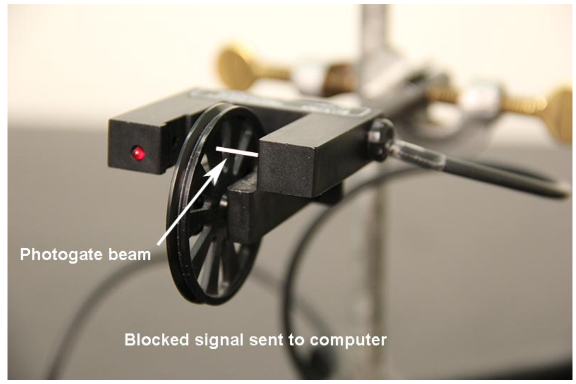
- Computer and Pasco interface
- Large glider
- Scale and weight set
- Photogate and picket fence
- Rag box for collecting picket fence

INTRODUCTION

In this experiment, you will test Newton's Second Law by allowing a falling weight (i.e., a known force) to accelerate a glider of known mass along an air track. A string connecting the falling weight to the glider passes over a smart pulley.

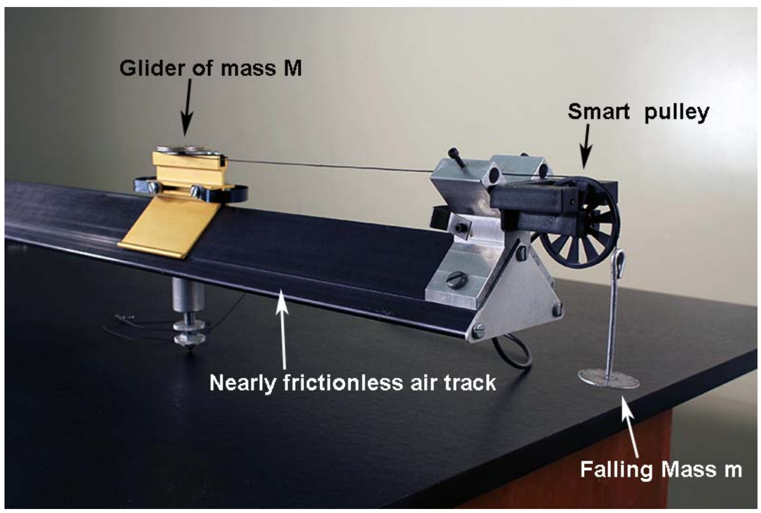
The smart pulley has low friction and low inertia, and its rotation is monitored by an attached photogate. One arm of the photogate emits a thin beam of infrared light which is detected by the other arm. The computer discerns whether the beam strikes the detector or is blocked by a spoke in the pulley sheaf. The small LED light in front of one arm illuminates when the beam is blocked. By accurately timing the signals that arrive from the photogate, the computer is able to track the motion of any object linked to the pulley.





THEORY

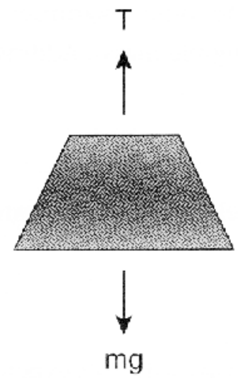
Consider a glider of mass M on a nearly frictionless air track. This glider is attached to a small mass m by a string passing over a smart pulley. The Earth exerts a downward force on the small mass which is equal in magnitude to its weight mg.



Reasoning somewhat intuitively, we can say that this gravitational force causes the entire system of mass $M + m$ to accelerate. Newton's Second Law can then be written as

$$mg = (M + m)a. \tag{1}$$

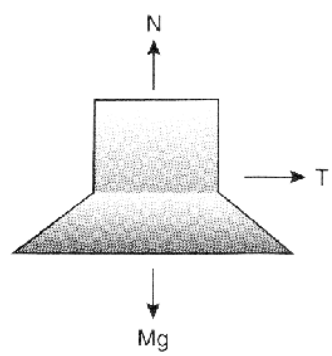
More rigorously, let us draw free-body diagrams for each of the two masses. The forces exerted on the small mass m are its weight mg (downward) and the tension T in the string (upward). These two forces cause m to accelerate downward:



$$\sum F_y = mg - T = ma. \tag{2}$$

Note that we have assigned a positive sign to quantities pointing in the (downward) direction of motion.

The forces exerted on the glider of mass M are its weight Mg (downward), the normal force N from the track (upward), and the tension T in the string (rightward). Since there is no motion in the vertical direction:



$$\sum F_y = N - Mg = 0 \tag{3}$$

or

$$N = Mg. \tag{4}$$

In the horizontal direction,

$$\sum F_x = T = Ma. \tag{5}$$

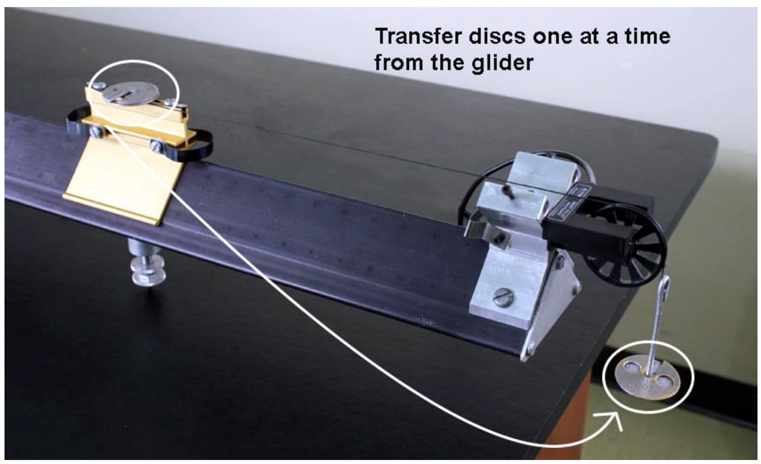
The glider and small mass have the same magnitude of acceleration a since they are connected by a taut string (of negligible mass). Adding Eqs. 2 and 5, we obtain

$$mg = (M + m)a \tag{6}$$

as postulated above. Thus, the acceleration of the system is

$$a = mg/(M + m). \tag{7}$$

If we wish to test Newton's Second Law, we might think of using different small masses m and checking whether the acceleration a is proportional to the gravitational force mg. Eq. 7, however, shows that a is not simply proportional to m, since the denominator also depends on m. Thus, holding M constant while increasing m causes the total mass of the system to increase. On the other hand, if we add, say, three more small masses (each of mass m) to the glider and transfer them one at a time to the hanger (also of mass m), then the total mass $M + 4m$ of the system remains constant. Hence, we can test whether the acceleration of the system is proportional to the gravitational force as it increases in magnitude from mg to $2mg$, $3mg$, and $4mg$. (Note that when using this method, you need to decide how many measurements to make before doing the experiment, and then add the corresponding masses to the glider.)



INITIAL SETUP

1. Turn on the air track and level it by adjusting the leveling screw such that a glider on the track has no apparent tendency to move in either direction. Since air tracks are often bowed in the middle, place the glider at several different positions on the track to verify that it is level.

2. Turn on the signal interface and computer, plug the smart pulley into the interface (inserting the plug into digital channel 1), and call up Capstone and choose the "Table & Graph" option.

3. In the "Hardware Setup" tab, click on channel 1 and select "Photogate with Pully". Click on the "Select Measurement" button on the y-axis and choose "Position (m)". Click the "Add new plot area..." button above the graph twice to add two additional graphs. Plot "Linear Speed (m/s)" on the y-axis of one graph and "Linear Acceleration (m/s^2)" on the y-axis of the other.

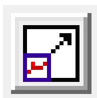
4. Using approximately 1.5 meters of thread, connect the 5-gram mass hanger to a glider. Make sure the thread passes over the smart pulley so the hanger will accelerate a glider down the track.

PROCEDURE

1. Weigh each glider to obtain its mass, and record the values in the "Data" section.

2. Attach (or tape) three 5-gram masses to the small glider, such that only the 5-gram mass holder accelerates the glider. Turn the air-track blower on, and set one glider on the track as far from the pulley as the thread allows. Click "Record", and immediately release the glider so that it begins to move. Just before the hanger hits the floor or the glider reaches the end of the track, click "Stop".

3. Check the graph window and use the "Scale-to-fit" button, if necessary. Check that you are obtaining reasonable plots of the glider's position, velocity, and acceleration. As usual, the acceleration graph may look ragged.

    scale-to-fit button at top left of graph tool bar

4. Read an "eyeball" value of acceleration directly from the graph (This is just an estimate) and record this value in the "Data" section.

5. Click on the velocity graph then click on the "Highlight rang of points..." button. A box will appear in the velocity graph. Drag this box over the data of interest (the linear part). Click inside the box to highlight the data. Click the "Apply selected curve fits..." button and select linear. A box appears telling you the slope of the best-fit line. Record this slope in the "Data" section.

6. We will be recording and graphing data on an Excel spreadsheet. Call up Excel on your computer. When the program has booted up, you will see a menu bar with a set of icons above, and the spreadsheet cells in rows and columns below. Our plan is to record three trials of the acceleration for the accelerating mass, and then to calculate the average acceleration of the each of the three trials. Accordingly, prepare your spreadsheet like the one illustrated below.

	A	B	C	D	E	F
1	Acceleration of an air track glider in m/s^2					
2						
3	accelerating mass (g)	5	10	15	20	
4	acceleration, trial 1					
5	acceleration, trial 2					
6	acceleration, trial 3					
7	average acceleration					
8						
9						

If you have not used a spreadsheet before, it consists of a sheet of cells labeled by the numbers on the left and the letters on the top. You can enter numbers or text into the cells; the numbers can be manipulated mathematically later. To make an entry into a cell, click on the cell, and begin typing. The text appears on the menu line above, and you can edit it by deleting parts, or by dragging through and typing the corrected material. There are at least four ways of entering typed material into a cell: clicking on the green check, hitting "Enter", pressing an arrow key to move to a nearby cell, or clicking on a new cell.

7. Make sure three 5-gram masses are still attached to the small glider, with the only 5-gram mass holder hanging down. Set the system into motion. Obtain the acceleration as described in step 5, and record its value in your spreadsheet. Perform a minimum of three trials. (As data runs accumulate on your velocity graph, you can select run numbers in the box on the graph and delete them to see the current data more clearly.)

8. Transfer one 5-gram mass from the glider to the mass holder, such that the holder and one 5-gram mass accelerate the glider. Set the system into motion, obtain the acceleration, and record its value in your spreadsheet. Perform a minimum of three trials.

9. Transfer another 5-gram mass from the glider to the mass holder, such that the holder and two 5-gram masses accelerate the glider. Set the system into motion, obtain the acceleration as before, and record its value in your spreadsheet. Perform a minimum of three trials.

10. Transfer the final 5-gram mass from the glider to the mass holder, such that the holder and all three 5-gram masses accelerate the glider. Set the system into motion, obtain the acceleration as before, and record its value in your spreadsheet. Perform a minimum of three trials.

