12050 Air Table, Precision Student

Purpose:

The air table provides a frictionless, two dimensional surface for the study of mechanics. With the proper accessories, studies can be conducted in velocity, acceleration, Newton's Laws, center of mass, elastic and inelastic collisions, linear and angular momentum, conservation of momentum, moment of inertia, centripetal force, simple and complex harmonic motion. Refer to the enclosed air table manual for specific experiments.

Contents:

One	(1)	Air Table
One	(1)	Air Hose
One	(1)	Hose Tee
One	(1)	Rubber Stopper
Four	(4)	Corner screw assemblies each consisting of (1) cotter pin, (1) eyebolt, (1) knurled nut
One	(1)	Center Hole Plug, 1/4-20
Three	(3)	Leveling feet
Six	(6)	Pucks
Twelve	(12)	Steel Pins, 1 ½"
Four	(4)	Coil Springs
Two	(2)	Hook & Pile strips
Two	(2)	Screws (1 3/4 inch)
One	(1)	Laboratory Manual
One	(1)	Bumper wire
One	(1)	Coupling Nut w/ screw

Required Accessories:

Air supply

Optional Accessories:

Optional accessories that can enhance the use of the air table include the following, listed with Product Numbers:

Air Supply, Air Table #12060
Air Table Blinky #12018
Puck Launcher #12010
Magnetic Puck Set #12017
Puck Assortment #12024
Accelerometer Puck #12005
Multipurpose Puck #12007
Torque Puck #12026
Physical Pendulum/Inertia #12020
Additional useful accessories include, a stop watch, Polaroid camera, compression spring, pulley attachment, and small weights.

Assembly:

1) Install the leveling feet by first locating the three threaded inserts in the bottom of the table. Screw one leveling foot into each hole, secure with wing nut.

2) Attach the corner assemblies to the top of the table by first pushing a cotter pin into the holes in each corner. Pass an eyebolt through the eye of each cotter pin and install a knurled nut about half way up the thread. The eye end of the eye bolt should be pointing toward the center of the table.

3) Pass the bumper wire through the eye of each of the eye bolts. Position the coupling nut near the last corner. Pass both free ends of the bumper wire through the coupling nut, passing in opposite directions. Holding the coupling nut as close to the cotter pin as possible, pull the wire taught in both directions and tighten the set screw of the coupling nut. Trim excess wire to

remove the eye and finger hazards. The final position of the coupling nut should be so close to the corner that a puck will not be able to hit it.

4) The bumper wire can now be tensioned to the desired amount by tightening the knurled nuts on each of the corner posts. Do not over tighten the wire. Just enough tension to keep the wire straight is sufficient.

Operation:

Connect an air supply to the table and turn it on. Wipe the surface of the air table clean using a damp cloth. The pucks will not float properly if the table is covered with dirt, especially grit. Place a puck on the table and let it float to test levelness. The levelness of the table can be achieved by working with the three leveling screws in the base. One needs to level the table each time it is used and before beginning to collect quantitative data.

This precision air table is built using the same construction equipment, methods, and materials as the original Ealing student air table. It's honeycomb core provides exceptional stability, and table surface flatness to within ten thousandths of an inch. Several tables can be run from the same external air supply. Several peg holes are provided around the perimeter for the attachment of steel pins with which to mount springs to study oscillations and rubber bands for launching pucks. The table is also equipped with a 1/4-20 threaded hole through its center for circular motion/orbiting experiments

Maintenance:

Proper care of the air table is essential for long life and maintaining a flat surface. When the table needs cleaning, first turn on the air. Dust can now be removed by gently wiping with a clean damp cloth. For more serious problems use a little water and a mild detergent. For long term storage it is advisable to cover the table and stand it on end against a wall to avoid any accidental marring of the surface.

Time Allocation:

To prepare this product for an experimental trial should take less than ten minutes. Allow an additional fifteen minutes the first time to mount and adjust the bumper wire. Actual experiments will vary with needs of students and the method of instruction, but most are easily concluded within one class period.

Feedback:

If you have a question, a comment, or a suggestion that would improve this product, you may call our toll free number.

Introduction to Student Use:

The air table provides you with a powerful tool for performing a large number of experiments. This laboratory guide is designed to help you use the air table effectively. It provides instructions for performing many experiments. The instructions have been written in an open ended fashion omitting a great deal of detail so that you have an opportunity to do your own thinking. A great many questions are asked. Finding the answer will require you to pull together information from your text book, your classes, and other books that are available to you, plus using your own ingenuity. If something puzzles you, devise your own experiment to solve the puzzle.

Measuring Techniques:
There are two principle measuring techniques for acquiring data in air table experiments. The first uses an ordinary stop watch (or an electronically triggered stop clock) to determine the time it takes for the puck to move from one position to another. This technique is sufficient for some experiments. The second commonly used method for collecting data is strobe photography. An air table Blinky (# 12018) can be used in place of external strobe equipment. The Blinky is a flashing light mounted on a puck. The flash rate can be controlled according to the needs of the particular experiment.

Instant cameras can be used to photograph the Blinky as it moves across the air table. The camera should be mounted on a tripod for best results. The black background of the air table provides good clarity in the photograph. Most instant cameras use photocells. To obtain a time exposure, the photocell should be covered while the puck moves across the air table. If an external strobe is used, the puck should be marked with a white spot at its center and a white line to indicate rotation.

Lighting Techniques:
Strobe photography can also be done using a motor strobe. This is merely a slotted disk mounted on a synchronous motor that operates in synchronization with the AC line - 3600RPM or some submultiple for 60 Hz. (3000 RPM or a submultiple for 50 Hz). The strobe rate in openings per minute is the (rotation rate) x (the number of slots) provided the slots are equally spaced around the wheel. Divide by 60 to reduce this number to hertz or events per second. Reduce the rate by covering slots, but be sure that the uncovered slots are equally spaced. For instance, with 12 slots, you can have 2, 3, 4, 6, or 12 slots open. Some disks come with a second disk for covering slots. Alternately, just use black tape. Science First produces a motor strobe #16700 for use with Polaroid cameras.

A disk strobe is mounted in front of the lens and is positioned so as much lens as possible is centered in the slot area. If possible, isolate the motor and the camera to prevent the transmission of vibration to the camera.

Xenon Strobes:
Xenon flash tubes are operated by charging a capacitor to high voltage and then suddenly dumping all the stored energy through the flash tube which is filled with xenon gas. This energy turns to heat and light in an exceptionally short time - on the order of 1 µsec. The peak intensity of a typical tube is from 1 to 10 megalux - almost 3 orders of magnitude brighter than most familiar steady state sources. A strobe lamp consists of a timing circuit and a firing circuit. Many strobes use a variable timing circuit, but this has the disadvantage that the frequency is rarely well known. If you have a variable strobe, Check to see if there is any provision for calibration. Some strobes can be synchronized to an

internal vibrating reed driven by the AC line. If so, the instructions will be on the instrument.

Which Pucks Photograph Best:

Two types of puck are suitable for photographic purposes. Solid black pucks with white markings or the solid white pucks which are almost covered with red work equally well. Since most film is not sensitive in the red, the red will appear black in a photograph. The Avery Label Company makes a number of suitable white tapes which come mounted on a backing strip from which the tape or labels may be easily removed. Particularly useful are spots of small diameter and continuous strips. When decorating pucks for use in photography, remember that any white area that is photographed will obscure information provided by an overlapping image, thus the most satisfactory decoration techniques use thin lines, rings of small thickness, or small spots. The center of the standard ealing puck can be made more photographable if a round headed brightly plated screw is placed on the top of each puck post. These will reflect light into the camera in the same manner as a polished ball bearing.

Background lighting - When taking pictures, it is not necessary that the lab be light tight and that no one else's strobe be flashing. In fact, you can have a 25 watt bulb mounted in a shaded stand to see with. Just shut it off when you photograph. It is not necessary that your neighbors shut their lamps off unless they are directed toward your mirror or table surface.

Proper Placement of Lamps:

The secret to good multi exposure photographs is summed up in one word: contrast. Contrast can be thought of as the difference between the maximum and minimum illumination divided by the average illumination. White marks on black have good contrast; white on light gray shows poor contrast and so does light gray on slightly darker gray.

Consider an ordinary black and white photo of light and dark areas, and assume that for the film in use black areas are those reflecting 1 unit of light, dark gray 10, light gray 100, and white 1000. If we select the correct camera setting and photograph a white puck on a black air table, the photo will have good contrast; black is dark black and white is really white. What happens if we now photograph a moving puck with 10 flashes? To have the puck appear just as white as before, each flash must throw as much light on the puck as in the original photograph. This sounds fine; but what about the black? It now receives 10 times as much light and is recorded as dark gray giving poorer contrast. If the original light is divided into 10 equal flashes, the background is black, but the puck appears light gray. You cannot win! The larger the total number of flashes, the worse the contrast.

Note in the previous example the contrast could be restored by making the black area reflect only 0.1 units of light instead of 1 unit. You can improve contrast by making the background appear blacker to the camera. Consider the smooth black table as if it were a mirror. There are clearly some positions where your lamps would reflect all their light right up at the camera. Even though the table looks black, it is enough like a mirror so these positions should be avoided. The best positions place the light rays almost parallel to the table. One can also get a blacker background by following the puck or pucks with the light beam. Then only the background right next to the pucks is exposed during any one flash.

Camera stands with a mirror present special problems, since the lamps must not illuminate the camera lens either directly or by reflection in the mirrors. The best lamp position is on either side of the table with the light beamed down about 20° with respect to the horizontal. The further the lamp is from the table the more uniform the illumination is but the intensity is reduced. For some experiments the only solution is one lamp on each side of the table. Note, it is immaterial whether the lamp flashes or a disk chops the light; the contrast problem is the same.

For data runs that involve only a few strobes set the lamp or lamps at a fairly high angle for a good dark picture. For runs needing many flashes place the lamps so their beams are almost parallel to the table and use the highest intensity as well as extra lamps. Alternatively, use a narrow beam of light and follow the puck or pucks. If you are following the pucks, however, you must still bring the light in at an angle close to horizontal.

Collecting Data with a Spark Recorder:

This section is included mostly for historical reasons. Spark recording on an air table such as this is an awkward and inconvenient process. More recent developments using photo gates and strobe photography make spark timers obsolete.

Most mechanics experiments ask for knowledge of the position, velocity, and sometimes the acceleration of one or more objects as a function of time. In practice this means sampling these quantities periodically. For instance, if the position of a mass m is known at a number of closely spaced equal time intervals, the observer not only knows the displacement x as a function of the time t but also the velocity v between each pair of points. One merely divides the distance Δx moved in one interval by the length of the interval Δt. That is $v=\Delta x/\Delta t$. The proper "place" to assign this velocity is most important and is the subject of a number of interesting experiments and theoretical proofs. It is sufficient to say here that the velocity v must occur somewhere between x_1 and x_2 if $v=(x_2-x_1)/\Delta t$.

A convenient way to locate an object like a puck on an air table is to let a spark jump from some point on the puck through a piece of sensitized recording paper to a metal plate, thus leaving a spot on the paper. To do this, the spark must first get to the puck from somewhere else by means of spark transfer wires. Since neither the metal plate nor the transfer wires actually touch the pucks, the recording method itself is frictionless and does not disturb the experiment.

Sparks are obtained by discharging a capacitor through an automobile type spark coil. The output of this coil is a pulse of about 40 kilovolts, enough to jump several spark gaps in series. The timing of the discharge is done in many ways. Sometimes a motor rotates a contact switch, and sometimes the 50 or 60 Hz line is used directly. The latter technique however, gives a spark rate that is inconveniently fast for use on air tables.

Cleaning and Marking the Air Table:

Proper care of the air table is essential for long life and for maintaining a flat surface. The table should be covered between classes by a cover. For long term storage, it is advisable to set the table on end with the dust cover in place. This is recommended because, when left horizontal the table tends to be used as a storage place which may damage the surface and later the flatness. Storing the table flat in a closed cabinet where it is protected is permissible.

When the table needs cleaning, turn on the air. This is important for two reasons. First, the air keeps dirt from being forced into the tiny holes; and second, the circulating air warms the table and helps to dry it quickly. Remove dust by gently applying a clean damp cloth. For more serious problems use water and mild detergent. If a solvent is used, test to be sure it does not act chemically on Formica. Be extremely careful with any flammable solvent. The air can quickly turn a quantity of solvent into a major fire hazard. When using either water or solvent, wipe lightly to eliminate the possibility of dirt scratching the table surface. CAUTION: *do not use steel wool, scouring pads or abrasives.*

Many experiments require the pucks to be returned to a predetermined position several times. Either a *soft* pencil or magic marker will leave a temporary mark without damaging the table. Similar marks may be used to establish lines perpendicular to the table edge using a T-Square or lines concentric with the center using a large compass. Do not use crayons, china markers or any wax based marker since they will clog the tiny holes. Do not use ball point pens which may scratch the surface. Clean the marks off the table afterwards with water or solvent as discussed above. Xylene is a good solvent for the non -water-base marking pens. It is nontoxic and has a high flash point so that there is little fire hazard. Do not use acetone or carbon tetrachloride; they are not safe.

The pucks will stand still when there is no air coming up from below. If they are already moving, they will "stop dead" provided that the air in the table is "dumped" fast enough. Your table is provided with air via a T-shaped fitting with a cork in one end of the Tee. If you remove this cork, the air will instantly suck out of the table dropping the pucks. Note , if you are sharing an air supply with other students, coordinate with them. Dumping your air will reduce their pressure.