11. To calculate the average acceleration of the first three trials, in cell B7 of the Excel illustration above, type the material between the quotes, "=Average(b4..b6)", and click the green check in the tool bar (or hit "Enter"). The equals sign signals Excel to do a calculation. This operation will average the numbers in cells B4, B5, and B6. It does not matter that the B's are typed in lower case in the Average function. *Note: If you set up your spreadsheet slightly differently from the one pictured above, the relevant quantities may be in different cells than listed in the preceding lines. In that case, you need to determine which (a) in which cell to place the average function and (b) which cells to average over, in order to obtain your average accelerations in an appropriate place.*

12. Now comes the great virtue of spreadsheets. You do not need to type the Average function into the cells for the other trials. Instead, position the cursor at the lower right corner of cell B7 (the one in which you just did the Average calculation), so that it turns into a lopsided square shape. Now drag over cells C7, D7, and E7. Excel automatically calculates the averages of the other trials with the proper cell references. (By the way, if you were now to change one tf the values of the trial accelerations, Excel would automatically and instantly recalculated the average.) Your spreadsheet should now look something like the illustration below:

	A	B	C	D	E	F
1	Acceleration of an air track glider in m/s^2					
2						
3	accelerating mass (g)	5	10	15	20	
4	acceleration, trial 1	0.1337	0.2855	0.4331	0.5777	
5	acceleration, trial 2	0.1343	0.2846	0.4326	0.5823	
6	acceleration, trial 3	0.1368	0.2850	0.4333	0.5824	
7	average acceleration	0.1349	0.2850	0.4330	0.5808	
8						
9						

(Dragging the calculation across the cells is called the "Fill Right" operation. There is also a "Fill Down" operation for dragging a calculation down a column. Positioning the cursor at the corner of the cell is a short cut to these operations. They can also be accessed from the "Edit" pull down menu.)

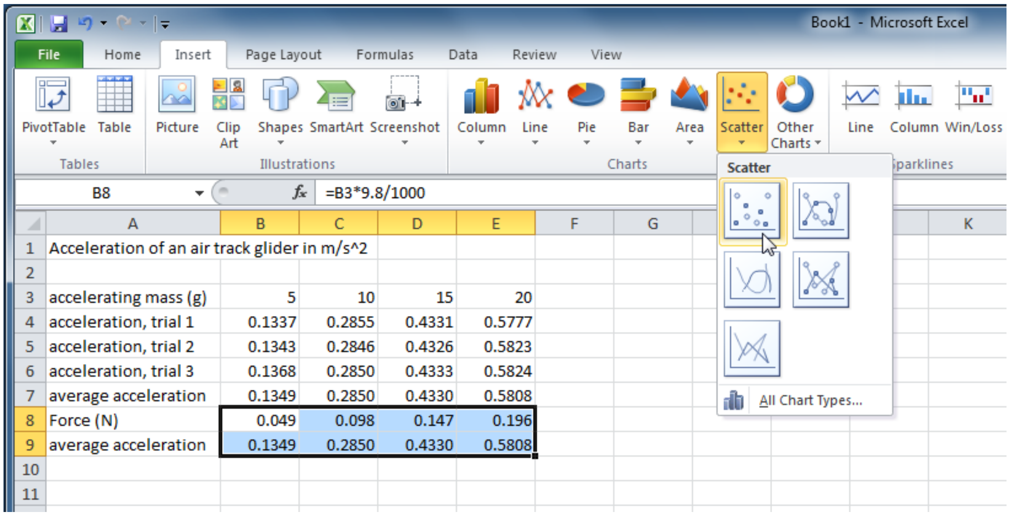
13. In cell A8 of the illustration above, type "Force (N)". In cell B8, type the expression between the quotes, "=B3*9.8/1000". This will take the mass entry in cell B3, divide it by 1000 to convert to kilograms, and multiply by 9.8 to convert to newtons. Then drag this calculation across the other three cells C8 – E8 to calculate the force for each case.

14. We will now have Excel chart this data. First, if we leave the acceleration data above the force data, the acceleration will be plotted on the x-axis and the force on the y-axis. Since we consider the force to be the independent variable in this experiment, we would prefer it the other way. Accordingly:
    - Click the label "7" to select row 7,
    - Pull "Edit" down to "Copy" (or simply hit CTRL+C, the control button and the C button together, to copy),
    - Select row 9, and
    - "Paste Special" the "Values" into row 9.

	A	B	C	D	E	F
1	Acceleration of an air track glider in m/s^2					
2						
3	accelerating mass (g)	5	10	15	20	
4	acceleration, trial 1	0.1337	0.2855	0.4331	0.5777	
5	acceleration, trial 2	0.1343	0.2846	0.4326	0.5823	
6	acceleration, trial 3	0.1368	0.2850	0.4333	0.5824	
7	average acceleration	0.1349	0.2850	0.4330	0.5808	
8	Force (N)	0.049	0.098	0.147	0.196	
9	average acceleration	0.1349	0.2850	0.4330	0.5808	
10						
11						

(If you were to use "Paste" instead of "Paste Special", Excel would have copied the cell averaging formulas and averaged wrong numbers in row 9.)

15. Now we chart:
    - Select the two rows of cells B8 through E9.
    - In the "Insert" tab menu, select the "Scatter" option without connecting lines:



- After clicking on this line-less scatter option, the chart should appear.
- From here (and whenever the chart area is active or highlighted) you can work with the "Chart Tools", which are organized by the "Design", "Layout", and "Format" tabs.
- Within the "Design" tab, in the "Chart Layouts" area, click on the left-most (and upper-most) layout option. This will place titles on the chart that you can edit or delete.
- Create your own title and labels for the axes.

16. Now we fit a line to the data; Excel calls this a "trendline". While the chart area is active or highlighted (click on the chart if you need to), select the "Layout" tab of the "Chart Tools" and click on "Trendline" in the "Analysis" area. Select "Linear Trendline". We want to find to find a numerical expression for this linear fit to the data: Again, click on "Trendline" but now select "More Trendline Options...". In the pop-up window, make sure "Linear" is selected, and check the box beside "Display Equation on chart". Click on "Close". Since we are plotting $a = F/m_{\text{total}}$, the slope of the equation (the factor multiplying x) is $1/m_{\text{total}}$. Calculate this experimental m_{total}, enter it in the "Data" section, compare it to the value of m_{total} obtained by weighing the glider plus the 20 grams of small masses used to accelerate the glider $(M + 4m)$, and calculate the experimental error. Show your results to your TA.

DATA

1. Mass of small glider = ________________________________

   Mass of large glider = ________________________________

5. "Eyeball" value of acceleration = ________________________________

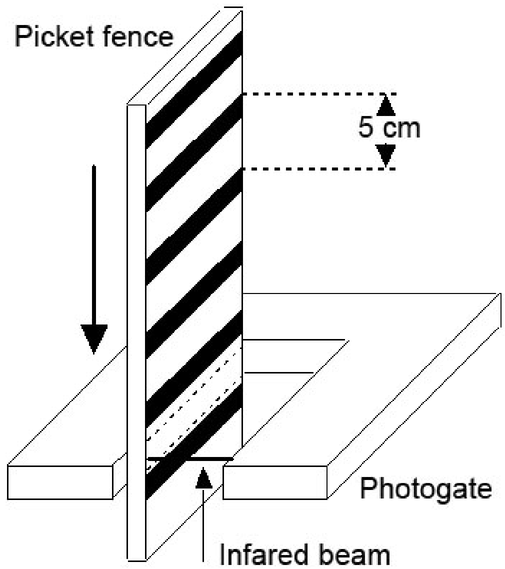
6. Slope of velocity graph = ________________________________

17. Experimental mass = ________________________________

    Experimental error = ________________________________

ADDITIONAL CREDIT: FREE-FALLING PICKET FENCE (3 mills)

Here you will need a photogate, a picket fence, and a rag box to catch the falling fence. The picket fence is a strip of clear plastic with evenly spaced black bars. When the fence is dropped through a photogate, the light beam is interrupted by the bars; since the fence accelerates while falling, the bars interrupt the beam with increasing frequency. The software calculates the distance fallen, as well as the corresponding velocity and acceleration. This acceleration should be constant and equal in magnitude to g.



Under "Hardware Setup", select "Picket Fence" to add the sensor. Insert the physical plug of the photogate into the appropriate digital channel of the interface. Drag a new graph over from the graph icon on the right side of the screen. Click the "Select Measurement" button on the y-axis and select "Acceleration (m/s^2)". Arrange the photogate in such a way that the falling picket fence will be caught by the rag box on the floor.

Click "Record", drop the picket fence through the photogate, and click "Stop". Since the entire motion occurs within a fraction of a second, you may not see much on the graph. Expand the time scale using the "Scale-to-fit" button. Again, the acceleration graph may look ragged. Use the " Display selected statistics..." button to find the mean value of the acceleration. Record the magnitude of the acceleration due to gravity with experimental error below.

Experimental g = ______________________________

Experimental error = ______________________________

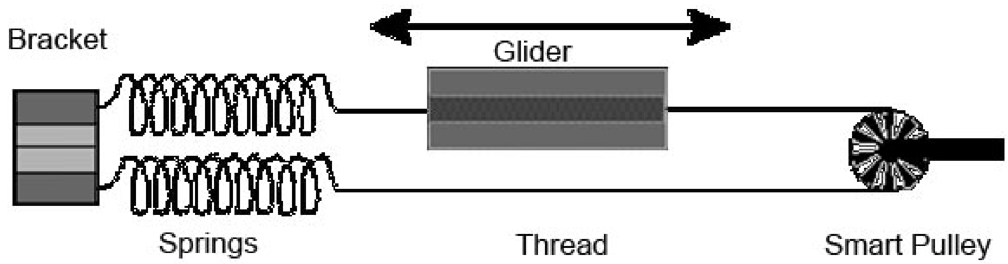
This short experiment illustrates the power of computer measurement. It appears easy, but be sure you understand what is happening in the measurement and can explain the results to your TA.

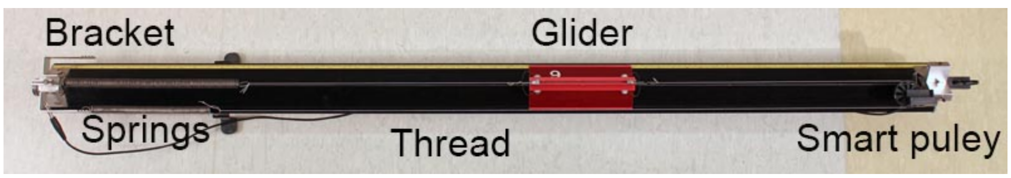
Conservation of Energy

APPARATUS

Shown in the diagram and picture below (both with a top-down view):

- Air track, springs and bracket, thread, glider
- Smart pulley and mount
- Dumb pulley (on the same mount)





Not shown in the images above:

- Computer and Pasco interface
- Scale and weight set
- Mass hanger

THEORY

In this experiment, you will test the Law of Energy Conservation by monitoring an oscillating air track glider connected to springs by a thread which passes over a smart pulley.

Consider a glider of mass M on a nearly frictionless air track. As the glider oscillates back and forth, there is a continuous exchange of mechanical energy between two forms: kinetic energy contained in the moving glider, and potential energy stored in the stretched or compressed springs. The Law of Energy Conservation tells us that the total mechanical energy of the system (i.e., the sum of the kinetic and potential terms) remains constant in time. In reality, however, a small amount of mechanical energy may be lost to friction.

INITIAL SETUP

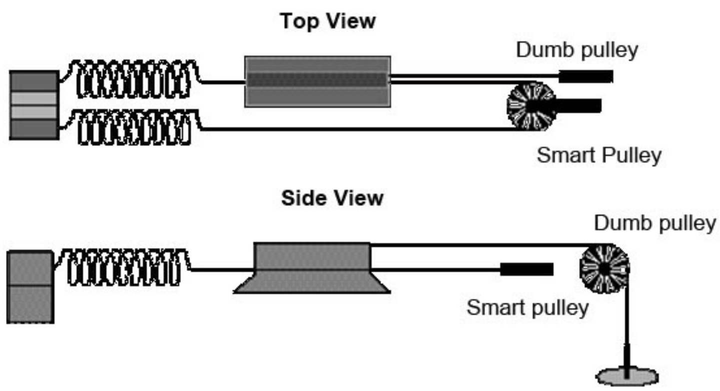
1. Turn on the air track and level it by adjusting the leveling screw such that a glider on the track has no apparent tendency to move in either direction. Since air tracks are often bowed in the middle, place the glider at several different positions on the track to verify that it is

level.

2. Weigh the glider to obtain its mass, and record this value in the "Data" section.

3. Assemble the springs, glider, smart pulley, and thread as shown in the figure below. One spring is attached to a bracket at the end of air track and to one end of the glider. The other end of the glider is attached to a second spring by a thread which passes over the smart pulley. The second spring is then attached to the bracket. The springs should be tensioned so that you can get an end-to-end glider motion over a distance of at least 40 cm without either spring being completely compressed.

4. Mount a dumb pulley (which has low friction, but is not connected to the computer) on the same fixture that holds the smart pulley, albeit in a vertical plane. Using a long piece of thread, connect the mass hanger to the glider. Make sure the thread passes over the dumb pulley so that weights added to the hanger will displace the glider.



PROCEDURE PART 1: MEASURING THE SPRING CONSTANT k

1. Our first task is to measure k, the force constant in $F = -kx$ of a Hooke's Law spring. Call up a blank Excel worksheet and prepare three columns to record the total mass in the hanger (including the mass of the hanger itself) in grams, its weight in newtons, and the position of the glider in meters. In the mass column, type "0" and "10" in the first two cells. Select these two cells, position the cursor at the lower left corner of the bottom cell until it turns into a lopsided square, and drag down the column to fill it with a series up to 60 grams. The running yellow box shows how far the series continues.

2. Fill down the next column with the force values. Remember how to do this? Type "`=A3*9.8/1000`" in the cell next to the mass value of zero, *being sure to use the correct cell designation corresponding to your spreadsheet* (where we typed "`A3`" above, you should type the cell containing the first value in the mass column). Then fill down the forces next to the masses.

3. Now make the measurements. Turn on the air blower, and help the glider come to equilibrium. Add mases to the mass hanger, one at a time, and read the distance (in meters!) from the scale on the air track aligned with one corner of the glider. On your spreadsheet, record the distance corresponding to the addition of each mass in the mass hanger. Be sure that you use values corresponding to the entries in the mass column (including the mass of the hanger itself). If you need to use different masses, change the mass entries; the forces will be

recalculated instantly.

4. When you have filled in the distance column next to the force column, chart these variables against each other in Excel, and find the slope. Here is a reminder of how this is done:
   - Select the cells with numbers in the force and distance columns.
   - In the "Insert" tab menu, select the "Scatter" option without connecting lines. After clicking on this line-less scatter option, the chart should appear.
   - Within the "Design" tab of the "Chart Tools", in the "Chart Layouts" area, click on the left-most (and upper-most) layout option. This will place titles on the chart that you can edit or delete.
   - Create your own title and labels for the axes.
   - In the "Layout" tab of the "Chart Tools", click on "Trendline" in the "Analysis" area. Select "More Trendline Options...". In the pop-up window, make sure "Linear" is selected, and check the box beside "Display Equation on chart". Click on "Close".

   Convince yourself that the slope is $1/k$ and not k. Record the value of k in the "Data" section.

PROCEDURE PART 2: PLOTTING ENERGIES

1. Unhook the mass hanger string. Hook up the smart pulley physically and virtually, in Capstone (the sensor is called "Photogate with Pulley"). Choose the "Table & Graph" option in Capstone. Choose "Position (m)" for the y-axis of the graph. Add another graph by clicking the "Add new plot area..." button. On this new graph, select "Linear Speed (m/s)" for the y-axis. Add a third graph and plot "Linear Acceleration (m/s^2) on the y-axis.

2. With the air blower on, pull the glider out, click "Record", let the glider oscillate several times, and click "Stop". The velocity and acceleration graphs resemble the sinusoidal oscillations of a simple harmonic oscillator, but the position graph consists of a series of S-shaped curves increasing in y value. This shape results because the smart pulley does not distinguish between the forward and reverse directions of motion; it merely counts the number of times the spokes block the photosensor and records the result as positive distance. Thus, each S-shaped curve on the position graph is produced as the oscillator moves from one endpoint of its motion to the other.

3. Now record just half of an oscillation. Pull the glider back, click "Record", then release the glider. **Make sure to click "Record" at least a second or two before releasing the glider.** Click "Stop" as soon as you see the glider start to reverse directions, making sure not to stop it too early. Your postion graph should be S-shaped and your velocity graph should look like an upside-down "U".

4. Click "Select Measurement" in the table and choose "Position (m)". Copy the values over to a column in Excel. Next, change the selected measurement in your table to "Linear Speed (m/s)". Copy these values to a different column in Excel.

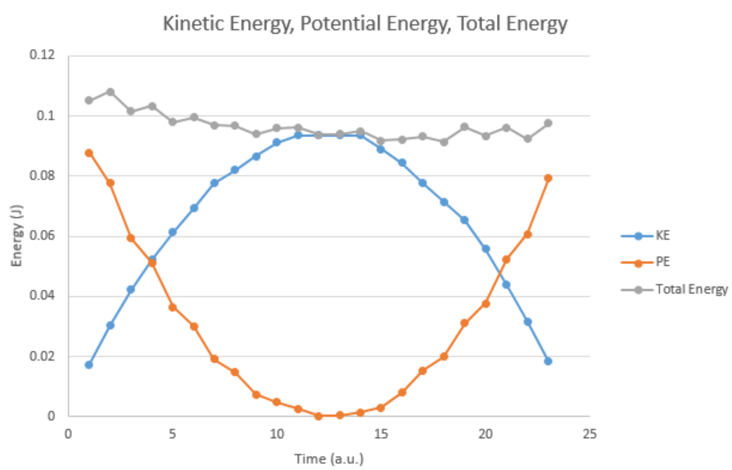
5. Calculate the kinetic energy as a function of time using your velocity measurements, by setting up a formula in Excel. Recall that the kinetic energy of an object with mass m and speed v is $KE = (1/2)mv^2$. Now plot kinetic energy in Excel. You should get a curve that looks like

an upside-down "U".

6. Calculating the potential energy with the smart pulley is trickier. First, as demonstrated above, the pulley does not distinguish between forward and backward motion, so we can look at only the first half-oscillation. Second, when we pull the glider out and "Start" the distance measurement, the software assigns zero to the first distance measurement. However, we want to assign zero to the equilibrium position. In other words, we want to calculate $PE = (1/2)k(x - x_0)^2$, with x_0 the equilibrium position. Use the average value of position as x_0 and set up another Excel formula for calculating the potential energy (remember that k is the stiffness of the springs that you measured earlier). Plot potential energy as a function of time. It should be somewhat U-shaped.

7. Create an Excel formula that calculates the total energy (kinetic + potential) as a function of time. Plot all three of these (kinetic, potential and total) on the same graph. To add a data set to a graph, right click on it and click "Select Data...", then click the "Add" button. Clear the "Series Y values:" box and then select the column you want to add. Then click "OK" two times. The new data set should appear in the graph.

8. Once all three data sets are plotted on the same graph, check that it makes sense physically. The total energy of the system is constant in theory. However, you may see a slight reduction in total energy as time passes. This is because energy is slowly lost due to friction and wind resistance. Label the axes of your graph and show it to your TA. Your graph should look something like the figure below:



DATA

- (Initial Setup, step 2) Mass of glider $m =$ ____________________________
- (Procedure Part 1, step 4) Spring constant $k =$ ____________________________
- (Procedure Part 2, step 6) Equilibrium position $x_0 =$ ____________________________

ADDITIONAL CREDIT (3 mills)

The glider-spring system is a simple harmonic oscillator. You will study the physics of such systems later in the course. A crucial feature of such systems is that their motion is cyclic, repeating itself with a certain frequency. Your task is to determine this frequency.

An object's motion is cyclic only if the motion repeats itself after a given time interval. The time the motion takes to repeat itself is called the *period* of the motion. The frequency f of the cycle is then defined as the number of cycles per unit time, and is related to the period by

$$f_{\text{experimental}} = 1/T$$

First devise a method and obtain the frequency of oscillation from your Capstone measurements (or make new measurements). Next use your values of k and m to check your result against the following formula for the frequency of oscillation:

$$f_{\text{theoretical}} = \frac{1}{2\pi}\sqrt{k/m}.$$

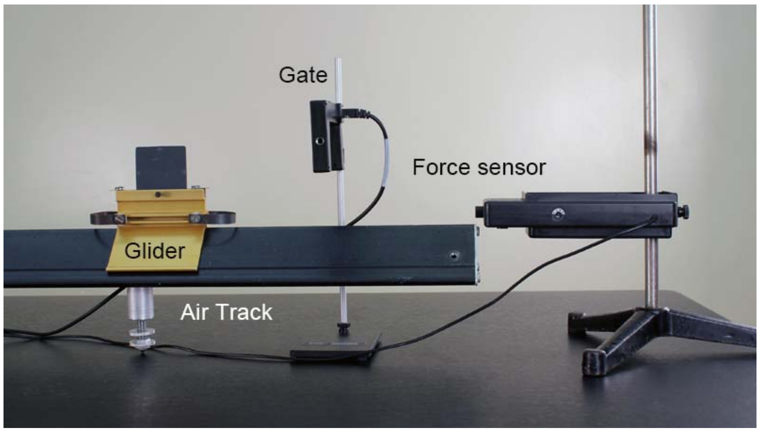
Report the results with experimental error.