When a puck is left standing on even a level air table, it will drift slightly. When preparing a collision with a puck at rest, leave the air supply off until an instant before you launch the incoming puck. In this way the puck at rest will not have time to start drifting.

It is frequently enough to know the location of the pucks at just two instants of time. The first instant is provided by an event such as a collision of a moving puck with one at rest. The second instant is provided by removing the air supply to freeze the pucks. Since the collision point of the puck initially at rest is known, you can then measure the distances that both pucks have traveled in the time since impact. You then know the ratio of the velocities of the pucks after the collision but not the exact numerical velocities themselves.

The air dumping technique is particularly applicable in center of mass experiments. For instance, you can cause a group of pucks to " explode" in the center of the table, and then remove the air before any of them have reached the sides. Then you may check out wether the center of mass has moved by a leisurely measurement of the radius vectors.

Initial conditions are important when studying oscillating systems. By turning off the air, you can preset the position of pendulums, coupled pendulums, or pucks joined by springs. The only limitation is that springs must not be so strong that they move the pucks with the air off.

When a puck is placed on a level air table it may drift slightly. The error introduced due to the drift will be negligible. The springs provided with the table can be stretched many times their normal length without exceeding their elastic limit.

Threaded holes are provided at various points on the table for screws that can be used to attach springs, rubber bands, and thread for various experiments.

A puck launcher may be improvised by attaching two screws to the table and stretching a rubber band between them. A more versatile device is The Puck Launcher #12010.

Velcro tape is provided with your air table. The tape may be cut to any convenient length. It may be easily attached to the air table pucks.

The Velcro will provide perfectly inelastic collisions in your experiments. Take care that the Velcro does not contact the table.

It is useful to have available a set of blocks of various known thicknesses to provide an easily reproducible tilt to the air table.

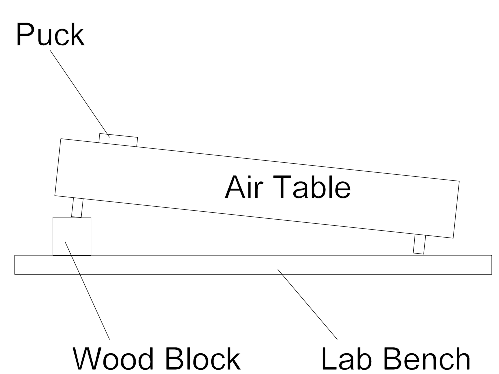
In any experiment where increasing masses are required , the puck masses may be increased by connecting additional pucks or by adding washers to a single puck using the 1 3/4 screws supplied with the table. If double or triple mass pucks are required, use a balance and washers to verify that the correct multiple is arrived at.

Experiment #1
Motion in a Straight Line

Carefully level the air table. Project a puck along the level table and record its motion. From the record of the motion determine the velocity and acceleration of the puck.

Raise the end of the table with the single leg, 2 or 3 cm. Release the puck from the raised end of the table. Time its motion until it strikes the opposite end of the table. What distance did the puck travel? What is the average speed of the puck? Did the puck accelerate? How do you know?

Release a double mass puck from the raised end of the table. Determine the acceleration of the double mass puck down the table. How does the acceleration compare with that of the single puck? Are you surprised? Can you explain? Can you relate this experiment to Galileo's famous experiment where he dropped balls of various masses from the Leaning Tower of Pisa? What is the average speed of the puck? Repeat the experiment moving the puck by 30 cm increments each time toward the lower end of the table. Make a table of average speed and distance traveled. Can you determine the acceleration of the puck from your data? Try the experiment with a triple mass puck.



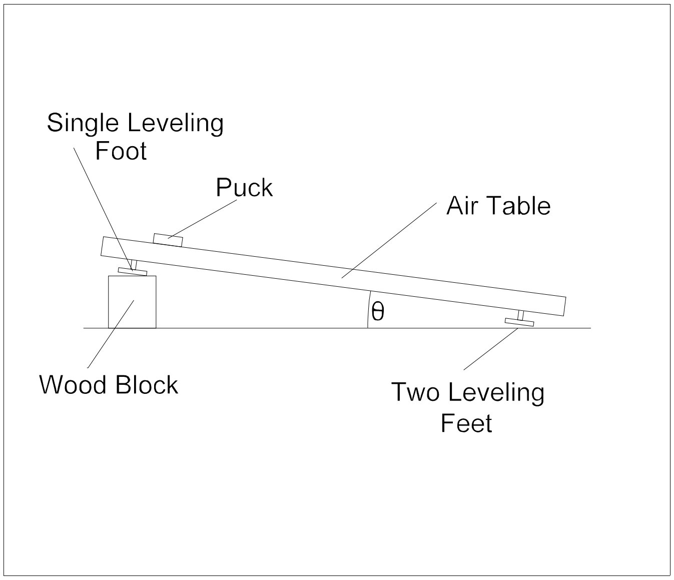
Experiment #1 **Figure #1**
A block with height h is placed under one leveling screw to tilt the air table to an angle θ with respect to the horizontal.

Use the same setup as in Part 2. Launch a puck from the low end of the table so that it travels up the incline and reaches almost to the top. Record the motion of the puck. What is the average speed of the puck as it moves up the incline? What is its acceleration? If you launch the puck with different initial velocities will the average velocity change? Will the acceleration change?

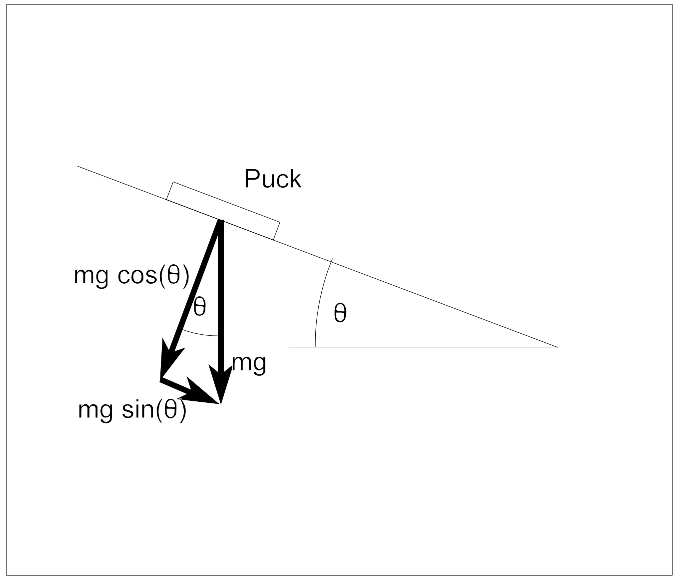
In parts 2 and 3 a component of the puck weight provided the accelerating force. In this experiment an external weight will be used to provide the accelerating force. Attach a pulley to the edge of the air table. Set up your equipment as shown in Figure 2. Tie a small weight to a heavy thread. Hold the puck in place until you are ready to record its motion. Release the puck. From the record of its motion find the average speed during the motion. Where was the speed greatest? Determine the acceleration of the puck. How does acceleration compare with that in part 1? Explain any differences.