Momentum and Impulse

APPARATUS

Shown in the picture below:

- Air track
- Glider with bumper and flag
- Photogate
- Force sensor



Not shown in the picture above:

- Computer and Pasco interface
- Vernier calipers or meter stick to measure glider flag
- Scale and weight set

THEORY

Newton's Second Law tells us that the net force acting on an object is equal to the object's mass multiplied by its acceleration: $\mathbf{F}_{\text{net}} = m\mathbf{a}$. Using $\mathbf{a} = \mathrm{d}\mathbf{v}/\mathrm{d}t$, where $\mathbf{v}$ is the object's velocity, we can rewrite this law as

$$\mathbf{F}_{\text{net}} = m\,\mathrm{d}\mathbf{v}/\mathrm{d}t. \tag{1}$$

Newton himself believed that this relation should also account for the possibility that the mass is varying:

$$\mathbf{F}_{\text{net}} = \mathrm{d}(m\mathbf{v})/\mathrm{d}t. \tag{2}$$

Examples of varying masses include rain falling into a rolling open box car and a rocket expelling gases. The above equation can be rewritten as

$$\mathbf{F}_{\text{net}} = \mathrm{d}\mathbf{p}/\mathrm{d}t, \tag{3}$$

where $\mathbf{p} = m\mathbf{v}$ is the *momentum* of the object. Eq. 3 is the most general definition of force: the change of momentum with time. If we write it as a differential equation,

$$\mathrm{d}\mathbf{p} = \mathbf{F}_{\text{net}}\mathrm{d}t, \tag{4}$$

and integrate with respect to time, then Eq. 3 becomes

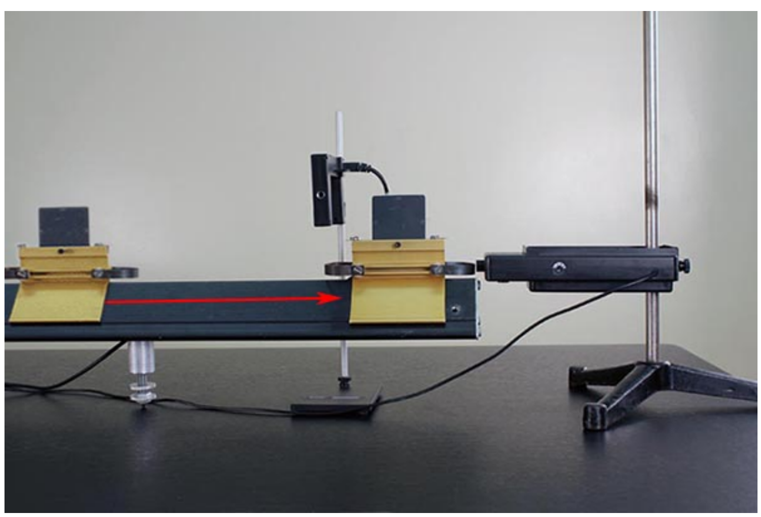
$$\Delta \mathbf{p} = \mathbf{p}_2 - \mathbf{p}_1 = \int \mathbf{F}_{\text{net}}\, \mathrm{d}t. \tag{5}$$

The right side of Eq. 5 is known as the *impulse*, and the left side is the change in momentum. The notion of impulse is often associated with a force that acts for a short period of time. Examples of such forces include a bat hitting a ball and the impact between two objects moving at relatively high speeds.

In this experiment, you will verify Eq. 5 by allowing a glider on an air track to pass through a photogate and strike a force sensor. The sensor allows you to measure the force on the glider as a function of time. This time interval is relatively short, so the impulse approximation is valid. The velocity of the glider is measured when it crosses the photogate, just before and just after the collision. These two velocity measurements, along with knowledge of the glider's mass, allow you to calculate the change in momentum (i.e., the left side of Eq. 5). The sensor generates a force-versus-time curve on the computer, which can be integrated to obtain the impulse (i.e., the right side of Eq. 5). The glider has a foam bumper, so its collision with the force sensor is *inelastic*. In other words, kinetic energy is not conserved during the collision, but the change in momentum is still equal to the impulse.

PROCEDURE

1. Level the air track carefully. Mount the force sensor horizontally on the vertical rod of the ring stand at the end of the track so the glider bumper will strike the sensor as the glider moves down the track. Set up the photogate so the glider flag clears the gate by a few centimeters before the bumper strikes the sensor. Refer to the picture below. Note that while the sensor has two interchangeable end parts (a screw hook for hanging objects from the force sensor, and a rubber bumper for the impulse measurements in the actual experimental runs), we will only be using the rubber bumper in this experiment.



The glider then bounces off the sensor and passes through the photogate again. In an experimental run, you should record the two photogate velocity readings and the force-versus-time curve from the sensor.

2. Weigh the glider, and record its mass (in kilograms) in the “Data” section.

3. Open Capstone and choose “Table & Graph”. Under “Hardware Setup”, click on Channel 1 and choose “Photogate”. Then click on Channel A and choose “Force Sensor”.

4. We want to set up the photogate to measure the velocity of the glider.

   a. Click on “Timer Setup” and then click “Next” twice.

   b. Select “One Photogate (Single Flag)”. Make sure “Speed” is selected and click next.

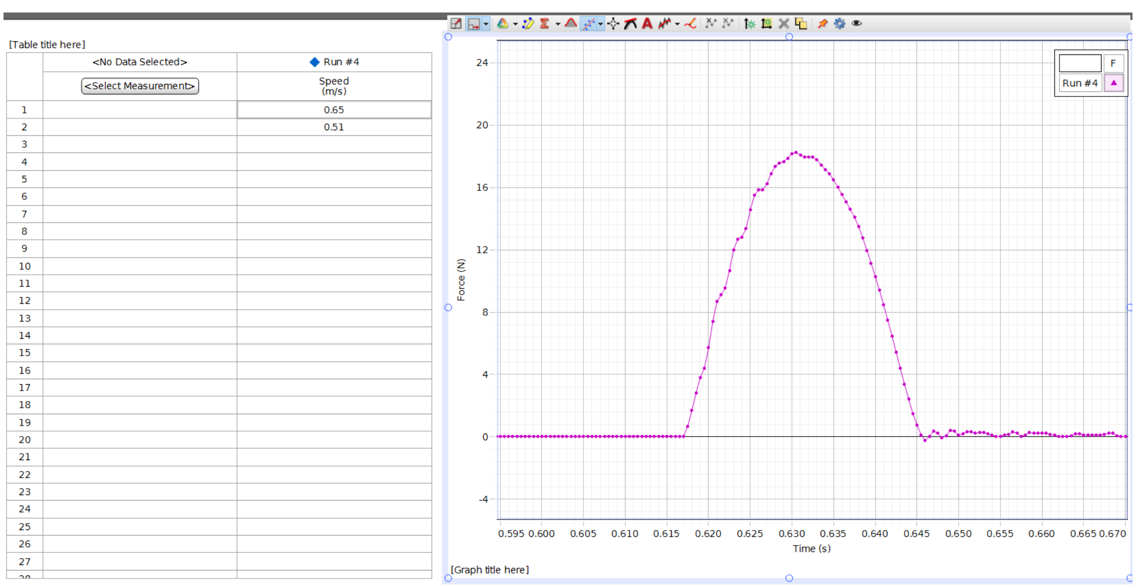
   c. Make sure the flag width is entered in the white box (0.05 m). Then click “Next” and then “Finish”.

5. Click on “Select Measurement” in one of your table columns and select “Speed (m/s)”. Click on the y-axis of the graph and choose “Force (N)”.

6. At the bottom of the screen, set the sampling rate to 2000 Hz. Note that the computer will then take a force reading every 1/2000, or 0.0005, second.

7. Turn on the air track, and push the “Tare” button on the side of the force sensor to zero its readings. Click “Record” and send the glider down the track so it passes through the photogate, strikes and bounces off the force sensor, and crosses the gate again. Click “Stop”. Your table should show two velocity readings at the top. The second velocity value is smaller since the collision is inelastic.

8. Zoom in on the part of the graph where the glider hit the force sensor. Your data should look something like that of the image below.



9. Use the “Display are under active data” button to calculate the area under the curve. Use the “Highlight range of points...” button to select only the data of interest.

10. Use the two speed recordings in your table to calculate the change in momentum from this

collision. When you calculate the change in momentum from mv_1 to mv_2, should you add or subtract these two numbers? Pay attention to the direction the glider is moving and remember that the photogate measures speed, not velocity.

11. Have each lab partner make three measurements with different glider speeds to check the relation $\Delta\mathbf{p} = \int \mathbf{F}_{\text{net}}\text{d}t$.

12. In the "Data" section, record the three values of change in momentum and impulse, as well as the percentage difference between each set of values.

DATA

2. Mass of glider (kg) = ____________________________

12. In the table below, enter your measured changes in momentum, impulses, and the percentage differences.

	A	B	C
1	Change in P	Impulse	% difference
2			
3			
4			

ADDITIONAL CREDIT (5 mills)

In this experiment, you need to perform an integral over your force data to calculate the impulse. Capstone performs a summation algorithm to calculate the area under a curve. You can do this same technique using Excel.

The impulse is the area under the force-versus-time curve. Like any integral, it can be approximated using a Riemann sum:

$$\text{Impulse} = \int \mathbf{F}_{\text{net}}\text{d}t = \sum \mathbf{F}_i\,\Delta t_i = \Delta t \sum F_i,$$

where we were able to pull out the Δt in the last step because the time intervals $\Delta t_i = 0.0005$ second are all equal.

You can obtain the force sum with an Excel function such as "=Sum(b3..b147)". Perform this calculation on one of your data sets and compare to the results from Capstone. You will need to make a table of force measurements and copy it over to Excel.

Finally, use this force sum to calculate the impulse. As in the main part of the lab, compate this value to the glider's change in momentum and calculate the percent error.

Biceps Muscle Model

Introduction

This lab will begin with some warm-up exercises to familiarize yourself with the theory, as well as the experimental setup. Then you'll move on to the experiment itself.

Rather than giving you explicit steps to follow at every stage, at times we'll provide you with a problem to investigate and some hints on how to proceed. It will be something of a challenge to figure out how exactly to accomplish each step, but this will be much more like doing science in the real world. We hope you enjoy the process!

Learning outcomes

By the end of this lab, you will be able to:

i. Describe how torque depends on applied force and distance of force from pivot point.

ii. Understand that angle at which a force is applied affects the applied torque.

iii. Use concepts of torque to understand aspects of the human arm.

iv. Relate the biceps muscle force to weight lifted by the hand.

v. Extrapolate a linear model from experimental data

vi. Use experimental results and critical thinking to make predictions about future results

Warm up exercises

Warm up I: Torque

Before you start the main portion of the lab, here are some warm up questions to introduce you to the key concept of torque.

1. A 60 kilogram parent sits on a seesaw, 1 meter to the right of the pivot (as pictured in figure 1). How far to the left should a 30 kilogram child sit in order to balance the seesaw?

   If you're unsure how to approach this problem, try to answer it intuitively. Perhaps you can give a range of possible values?

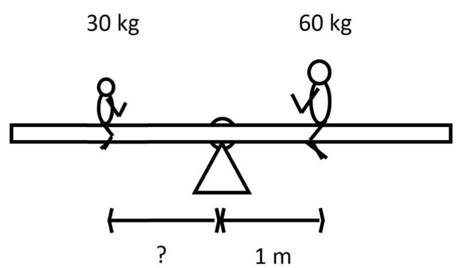


Figure 1: Diagram for warm up problem 1.

2. Now reconsider the previous problem in light of a more formal introduction to torque:

   The torque of each person about the pivot point is the product of the person's weight and the distance of the person (strictly speaking, the person's center of mass) from the pivot. The sign of the torque is positive if it would cause a counterclockwise rotation of the seesaw. The net torque is the sum of the individual torques from each person. To remain at rest, an object like this seesaw must have zero net torque acting on it.

   If you didn't use quantitative reasoning in your answer to the previous problem, go back and do so now.

3. Consider now a slightly modified seesaw setup (pictured in figure 2), with a child of weight W sitting a distance L to the left of the pivot. This time, the seesaw is balanced by the pull from a vertical rope, attached at a distance r to the *left* of the pivot. Assume that $r < L$, meaning the rope is attached between the child and the pivot.

   (a) Before doing any calculations, make a prediction. Do you think the force F will be larger, smaller, or the same as the child's weight W?

   (b) Now do the calculation: Express the upward force F exerted by the rope in terms of W, L, and r.

   (c) Finally, evaluate your prediction in light of the previous result. Remember that r is always smaller than L. Was your prediction correct? If not, are you surprised by this result?