Experiment #2
Acceleration on an Inclined Plane

Object:
In this experiment your will study the motion of an object starting from rest on a frictionless inclined plane. The raw data will be a measurement of the object's position as a function of time. This data and the computed quantities which are velocity and acceleration will be plotted on linear graph paper in search for two variables that have a simple linear relationship. Any variables that do not yield a



Experiment #2 **Figure #1**
A block with height *h* is placed under one leveling screw to tilt the air table to an angle θ with respect to the horizontal.



Experiment #2 **Figure #2**
Resolution of forces acting on a puck on a tilted air table.

straight line on linear graph paper will be plotted on log-log paper in an attempt to find simple equations that relate the measurements.

Experiment Design:

You will need an inclined plane whose tilt angle is known precisely. To tilt the air table by a computable amount, first level it by adjusting the leveling screws until a puck placed at the center will remain essentially stationary. Then lock all three screws and check again. Next place a block under the single foot to raise this end by an amount h. Figure 1 shows how the block tilts the table through an angle θ.

Now consider the puck itself. In the figure, the puck's weight is resolved into forces parallel and perpendicular to the inclined plane. If the puck is released, it will accelerate at an effective rate $a=g \bullet \sin(\theta)$. Thus, if you measure a, and $\sin(\theta)$, you will also be able to determine g, the local gravitational constant.

To release the puck without giving it an extra push with your fingers, use a thin piece of thread. Tie the puck center post to the thread and the thread to a post placed along the side of the air table. Then burn the thread. An easier method, but one requiring more care on your part, is to hold the puck by a long loop of thread with both ends under your finger. To release, merely raise your finger quickly. In either case the puck should be started from a position near the "upper" wall of the table.

For the most accurate experiment your puck should "fall" along an absolutely flat section of the table. You can locate the best section of table after leveling but before adding the tilt block. Another way to get rid of flatness as a problem is to use relatively large tilt angles such as 1 to 3 inches (3 to 8 cm). Why will this help?

Data Collection - Always try to get the most out of the equipment you have available. In particular, let the equipment "tell" you the best way to collect data. With spark or strobe systems, the interval between sparks or strobes is precisely known and so position (unknown) is measured as a function of time (known). With a photocell gate on the other hand, it is easier to make the position of the gate the known quantity and to measure the unknown quantity, time. Your instructor will tell you which system or systems you will have available so you can plan your experiment accordingly.

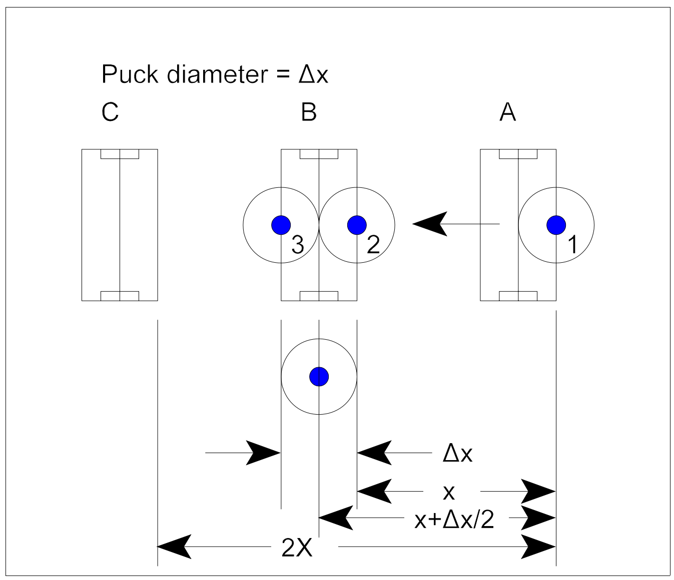
Data Collection, Strobe or Spark - To select the best strobe rate, first do a preliminary experiment to see roughly how long it takes the puck to "fall" across the table. Assume that it takes 2 seconds. If you want 10 points on your photograph, you need 10/2=5 per second, so the strobe should be set to 5 Hz. Of course, you may be required to use a less convenient rate, usually one that is too fast. You can live with this by changing the tilt or by using every second or third data point. A further inconvenience may be that the strobe misses a data point. Such a missing point is always apparent on the data records as an extra large gap in the record. It is all right to ignore such a point, but remember that if the time between sparks or strobes is Δt, you must use $2\Delta t$ between the recorded points when the one in between is missing.

Data Collection, Photocell Gate - With a single photocell gate, you can measure how long, Δt, it takes a puck of diameter, Δx, to pass through the gate. From this information you can readily compute the average velocity $v=\Delta x/\Delta t$.

With 2 photocell gates, you can measure how long it takes your puck to move from the release point to the second gate. To do this, place the first gate so that the puck is almost "into" the gate. Thus, if the puck moves just one more mm down the table, the light will stop reaching the photocell. You can then wire the timer so that the first gate turns it on and the second gate turns it off.

If you have only one photocell gate you will need a switch to start the timer. A small micro switch is best. You can use one finger to simultaneously hold down the switch and the string that holds the puck. Lifting the finger will start the puck and timer together. When the puck gets to the photocell gate, The timer will stop. Note, with most timers, the timer will start again after the puck is through the gate. To prevent this you can "catch" the puck in the middle of the gate by placing a piece of masking tape across the table. Your instructor will tell you what kind of gate system to expect before you come to laboratory.

The chief problem with a photocell gate system is keeping track of what you are really measuring. Consider figure 3 below: If gate A starts a timer and B stops it, clearly the time t recorded is that required to go the distance x. Note, however, that if gate B is now used to measure the velocity it will measure Δt for an average velocity not at x but at $x + (\Delta x/2)$ and that the time to this velocity determination is $t + (\Delta t/2)$ not just t.



Experiment #2 **Figure #3**

A puck of diameter Δx is released "in" gate A and allowed to travel through gate B.

To get a reasonable number of data points for this experiment, the first distance, x, should be about 1/10 of the distance that the puck is free to fall. You can make measurements at x, $2x$, $3x$, ... etc.

Procedure, Strobe or spark data collection:
Make a record of about 10 sparks or strobes to record position as a function of time. Number the points 1, 2, 3, ... and measure each distance x with respect to the location of the puck before it was released. Thus, the raw data to be used in plotting will be x_1, x_2, x_3, ... and the values t_1, t_2, t_3, ... which are determined from the spark or strobe rate. Of course, the necessary measurements must be made for determining the tilt of the table, for instance the riser block height or $sin(\theta)$.

It is important to note that while the interval between t_1, and t_2 is precisely known from the spark or strobe rate, the time t_0, one spark or strobe interval earlier, has *no* correlation with the instant you released the puck. For, certainly, the pulse generator has no way of "knowing" when you released the puck; and if you have a normal reaction rate, you could not possibly coordinate your release with the pulse generator. This point is important since, for many of the graphs, things only work out nicely if the time axis starts at the time of release; and you won't know this release time without "working for it".

Photocell gate data collection **-** Select about 10 points along the path of the falling puck. For each point determine the length of time Δt it takes a puck of width Δt it takes a puck of width Δx to pass through the gate. Also determine the time for the puck to move from the release point until it is halfway through the gate. Of course, you should also record the x positions and such useful data as the table tilt or the riser block height.

Data Analysis **-** The object of this part of the experiment is to use graphs to determine the equations that most conveniently relate the variables. These equations themselves are no secret. They are all in your text book, and if you get stuck and can go no further, you may want to look them up to see if the equations will suggest to you where you went wrong. The best procedure, however, is to forget that these equations are in the text and to see if you can work out the relations using nothing but your own data.

The x versus t graph **-** Locate the points t_1, t_2, t_3, ...etc. on the t axis (horizontal axis) of a piece of standard x-y coordinate paper. For each point, plot the value of x corresponding to it. Does this plot result in a straight line? Can you tell from the plot when the puck was released? Can you *easily* use this plot to find a relation between x and t? If not what is the most important "defect" in this plot that makes determination of the relation difficult? Do you recognize the general shape of the graph? If so, what, if anything, does it suggest that you do next? Do not answer these questions as such in your report. Instead, let them help you make one or more conclusions on the graph or in your report.

The v versus t graph **-** You can compute the velocity v corresponding to a number of points from the relation $v=\Delta x/\Delta t$. For spark and strobe data, a typical velocity is $v=(x_2-x_1)/\Delta t$. This velocity "must" have occurred somewhere between the points x_1 and x_2. Your problem is to decide where to plot it. The most plausible point, the halfway point, turns out to be correct., but we will *not* prove this important assumption. You will have a proof of sorts, however, if it gives you good results. Thus you should plot the velocity $v=(x_2-x_1)/\Delta t$ at a point on the time axis $t_1+\Delta t/2$. Of course, if you are using a photocell gate, the "right" point for plotting the velocity will be more apparent. *Plot v versus t for all calculated values of v*. Does this plot yield a straight line? If so, find the slope of the best fit straight line. What is the meaning of the intercept where this line crosses the t axis? Does this give you any information about your x vs t plot? What are the units of the slope? Are they correct for an acceleration? If so, find the acceleration and from it compute *g*, the local gravitational acceleration. Again, state in complete sentences all the conclusions you are able to make from this graph.

A log-x vs log t plot - (optional - consult with your instructor about doing this part). Read the section on log-log plots in the appendix on graphical analysis. Note especially the necessity for knowing the actual zero point for both variables. From the v vs t plot you can determine exactly where the puck was released. Use this time as $t=0$ and plot x and t on log-log paper. Is the resulting plot a straight line? What is the slope of this line? Be sure you understand how to compute this slope. See the appendix. From the best fit curve, determine the relationship between x and t. How does your relation compare with the standard textbook formula? Can g be computed from this relation? State your conclusions in full.

Note that the object of this experiment was not to measure *g,* but that as a minor output you were able to compute this value. Several other experiments also yield values for g, so if there is time, try to determine how good this method is so you can compare it later. How could you improve the experiment as a method for measuring *g*?

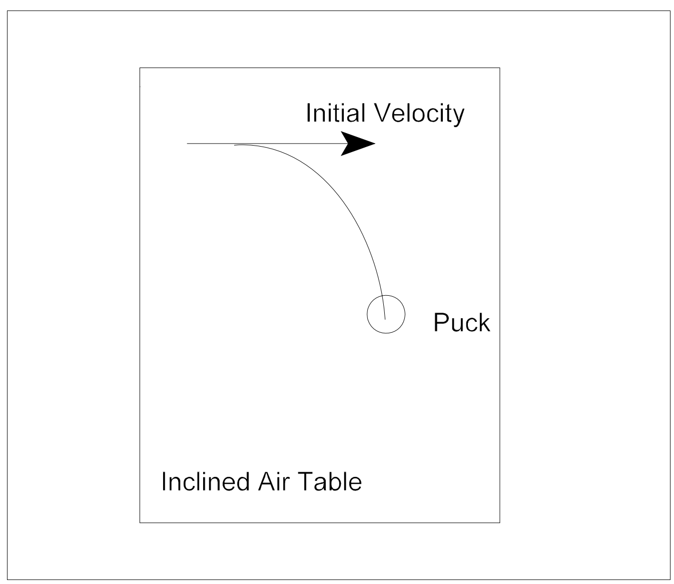
Experiment 3: Motion in 2 Dimensions:

In experiment 1 your studied the motion of an object moving in a straight line, that is, in one dimension. In this chapter you will study the motion of an object moving in 2 dimensions.

On a level air table, launch a puck across the table using the puck launcher. Determine the velocity imparted to the puck at this setting of the puck launcher. What is the resultant force acting on the puck as it moves across the table?

Raise the air table at one end about 2 or 3 cm. Release a puck from the raised end of the table so that it slides straight down in the Y direction. Determine the acceleration of the puck. Use the same puck launcher setting as in Part 1 and launch the puck up the table. How high up the table will it travel before it stops and begins to return to the starting point. What effect would changing the angle of tilt of the table have on the “height” to which the pucks travels assuming the same launch velocity is used? What happens if you change the puck launcher setting while keeping the tilt angle constant? Explain your answer.

Using the same puck launcher setting and table tilt as in parts 1 and 2 project a puck in the X direction as shown in figure 1. Record the motion of the puck. After the puck is launched, what force or forces act on the puck? Think about this as you analyze the photographic data. What is the acceleration component of the puck in the Y direction? How does this compare with the acceleration you determined in Part 2? What is the acceleration component of the puck in the X direction? How does this compare with the acceleration of the puck in



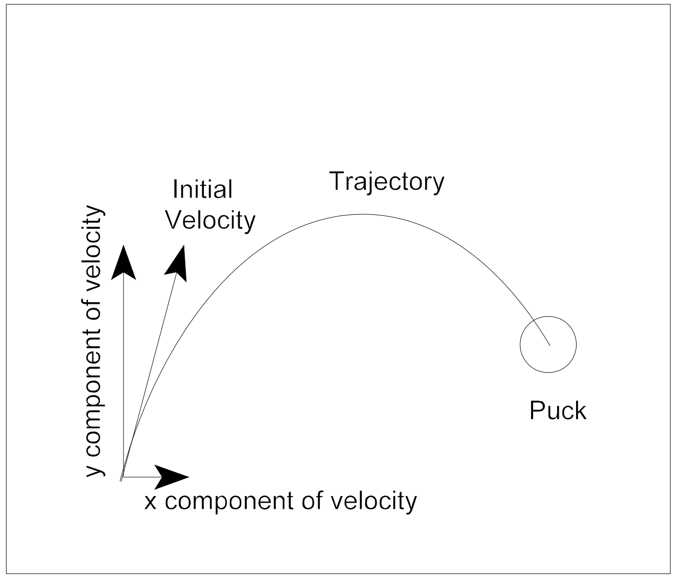
Experiment #3 **Figure #1**
Puck given an initial horizontal velocity.