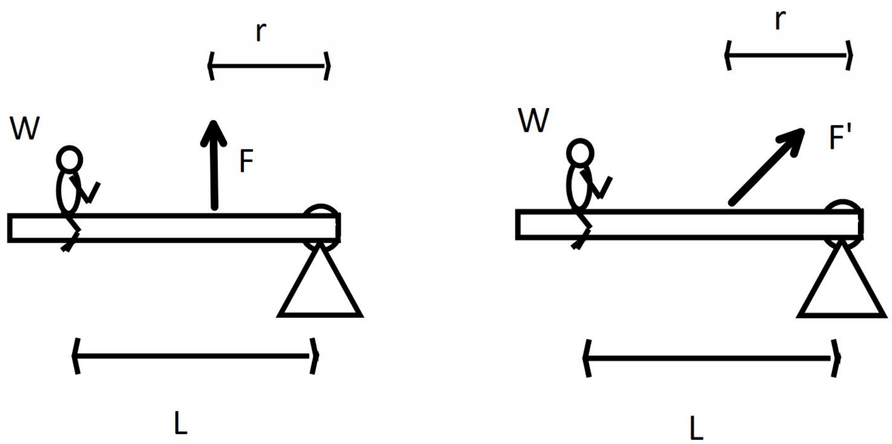


Figure 2: Diagrams for warm up problems 3 (left) and 4 (right).

4. Finally, imagine that the rope balancing the seesaw is at an angle, rather than being vertical (pictured in figure 2). Does the magnitude of this new force F' need to be larger, smaller, or the same size as the previous (vertical) force F in order to balance the seesaw?

   Hint: Remember that the force F' acts along the direction of the rope.

Warm up II: The apparatus

Before we get into equations, take a moment to understand the equipment.

1. (a) Label **both** the photograph of the experimental apparatus below and the anatomical drawing of the arm beside it with the following labels:

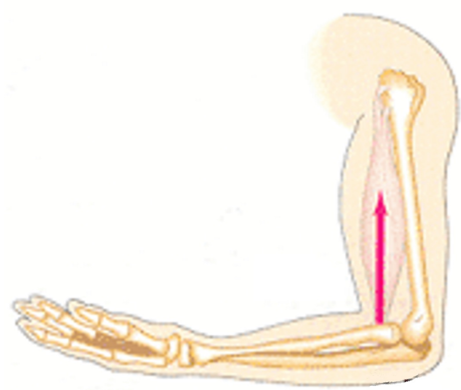
      - upper arm (humerus)
      - elbow
      - forearm
      - hand
      - biceps muscle

      Hint: If you're confused where to start, know that the horizontal bar on the apparatus models the forearm.

   (b) Now compare the photograph of the apparatus with the anatomical drawing. How are they similar and different? Do you think the experimental apparatus does a good job approximating the features of the human arm and biceps muscle? (Be sure to record your group's response to this question, realizing that there's no right or wrong answer.)

2. Label the free body diagram below with the following forces and distances:

   - r: The distance between the elbow and the point where the biceps muscle attaches to the forearm
   - R: The distance between the elbow and the hand
   - H: The force the hand (and anything it's holding) exerts on the forearm
   - B: The force the biceps muscle exerts on the forearm
   - W: The force due to the weight of the forearm, which acts on the center of mass of the forearm (already labeled on the diagram)
   - θ: The angle between the forearm and the direction of the bicep force (already labeled on the diagram)



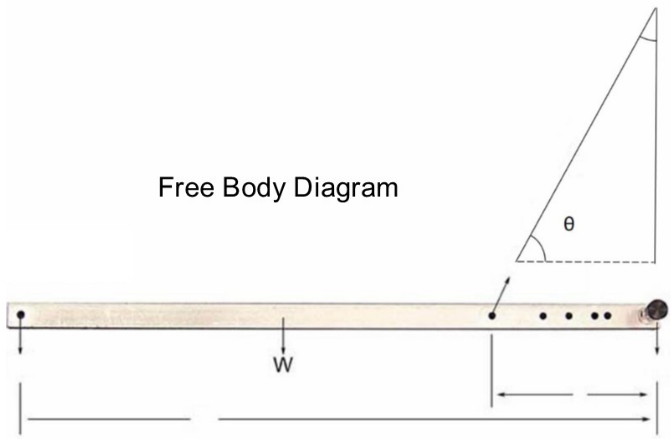
Initial Setup

Before we begin the experiment, we need to ensure the biceps muscle scale is correctly calibrated, as it is common for the scale to become miscalibrated after several lab sections.

1. Remove the forearm bar from the apparatus, so nothing is hanging from the biceps muscle scale.

2. Hang a 1 kg mass from the biceps muscle scale (making sure to use the keeper ring to prevent the mass from falling off).

   If the scale does not read 1 kg, you need to recalibrate it. Do so by turning the 'knurled ring'



at the top of the force scale, in the direction that increases or decreases the force reading as needed, until the scale reads 1 kg.

3. Do not adjust the knurled ring for the remainder of the experiment.

Procedure

Every time a person lifts a weight, throws a ball, or turns a page, there are forces involved throughout the muscular and skeletal systems. We wish to investigate just one example of those forces. Specifically, we'll examine the situation where you're holding a weight in your hand, with your forearm being held horizontal. We'll measure the forces exerted by the biceps muscle.

If you'd like, imagine yourself as a physical therapist or prosthetic limb designer, who wishes to combine physics with some general experimental design skills to determine some of the forces involved in lifting objects.

As we said before, you'll be given quite a bit more freedom in this lab. Part of that means you'll have to think critically about which steps you'll be taking, and you'll have to examine your results to check whether they seem reasonable. When you're making decisions like this, think back to some of the things you've done in the previous labs – many of those choices were made for good reasons, and represent good experimental practices.

1. **In everything that follows, make sure the forearm bar is horizontal.** We're focusing on this case (1) because every experiment needs to focus on specific scenarios in order to make meaningful conclusions, and (2) because keeping the forearm horizontal vastly simplifies both the measurements and the calculations.

2. Before you begin taking data, measure the experimental parameters of your apparatus. That is, measure and record the values of r, R, and W.

Furthermore, if you ever change any of these values in what follows, be sure to measure and record the new value(s).

Note that for the first several steps, you'll be keeping r fixed. It's up to you to choose whichever initial value for r you'd like, but we recommend starting with a fairly large r.

3. Start by measuring the biceps force B for some fixed weight H being held in the hand. Make sure to record this value (with units). Note that the force gauges are labelled with units of mass (kilograms) rather than units of force (Newtons). You need to multiply the mass readings by $g = 9.8\,\mathrm{m/s^2}$ to convert the mass values to their corresponding *weight* values. Note that you may wish to first just record the mass values, and convert to weight using Excel.

$$B = \Big(\text{Biceps gauge reading (in kilograms)}\Big) \times g$$

After doing this, B and H should both be recorded in units of force.

Note: H corresponds to the weight held by the hand – that is, the weight hanging off the forearm bar. It does *not* include the weight of the forearm, which is separately accounted for in W. (W, in turn, does not include the weight held by the hand.)

4. Now devise and carry out a procedure for measuring (and recording) the force B for different weights H. Make sure to explicitly write out the steps of the procedure. If you find you need to modify the procedure as you carry it out, that's okay – but be sure to change the written version to correctly reflect the steps you really carried out.

5. After taking several measurements (you can choose a number which seems reasonable), use your data to extrapolate a relationship between the biceps force B and the weight H in the hand: First, argue that your data shows a linear relationship between B and H. Then, write an explicit formula for B as a function of H. *Hint: In case this terminology is a bit unfamiliar, it might help to know that* $y(t) = \Big(10\,\mathrm{m}\Big) - \Big(4.9\,\mathrm{m/s^2}\Big)t^2$ *is an example of an explicit formula for y as a function of t (for a certain physical situation).* Make sure you specify the units of all quantities involved. Hint: You've performed similar steps in previous labs. Think back to any time you graphed your data and fit a trendline to the graph.

6. Choose a new value for H – one that you haven't measured yet, but that you are able to measure. Before you measure B, use your model to predict the biceps force B for this new value of H.

7. Now use the apparatus to measure B for this value of H. How does it compare to the prediction from your model? (Calculate the percent deviation.) If the two values don't exactly agree, do you think this is okay? Do you think it tells us our model is wrong? Why or why not?

8. Is your formula for B as a function of H consistent with the concepts of torque explored in the warmup problems? Why or why not?

Varying model parameters

Now that you've gained a bit of familiarity with the apparatus by taking some measurements, let's take a step back and think a bit more about what's going on.

9. Using a combination of your intuition for how your own arm works, and the knowledge of torque you developed in the warm up exercises, predict how the biceps force change when we increase each of the following parameters.

Fill in your own copy of the charts below, answering with "increases", "decreases", "stays constant", or "something else". (If you choose something else, explain why you chose that.)

Parameter change	Effect on B
$\uparrow R$	
$\uparrow W$	
$\uparrow r$	

10. The way our apparatus is set up, the easiest of the above parameters to vary experimentally is r. Devise and carry out an experiment to determine the effect that increasing r has on the biceps force B. Make sure to record the data that leads you to this conclusion. Do your results agree with your prediction in part 9?

Comparing results to theoretical predictions

In a previous step above, you experimentally determined a formula for the biceps force B as a function of the weight H in the hand. Now we'll compare this model to the one the theory predicts.

It turns out that we can analyze the torques acting on the forearm to determine a formula for B vs H. You actually have all the tools needed to do this from the warm up exercises at the beginning of this lab, and we encourage you to give it a try! But in the interest of time, we'll just provide you with the formula, which is as follows:

$$B = \left(H + \frac{W}{2}\right)\frac{R}{r\sin\theta}$$

11. Now that we have this theoretical model, we can use it to predict what the slope and vertical intercept of your graph of B vs H should be. First, use the theoretical model to predict the slope and vertical intercept of your graph in terms of symbols (i.e., variables) only. Next, plug in the actual parameter values that correspond to your experimental apparatus to get a numerical value for these theoretical coefficients (with units!). How does this prediction compare with your actual slope and vertical intercept?

Note: If you need to find the angle θ, you can do so by measuring two sides of the right triangle formed by the upper arm, the forearm, and the biceps muscle. You can then use the appropriate inverse trig function to find θ.

12. Using the formula above for B as a function of H, revist your predictions from part 9. That is, argue whether the formula given to you above agrees or disagrees with the predictions you made before.

Wrapping up

13. Note: This problem involves a bit of reading, but it should help you understand the importance of a key concept, which will help you on your homework and exams.

Imagine you and a friend wanted to predict the biceps force by directly analyzing the torques involve in the apparatus. You and your friend determine that the experimental parameters for your apparatus are $R = 50\,\text{cm}$, $r = 25\,\text{cm}$, $W = 2.5\,\text{N}$, $H = 2.5\,\text{N}$. Your friend attempts to use the theoretical model to predict the value of the biceps force. He claims that the torque exerted by the biceps must be equal and opposite to the torque exerted by the weight in the hand plus the weight of the arm itself, which is equal to $HR+WR/2$, in the counter clockwise direction. Furthermore, your friend claims that the torque due to the biceps is Br, in the clockwise direction. Since the torques must be equal and opposite, we have $Br = HR+WR/2$.

You read the biceps gauge and find it reads about 0.85 kilograms. Solve the equation above for B, and plug in the values of the experimental parameters given above. Does the resulting value for B agrees with the measured biceps force?

If your prediction is not consistent with the experimental result, go back and figure out what was wrong with your friend's argument above.

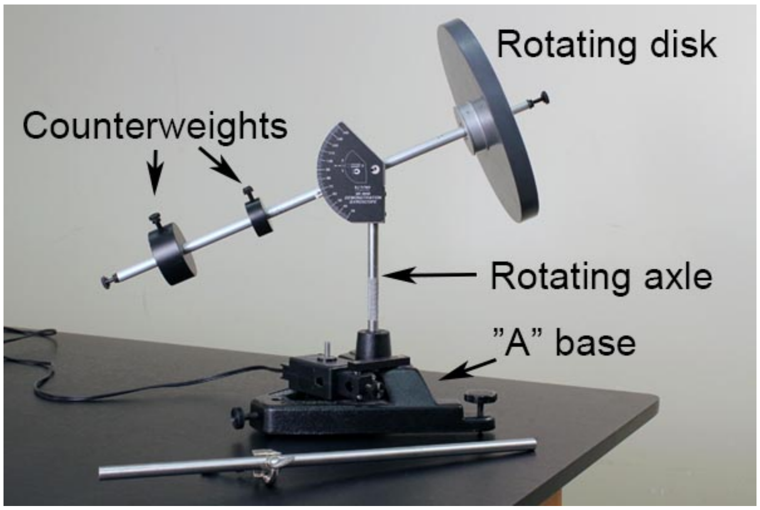
Was there a key torque concept your friend forgot to take into account?

Rotation and Gyroscopic Precession

APPARATUS

Shown in the picture below:

- Pasco gyro assembly with rotation sensor on base
- Support rod and clamp for gyro



Not shown in the picture above:

- Rotator with movable weights on stand with rotation sensor
- Vernier calipers
- Pan balance to weigh add-on weight
- Meter stick
- Weight hanger and weights
- Digistrobe
- String to spin wheel
- Computer and Science Workshop Interface

NOTE TO INSTRUCTORS

This experiment consists of two parts. Part 1 is a relatively straightforward measurement of the angular acceleration produced by different torques on an apparatus with variable rotational inertia. Part 2 involves the measurement of a gyroscope's precession as a function of its rotational inertia and rotational angular velocity, and requires somewhat more experimental ingenuity.

Most students cannot complete these two parts in one lab session, so you should choose which part you would like them to perform. The default option (in which you do not express a preference) is part 1. Another option, which you would need to choose at the beginning of the quarter in conjunction with the other instructors, is to reduce the "Biceps" experiment to one week by omitting parts 1 – 4 and to allow two weeks for this "Rotation" experiment.

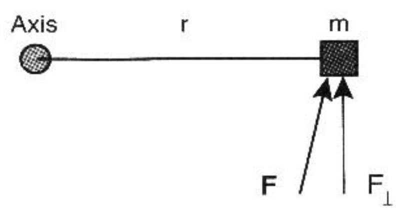
TORQUE AND ROTATIONAL INERTIA

We are all aware that a massive wheel has rotational inertia. In other words, it is hard to start the wheel rotating; and, once moving, the wheel tends to continue rotating and is hard to stop. These effects are independent of friction; it is hard to start a wheel rotating even if its bearings are nearly frictionless. *Rotational inertia* is a measure of this resistance to rotational acceleration, just as inertia is a measure of resistance to linear acceleration.

Automobile piston engines use a *flywheel* for this very purpose. The gasoline explosions in the piston chambers deliver jerk-like forces to the rotating crankshaft, but the large rotational inertia of the flywheel on the crankshaft smooths out the otherwise jerky rotational motion.

We also have an intuitive idea of *torque*, the tendency of a force to rotate a body. To produce the maximum rotational acceleration, we want to push perpendicular to the rotation axis, and at as large a distance r from the rotation axis as possible.

Consider a small mass m at a distance r from the rotation axis. If a force $\mathbf{F}$ acts on it , the linear acceleration of the mass around the circle will be $a = F_{\perp}/m$, where $F_{\perp}$ is the component of F perpendicular to the radius arm. The angular velocity $\omega = v/r$ of the mass is increasing, but the angular acceleration $\alpha = a/r$ is constant.



Multiply each side of the equation $F_{\perp} = ma$ by r, and manipulate the r's:

$$rF_{\perp} = mr^2 a/r = mr^2 \alpha, \tag{1}$$

or

$$\text{torque} = \tau = I\alpha. \tag{2}$$

We recognize the torque $\tau = rF_{\perp}$ in vector form $\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$. The rotational inertia I is equal to mr^2 for a small particle of mass m. For an assembly of small particles, each of mass m_i, we sum to get the rotational inertia:

$$I = \sum m_i \, r_i{}^2. \tag{3}$$

And if the mass distribution is continuous, we integrate:

$$I = \int r^2 \, \mathrm{d}m. \tag{4}$$

We can continue to define the rotational analogs to linear motion. For example, the *angular momentum* L is

$$L = I\omega, \tag{5}$$

in analogy to

$$p = mv, \tag{6}$$

and the *rotational kinetic energy* is

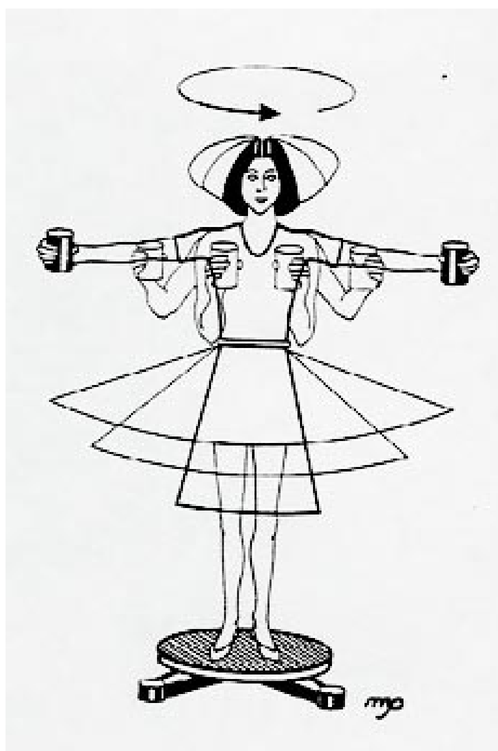
$$\text{rotational } KE = (1/2)I\omega^2, \tag{7}$$

in analogy to

$$\text{translational } KE = (1/2)mv^2. \tag{8}$$

Linear momentum $p = mv$ is conserved in the absence of external forces. Likewise, angular momentum $L = I\omega$ is conserved in the absence of external torques. One interesting difference between rotational motion and linear motion is that; since rotational inertia depends on the positions of the masses, it is easy to change the rotational inertia "on the fly", so to speak. A spinning ballerina, ice skater, or star with a large rotational inertia I and small angular velocity ω can increase the angular velocity of spin by pulling mass in to reduce the rotational inertia: the ballerina and ice skater by pulling in their arms and legs, and the star by collapsing smaller by gravity.

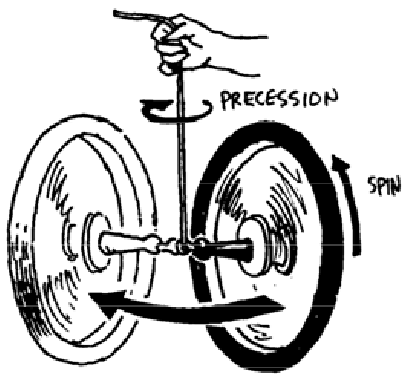
$$I\omega = I\omega.$$



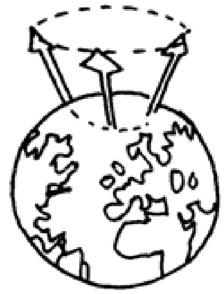
PRECESSION

A common lecture demonstration of gyroscopic precession is to hang a bicycle wheel by one end of its axle. If the bicycle wheel is not spinning, it flops down.

But if the wheel is spinning, it doesn't fall. Instead it *precesses* around: its axle rotates in a horizontal plane.

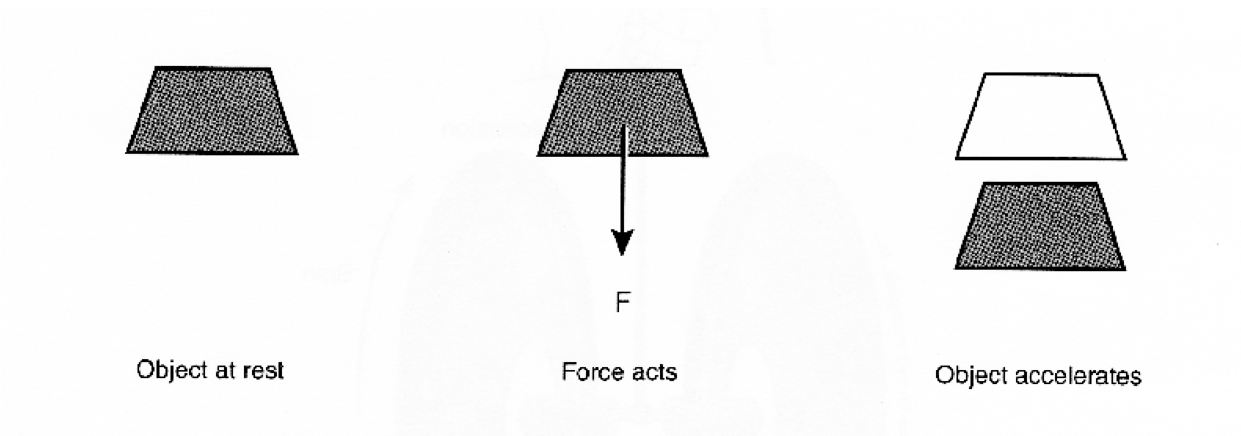


We are all familiar with the example of a precessing toy top. The spinning Earth also precesses around. Its axis is now pointing toward the North Star in the sky, but over time the axis slowly swings around, making a complete revolution in 26,000 years.

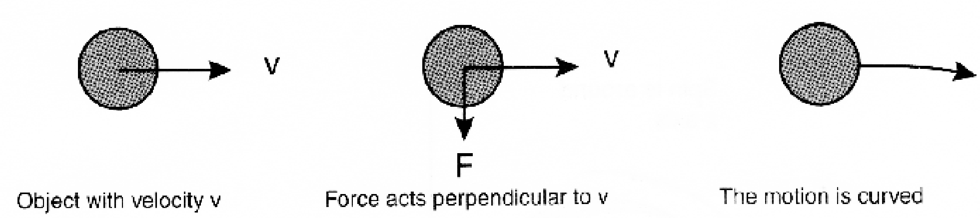


A necessary condition for precession is a torque aligned in a different direction from the spin. In the case of the bicycle wheel and the toy top, gravity acts downward on the center of mass so the torque is in a horizontal direction. In the case of the Earth's precession, the gravitational force from the Moon is acting on the equatorial bulge of the Earth to align the equatorial bulge with the plane of the Moon's orbit. We are particularly interested in the case when the torque is perpendicular to the spin axis.

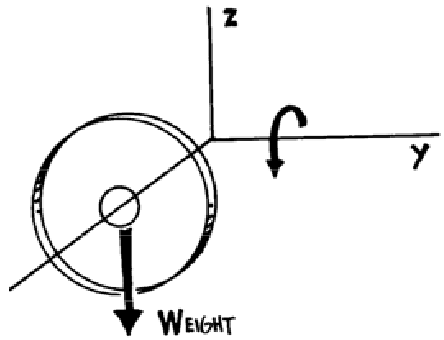
Let's try to understand precession in general. Consider linear motion first. If an object is at rest, and a force acts on it, the force will increase the speed of the object in the direction of the force.