Part 1? What would be the effect on the motion of the puck if the angle of tilt was changed while the launch velocity was kept constant? What would be the effect on the motion of the puck if the angle of tilt was kept constant while the launch velocity was varied?

In this experiment you will launch the puck at an angel with the X axis from the lower end of the table. Set up your apparatus as shown in figure 2 and project the puck up the incline. Vary the launch angle while keeping the launch velocity constant. Determine the angle that will allow the puck to reach the greatest height on the air table. (Maximum in the Y direction.) Determine the angle that produces the greatest range for the puck (maximum in the X direction) when it returns to the same level from which it was launched. Keep the launch angle constant and vary the launch velocity. How does this effect the maximum in the X and Y directions?

Experiment 4: Inertial and Gravitational Mass

The inertial mass of an object is a measure of the difficulty in changing the velocity of an object, that is, accelerating it. It is a measure of the resistance of an object to a change in its state of motion. In the equation $F=ma$, the proportionality constant m is a measure of the inertial mass. If we apply the same force to two different objects and their accelerations are measured to be the same then their inertial masses are equal. Gravitational mass is a measure of attractive force between two objects, for example, you and the earth. To measure the inertial mass of an object, we apply a force to it and measure its acceleration. Gravity is not a factor. We would obtain the same results anywhere in the universe. To measure gravitational mass we use a balance which compares the gravitational forces on two objects. If the gravitational forces are equal

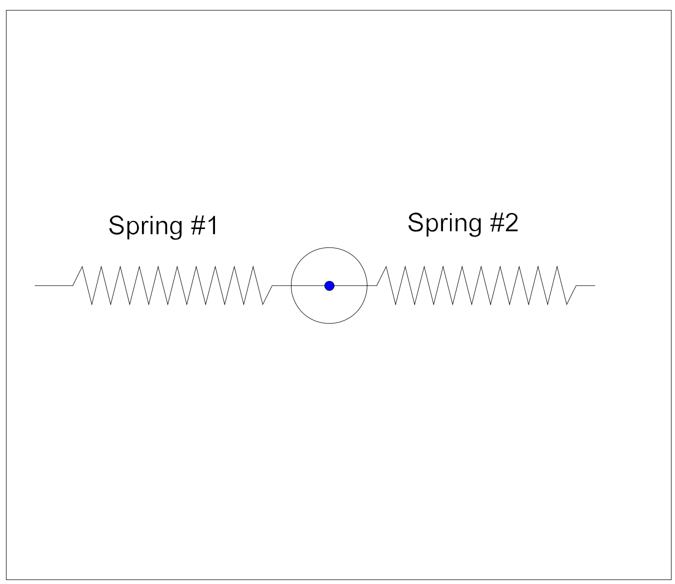


Experiment #3 **Figure #2**
Puck given an initial velocity with horizontal and vertical components.

then the masses are equal.

In this experiment you will measure the inertial and gravitational masses of the air table pucks and other objects and attempt to determine the relationship between these two types of mass.

Use the two springs from the air table accessory package. Arrange your apparatus as



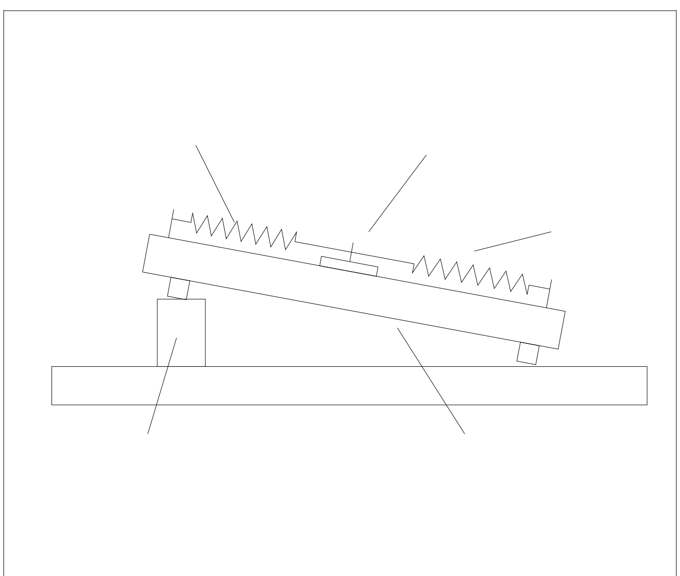
Experiment #4 **Figure #1**
Attaching low k springs to a puck.

shown in figure 1. Displace the puck about 30 cm and release it. Measure the time for five oscillations, then divide by five to get the time for one oscillation which is called the period. Why do you think you were instructed to measure 5 oscillations rather than one directly? Record your data in table 1. Continue the experiment by adding additional masses to the puck until you have completed table 1. From your data plot the period of oscillations as a function of mass.

Table #1

Period	Inertial Mass	Gravitational Mass

Now determine the period of several unknown masses. From your graph determine the inertial mass. To determine the gravitational mass of these objects use a standard laboratory balance. How do the gravitational and inertial mass compare? What is the relationship between inertial and gravitational mass? If the above experiment were performed on another planet, would the results be the same? Explain.



Experiment #4 **Figure #2**
Setup for measuring the mass of a puck on an inclined air table.

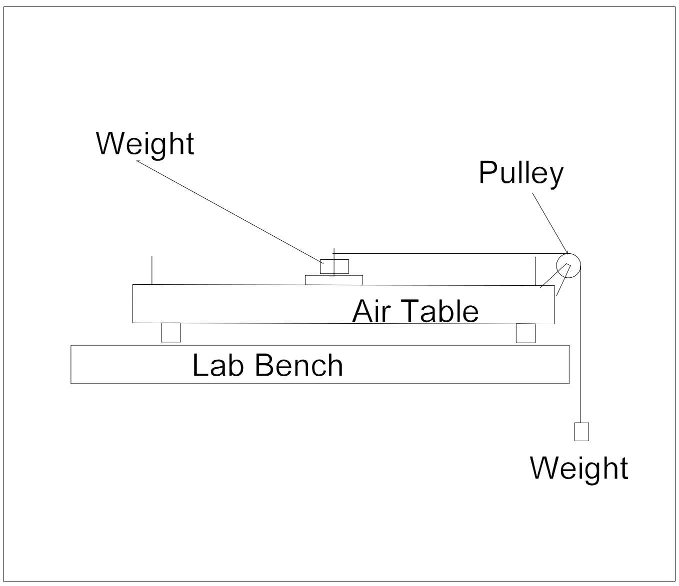
In this experiment you will attempt to measure mass using an inclined air table. In the previous experiment the spring forces caused the acceleration. What force or forces produce the acceleration in this experiment? What kind of mass are we determining, inertial or gravitational? Set up the experiment as shown in figure 2. Allow a puck to move down the track. Make the necessary measurements and compute its acceleration. Repeat the experiment four additional times adding different masses to the puck each time.

From your data, plot a graph of mass vs. Acceleration. Account for the shape of the graph. Can you determine the mass of an unknown object from the graph? Determine the gravitational mass of each object using a balance.

Experiment 5: Force and Motion

Carefully level the air table. With your hand or the puck launcher, project a puck across the air table. Catch the puck before it strikes the opposite end of the table. Record the motion. What is the velocity of the puck as it moves across the table? What is the acceleration of the puck? What is the resultant horizontal force acting on the puck as it moves across the table? Is there any point in its motion where an unbalanced force acts on the puck? Draw a velocity vs time graph of the motion of the puck. From your graph determine the distance traveled by the puck. Compare this with actual measurements of the distance. Draw an acceleration vs time graph of the puck's motion.

We know from experience that it requires an unbalanced force to make an object accelerate. In part 1, a force was applied briefly to accelerate the puck and then removed. What happens if a constant force is applied throughout its motion? In this experiment you will investigate the effect of constant forces acting on the puck. It is important in an experiment to deal with only one variable at a time. Therefore, the mass must be kept constant while the force is varied. Note that in figure 1, not only the puck but the string and the mass hanging from the string are all connected and therefore part of the same system. They all will be accelerated at the same rate. Therefore, the



Experiment #5 **Figure #1**
Experimental setup for force and motion.

accelerated mass is the sum of the puck and small masses. What would happen if Mass A accelerated faster than the puck? What would happen if Mass A accelerated more slowly than the puck? Are these situations possible? Since there is no friction on an air table to retard motion (unlike our everyday world) small forces will produce large effects. Therefore, select 4 small masses (about5 to 10 grams each) for the experiment. Attach 3 of the masses to the puck and 1 to the end of the string which passes over a pulley as shown in figure 1. The falling mass will supply the necessary force to accelerate the puck. Hold the puck in place until you are ready to begin the experiment. Release the puck and record its motion. From the record of the motion, plot a distance vs time graph for the puck. Next plot a velocity vs time graph. From the velocity *vs* time graph determine the acceleration of the puck. Is it a constant or variable? What situations would produce a constant acceleration? What situations would produce a variable acceleration. Which case do you have here? Repeat the experiment 3 additional times, each time transferring a mass from the puck to the end of the string. Plot a graph of acceleration vs force. Can you determine a relationship between force and acceleration from your graph?

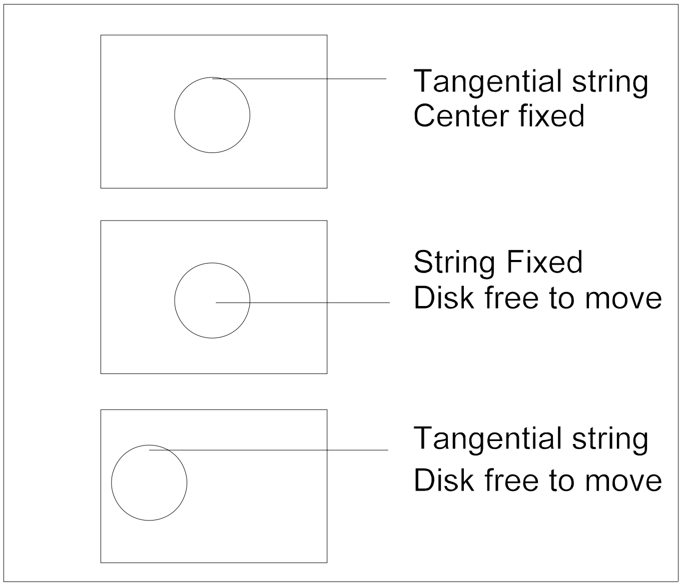
In part 2, the mass of the system was kept constant while the force was varied. In part 3, the force will be kept constant while the mass is varied.

Set up the experiment as you did in part 2, but use only one small mass. Attach the small mass to the string which passes over the pulley. Release the puck and record the motion. Now use a double mass puck and repeat the experiment. Use a triple mass puck and repeat the experiment. Finally, use a puck combination that is equal to four single puck masses. Plot a graph of acceleration vs mass. Can you determine a relationship between acceleration and mass?

Experiment 6: Linear and Angular Acceleration of a Disk

Object:

To study the acceleration of a massive disk under three circumstances: a tangential force is applied to the edge with the center fixed; a force is applied to the center of the disk with the disk free to move; and a tangential force is applied to the edge with the disk free to move. To compare the motion of the disk for all three cases with the force being constant.



Experiment #6 **Figure #1**
Three experiments that apply the same force to a disk by means of a string, pulley, and weight.

Discussion:

An important factor in this experiment is an assumption that you can make about the force exerted by a hanging weight of mass m. When the weight is stationary, it exerts a force $F=mg$ where g is the gravitational acceleration. Suppose that the string from which the weight hangs is passes over a low friction pulley and is attached to some object in such a way that the object can be accelerated at some rate a. Usually the tension T in the string is then given by $T=m(g-a)$; however, if $a \ll g$, you can neglect a and consider that the force mg is a constant. Remember this assumption when setting up your experiment. The mass m must be more than 100 times smaller than the other masses for the assumption to be valid.

In this experiment you will use a heavy disk of uniform thickness with a groove cut into the outer edge. For applying a tangential force to the disk, a string can be wrapped around the groove several times then led over a pulley to a hanging weight. The two important physical properties of a uniform disk of mass M are that its center of mass is in the center and that the moment of inertia I is $1/2Mr^2$.

Consider the first experiment (figure 1 top) in the adjacent diagram. The string is wrapped around the disk of mass M several times and then led over the pulley to the small weight m. Here $M \gg m$. The disk is held in place by the center post with a ball bearing and is floated without friction on the air table. What happens when the small weight is released?