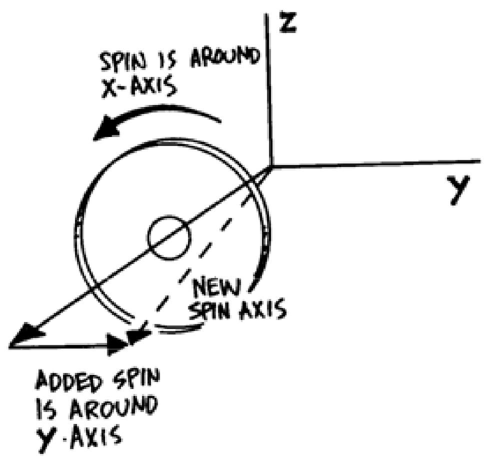
But if the object is already moving and the force acts perpendicular to the motion, the speed will not be changed. Instead the force will curve the velocity around, producing uniform circular motion if the force is always perpendicular to the velocity.



Something similar happens with rotational motion. When the wheel is <u>not</u> spinning, the torque from the weight produces an angular velocity about the torque axis, in this case the y-axis.



But if the wheel is already spinning, it has spin (angular velocity) about the x-axis. The torque of the weight adds some spin about the y-axis, perpendicular to the original spin. The resulting spin axis is turned a little in the xy-plane. The torque doesn't change the value of the spin; instead it "curves" the spin. (Again, note that here the torque axis is perpendicular to the spin axis. This need not be true in general, but we are considering this simplified case.)



Mathematically,

$$\boldsymbol{\tau} = \mathrm{d}\mathbf{L}/\mathrm{d}t, \tag{9}$$

which is the rotational analog of

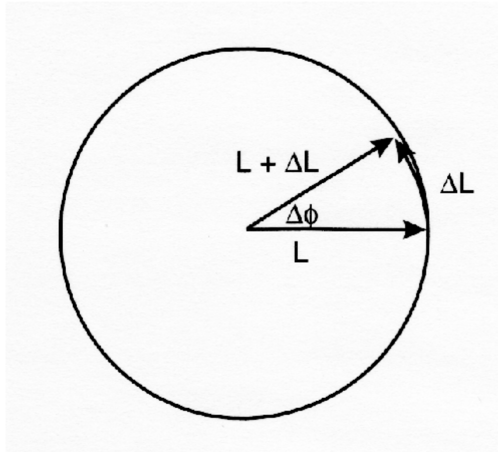
$$\mathbf{F} = \mathrm{d}\mathbf{p}/\mathrm{d}t. \tag{10}$$

To keep the ideas clear, we will call the angular velocity of the spinning object itself its *spin* ω, and the turning around of the spin axis the *precession* angular velocity Ω. The angular momentum $\mathbf{L}$ of the spin is $L = I\omega$, where ω is the angular velocity of the spin, and I is the rotational inertia of the wheel.

Thus, in a time Δt, the torque produces a change in the angular momentum of the spin given by

$$\Delta L = \tau \Delta t. \tag{11}$$

But for small changes in the angle ϕ of L, $\Delta L = L\Delta\phi$.



Thus,

$$\Delta L = L\Delta\phi = \tau\Delta t. \tag{12}$$

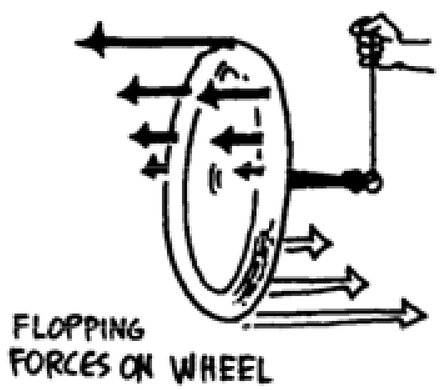
The angular velocity of precession $\Omega = \Delta\phi/\Delta t = \tau/L$, the last equality following from the equation above. Since $L = I\omega$, we have finally

$$\Omega = \tau/I\omega. \tag{13}$$

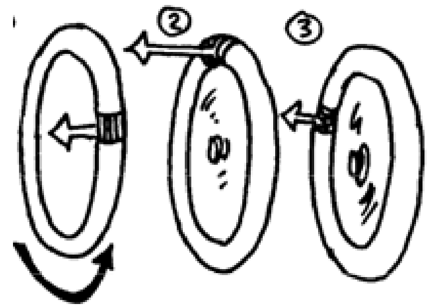
This then is our basic equation relating the precession angular velocity to the rotational inertia, spin, and torque.

We have shown that precession can be understood from the principles of rotational motion, torque, rotational inertia, angular momentum, etc., and we have even derived the equation for the magnitude of the precession above. But these concepts must be based on the simpler principles of force and acceleration. Let's see if we can understand precession from just the concepts of force and acceleration.

When the gyro bicycle wheel is in the hanging position, the torque exerted by gravity exerts an outward force on the top half of the wheel, and an inward force on the bottom half of the wheel — forces that would make the wheel flop over if it were not spinning.



Now look at a small piece of the wheel as it spins. As the piece comes over the top half of the wheel, the outward force on it grows to a maximum at the top, and decreases to zero at the far side position. Then, the force becomes negative, and grows to a maximum pointing inward at the bottom position, and decreases to zero again at the near side position.



Measure the angular position of this small piece of the wheel with zero angle $\theta = \omega t$ at the top position, increasing to $\pi/2$ radians at the far side position, etc. We can represent the force on the small piece then as

$$F = F_0 \cos \omega t. \tag{14}$$

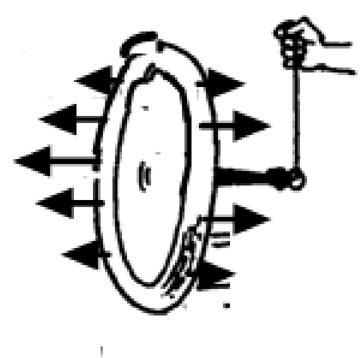
According to Newton's Second Law, the acceleration is proportional to the force:

$$a = a_0 \cos \omega t. \tag{15}$$

But, how does the small piece actually move? Its velocity is the integral of a, $v = \int a \, \mathrm{d}t$, and the integral of $\cos \omega t$ is proportional to $\sin \omega t$.

$$v = v_0 \sin \omega t. \tag{16}$$

The velocity reaches a maximum pointing outward at the far side position, is zero at the top and bottom, and is maximum pointing inward (negative) at the near side position.



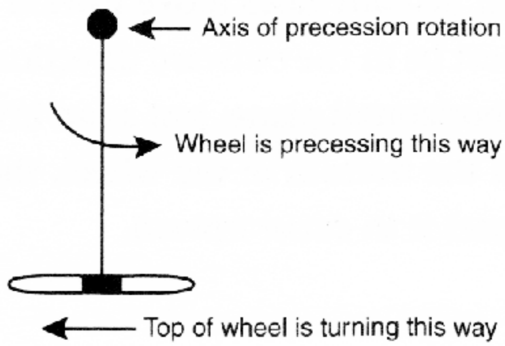
Thus, the forces from the torque don't push the wheel down; they push it around!

Finally, if we integrate the velocity, we should get the distance the wheel element moves:

$$x = \int v \, \mathrm{d}t = \int v_0 \sin(\omega t) \, \mathrm{d}t = -(v_0/\omega) \cos \omega t = -x_0 \cos \omega t. \tag{17}$$

This equation suggests that the wheel element is moving opposite the force on it: $F = F_0 \cos \omega t$. In other words, the wheel element should be moving inward at the top of the turn, while the force is outward. Can this possibly be true?

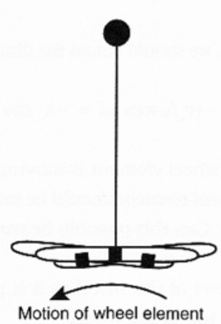
Indeed it can! Study the top views of the wheel as it is precessing around. The wheel element is just coming over the top of the wheel:



A few moments earlier, the wheel and wheel element were in this position:

A few moments later, the wheel and wheel element will be in this position:

Combine the pictures of the wheel:



So you see the wheel element actually does move inward at the top while the force is outward. In fact, the force must be in the outward direction to produce the curved path of the wheel element in the horizontal plane, just as an inward force produces uniform circular motion. Similarly, at the bottom of the wheel, the inward force on the wheel element from the torque causes it to curve inward.

PROCEDURE FOR ROTATION

1. You have a rotator device connected to a rotary motion sensor. The rotator device has movable masses on a rod. On the other end of the rotational motion sensor is a pulley with two wheels of different diameter. Plug the yellow plug of the rotational sensor into #1 digital channel of the Science Workshop interface, and the black plug into #2 channel. Open Capstone and click "Table & Graph". Under "Hardware Setup", add the rotary motion sensor to channels 1 and 2. On the y-axis, select "Angular Acceleration (rad/s^2)". Ready a falling weight with string wound around one of the drums, click "Record", let the weight fall (spinning up the rotator), and check that you are getting readings of angular acceleration. To record a value of the acceleration below, you can select an area of the chart, and use the "Display Selected Statistics..." button to get the mean value of the acceleration.

2. Remove the rod and mass assembly from the sensor, and separately weigh the masses and the rod (without its screw), and the pulley wheel. Measure the diameters of the two pulley wheels with the Vernier calipers, and convert to radii in meters. Record the information below.

Mass of movable weights in kilograms = ______________________________

Mass of rod without screw = ______________________________

Mass of pulley wheel = ______________________________

Radius of small pulley in meters = ______________________________

Radius of large pulley in meters = ______________________________

> Warning: In rotational experiments it is especially important to keep mass units (as in rotational inertia) and force units (as in torque) clearly distinguished.

3. According to the textbook, the rotational inertia of a rod of mass m and length l about an axis perpendicular to the rod and through its center is $(1/12)ml^2$. Calculate the rotational inertia of the rod. Does it make any difference that the rod is hollow?

   I of rod in $\text{kg} \cdot \text{m}^2$ = ______________________________

4. From the mass of the pulley wheel and its volume (which you can calculate from the radii of the two parts), you can calculate its density. From this you can calculate the rotational inertia of the pulley wheel. You may have to do some estimating.

   I of pulley wheel in $\text{kg} \cdot \text{m}^2$ = ______________________________

5. Do a trial experimental run in which the masses on the rotator are at the ends of the rod so that the rotational inertia is large. Use 100 – 200 g on the weight hanger and wind the string around the smaller pulley wheel. (This should be the smallest angular acceleration case.) Notice that the angular acceleration on the graph quickly jumps up and reaches an approximately constant value. You can select an area of this nearly constant value, and use the statistics button to get its mean value for the "measured angular acceleration" in the table below. Now do a trial experimental run in which the masses on the rotator are close to the center so that the rotational inertia is small. Use 100 – 200 g on the weight hanger and wind the string around the larger pulley wheel so that the torque will spin the rotator up to high speed. (This should be the largest angular acceleration case.) On the graph, notice that the acceleration quickly reaches a peak, and then falls off with time. Why isn't the of acceleration constant in this case? Where on the acceleration curve should you average the values of acceleration to get a good result to compare with the predicted acceleration? How can you adjust the apparatus or experimental parameters to get a better result for the small rotational inertia case?

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6. Using masses of 50 – 200 grams, hook the string on the pulley pin, wind the string around the pulley, and let the mass fall while you measure the rotational acceleration on the computer. Do three experimental trials for each case, and average them to find the rotational acceleration.

Do four cases: two different positions of the masses on the rod (as close to the center as possible, and as far out as possible), and two different pulley sizes. Compute the rotational inertia of the rod with masses (add the effects of the rods, the pulley wheel, and the masses), the torque, the predicted rotational acceleration, and the experimental error, and fill in the table below.

	A	B	C	D	E
1	torque	rotational inertia	predicted rotational	measured angular	experimental
2			acceleration	acceleration	error
3					
4					
5					
6					

When you add the rotational inertias of the rod, masses, and pulley wheel to get the rotational inertia of the entire rotating assembly, are you leaving out anything?

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PROCEDURE FOR GYROSCOPE

1. We want to check the precession, equation 13, $\Omega = \tau / I\omega$. Study your gyroscope for a moment. As you rotate the arm for precession, the rotary motion sensor at the base should move freely. (If not, adjust the screws that hold the sensor.) The rotary sensor from the first part of the experiment may still be set up on Data Studio. Unplug this rotary sensor and delete all the sensors and data. (Or quit Data Studio, and open it up new.) Plug the rotary sensor of the gyro precession into the Science Workshop interface, and drag a digits window to the rotary motion sensor symbol, and set it to measure the rotational angular velocity Ω. (You may have to double-click on the icon of the rotary motion sensor connected to the Science Workshop, and check the "Angular Velocity Ch 1 & 2 (ras/s)" box.)

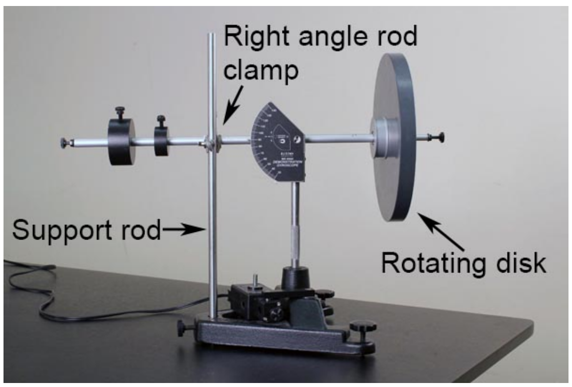
Check that you can get a reading of Ω from the computer. Notice that the angular velocity reading in the digits window jumps around, making it difficult to get a definite reading.

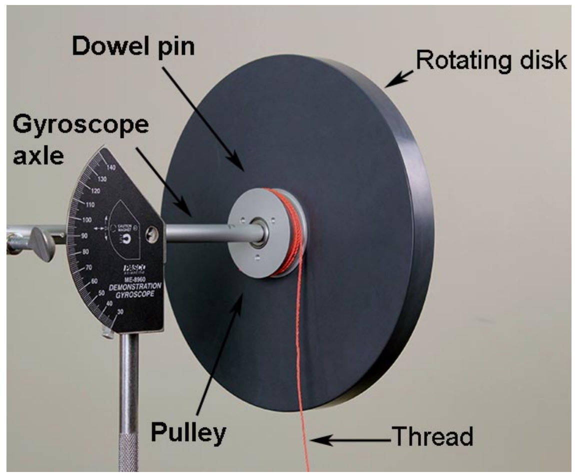
Drag a graph window to the rotation sensor, and set to it read angular velocity. Note that the reading on the graph also jumps around a little also as the gyro arm turns; but after you record the data, you can can select an area of the graph, and use the statistics button to get a mean value for the angular velocity.

2. We will be measuring the angular velocity ω of the gyro wheel with the Digistrobe. The Digistrobe meter reads in rpm, revolutions per minute. You will need to convert this to radians per second. Determine the conversion factor f in $\omega = f \times$ (rpm reading).

   $f =$ ______________________________

3. Insert the gyro arm support rod and clamp the rod as shown.

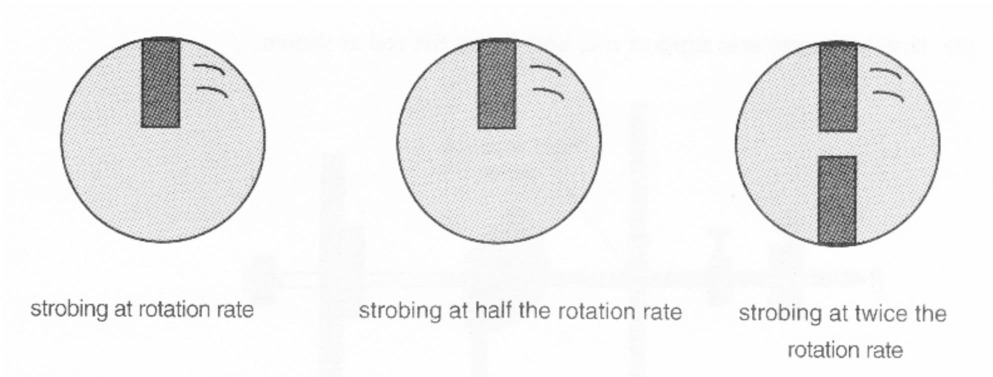




Wind a string around the gyro wheel pulley, and pull it off to spin up the wheel.

Turn on the Digistrobe, face it toward the spinning wheel, and adjust the flash rate until the mark on the wheel is stopped.

Now think for a few moments. If the strobe is flashing at the rate the wheel is rotating, the mark will, of course, appear stationary. However, if the strobe were flashing at half the rotation rate (or a third, quarter, etc.), the mark would also appear stationary. On the other hand, if the strobe were flashing at twice the rotation rate, you would see two marks, half a revolution apart.



Given these pieces of information, how will you determine the actual rotation rate from the strobe rate? (Write a brief answer below.)

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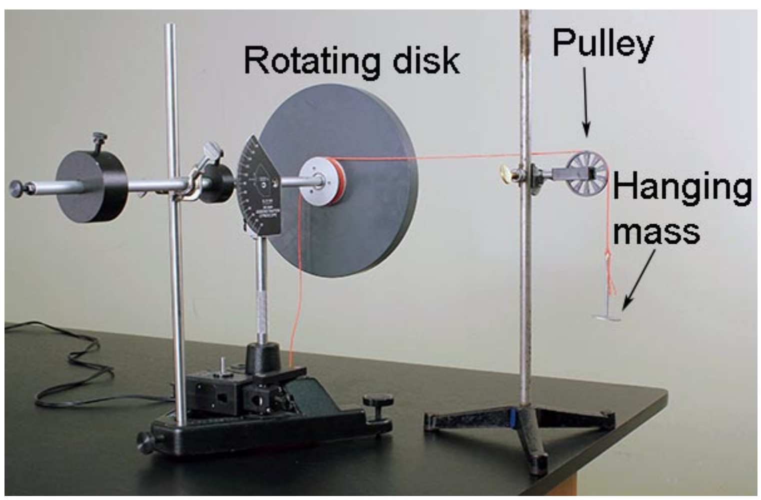
4. We need the rotational inertia I of the wheel. With the apparatus still clamped as above, arrange a known weight to fall through a measured distance h to accelerate the wheel. We leave the exact arrangement up to you. Measure the final velocity of the wheel with the strobe, and calculate the rotational inertia of the wheel from

$$(1/2)I\omega^2 = mgh. \tag{18}$$



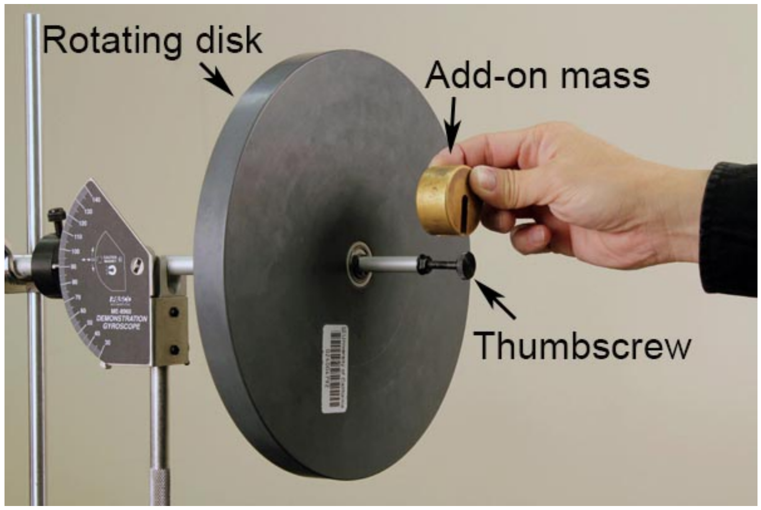
Be sure to keep your force and mass units straight. Make several trials until you have the strobe rate approximately correct, and need only to adjust it slightly just after the weights fall. Record I below.

$I =$ ______________________________

5. We need the tipping torque τ. Unclamp the gyro arm. The counterweight arm has a large and small weight. Adjust the positions of these weights so that the gyro arm is exactly balanced in the horizontal position. The small weight can be used to fine tune the balance. To produce the turning torque, you will attach the small add-on weight to the front of the gyro wheel.

Weigh this add-on weight (in newtons!), and measure the distance of its center from the axis of rotation. From these measurements you can calculate the torque.

$\tau =$ ______________________________



6. Now we are ready to precess! Spin up the wheel with a piece of string. Help the gyro start precessing with the arm horizontal by moving it along in the correct direction at the correct speed, and then release gently. Measure Ω on the computer, and ω with the strobe.

   $\omega =$ ______________________________

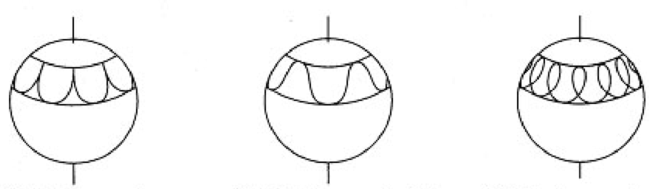
   measured $\Omega =$ ______________________________

   calculated $\Omega = \tau / I\omega =$ ______________________________

   percentage error = ______________________________

NUTATION

1. Spin up the wheel to high speed using the string. With the add-on weight producing a tipping torque, hold the shaft horizontally, and release suddenly. The gyroscope undergoes nutation, as in pattern A below.



(A) Released from rest (B) Released with forward speed (C) Released with backward speed

2. Start again with a smaller torque (just shift the counterweights a little), and with the wheel spinning and arm starting absolutely horizontally (supported by your finger), and then release

suddenly. (Use the angle scale on the gyro support to determine the 90° horizontal position). When the gyro is precessing and the nutation motion is damping out, the wheel end of the arm is somewhat below the horizontal position (read the angle scale). (After several precession revolutions, the nutation may be almost completely damped out with the gyro still precessing at a tilted angle. It may take a little experimentation with the torque and wheel speed to produce this situation.) Can you think of a general physics principle explaining why the gyro arm must be tilted down while the gyro is precessing when started from a horizontal position with sudden release? Answer below with brief explanation.

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In fact, there is yet another very general physics principle explaining why the gyro arm must be tilted down during precession if it is released from the horizontal position. Answer below with brief explanation.

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ADDITIONAL CREDIT (3 mills)

Perform the precession measurement three times with three significantly different ω's, and fill in the table below. Each lab partner must do this separately, doing the computer work him/herself, while directing the other lab partner to assist with the measurements.

	A	B	C	D
1	w(rad/s)	W (exp)	W(th)	% error
2				
3				
4				