This is a case of pure angular acceleration by a torque $\tau=rF$, so the angular acceleration α is given by:

$$\alpha= \tau/I = rF/(1/2Mr2) = 2F/Mr$$

To find out how the small weight moves it is only necessary to know the acceleration, a, of a point on the circumference of the disk.

$$a= r\alpha = 2F/M$$

If the string is attached to the center of the disk as in figure 1(middle), and then the disk is released, the motion is simple linear acceleration of the center of mass with no rotation. For the center of mass and for the small weight, the answer is the same:

$$a=F/M$$

The illustration figure 1(bottom) is a good test of your grasp of rigid body mechanics. Write our your answers to the following questions before you come to the laboratory. If you do not know an answer, give the most plausible guess you can since you will be able to test your answers by doing the experiment.

What path will the center of mass take when the disk is released? Your reference points are the center of mass, the string, and the pulley.

Will the center of mass accelerate? If so, what will the acceleration be?

What is the angular acceleration of the disk?

If the small weight falls 1 meter in 2 seconds in experiment (a), how far does it fall in the same intervals in (b) and (c)?

How much energy does the disk acquire in each of the three experiments? Hint: how far does the small weight fall?

Equipment:

Stopwatch: This experiment can be done entirely by using a meter stick and a stop watch. Since you are most interested in comparing three accelerations, consider arranging your experiment so that you measure how far the weight falls during some convenient time interval such as 3 sec. The more room available for the small weight to fall the better. You may want to raise the air table higher than the lab table.

Strobe photography: Use the standard camera setup, but be sure that you work out ahead of time a convenient flash rate for all three experiments. To measure what the string is doing, lightly stick a small dot of masking tape on the string. It will fall off when it gets to the pulley.

Pulley arrangements: Any small low friction pulley will do. You can get greater travel for the small weight by running the string under one pulley, then up high over a second pulley; however, unless air pulleys are used, the friction in the system may be an excessive penalty for the longer fall. It is probably worthwhile to use two pulleys if you are using a stopwatch to collect data.

Data Collection:

Set up and perform the three experiments so that you can again answer the questions you answered before coming to the laboratory. Acceleration can be measured from a distance s using the formula $s=1/2at^2$. For comparing accelerations, it is convenient to use the same value of t throughout.

Additional Questions:

You just made an important assumption that the force applied by the small weight was a constant. Justify this assumption quantitatively.

Are the various accelerations uniform? What is the minimum number of measurements that would enable you to answer this question?

Which experimental results did you find surprising? Why?

Experiment 7: Oscillations (Simple Harmonic Motion)

A regular back and forth motion is called a vibration or oscillation. In an oscillating system, energy is continually changing from potential energy to kinetic energy. If an object is acted upon by a restoring force whose magnitude is directly proportional to its displacement, it undergoes simple harmonic motion which is a regular series of oscillations. In this experiment you will analyze one type of system undergoing simple harmonic motion.

Use the two springs from the accessory kit. Suspend one spring from a suitable support. Hang a series of weights from the spring and make a graph of the spring as a function of the force applied to it.

Determine the spring constant. Write an equation for force, F, as a function of extension, X. Repeat this for the second spring. Using your graph, predict the force required to produce an extension of 20 cm. Suspend one spring and hang a 20 gram mass from the spring. Pull the spring down 10 cm. Find out if the time for each complete oscillation (period) is the same or different. Can you explain your results? Pull the mass down 20 cm and let it oscillate. How does the period compare with that in the previous case? Try additional displacements until you can determine the relationship of the period of the motion of the mass and its initial displacement. Next, vary the mass hanging from the spring. Determine the relationship of the mass hanging on the end of the spring and the period. In all the above experiments, what forces were acting on the mass? Draw a vector force diagram of the forces acting on the mass at the bottom end of its motion, at the top end, and at the midpoint.

In the vertical position only one spring was necessary to produce oscillations. Why? In this experiment we will need two springs to produce oscillations in a plane parallel to the earth. Do you think the same basic principles will hold in the horizontal direction as were true in the vertical? To find out, set up your apparatus as shown in experiment 5. Displace the puck and determine the period. Determine the period for several different displacements of the puck. How is the period affected by varying the puck displacement?

Next, vary the mass of the puck while keeping the displacement constant. Determine the period for several different puck masses. How is the period affected by varying the puck mass?

In this experiment use a strobe puck (Blinky) or an external strobe light. You will attempt to determine the velocity and acceleration of the puck at several positions during one half of an oscillation. Displace a puck (or Blinky) 30 cm and record its motion as it moves through equilibrium to the maximum displacement in the opposite direction. Do not photograph the puck on its return path. If you do so your photo will be unintelligible because the dots of light will run over each other. From your data, determine the velocity and acceleration of the puck at the midpoint, and end points of the motion. Where is the velocity a maximum? Where is it a minimum? Repeat this experiment on a tilted table. What force is introduced? What effect does it have? Before doing the experiment, Make some predictions using the same two springs and puck.
Can you predict the period of motion? Will the equilibrium position be in the same place on the table? What would happen (don't do it) if the table were tilted 90 degrees with respect to the horizontal? Can you predict the period?

Experiment 8: Momentum Changes in Explosion

In this experiment, we will study the explosion of two pucks. We can define an explosion as a sudden force pushing the pucks apart. What happens to the momentum of each puck? What happens to the momentum of the puck system? What is the initial momentum of the puck system? Place two pucks with a compression spring between them. Push on them so that the spring is compressed. Release the pucks and record the motion. What is the momentum of Puck B? What is the sum of their momenta? What happens if we push a puck against the bumper wire of the table and release it? Is momentum conserved? We see the puck moving in one direction but nothing appears to move in the opposite direction. Explain what is happening.

Repeat the experiment while increasing the mass of Puck A. Keep adding mass to A and repeat the experiment until you have obtained enough data to answer the following questions: How does the total momentum of the system before an explosion compare with that after an explosion? What if you did the experiment on a tilted table? What do you think would happen? Make some predictions then try it.

Experiment 9: Perfectly Elastic Collisions

Object:
To study the conservation of momentum and energy in a collision between two magnetic pucks of equal mass.

Introduction:
A perfectly elastic collision is one in which kinetic energy and momentum are both conserved. A close approximation of such an ideal elastic collision is provided by the interaction of two magnetic pucks, both of which are free to move on a frictionless surface. Since the forces involved are non contact and strictly radial, no angular momentum or angular kinetic energy is transferred or imparted to the pucks during the time when their magnetic fields interact.

Procedure:
Take two magnetic pucks of equal mass. One magnetic puck P_1 is placed near the center of the table; its initial velocity is to be zero. The second puck P_2 is launched toward the stationary one. Practice with the puck launcher so that you get a good collision. The pucks must not go so fast as to make physical contact. Stop recording data before the pucks hit the walls. Failure to do so will yield useless data, since you can accurately determine the time of collision only by counting back an equal number of points starting with the last recorded point for each puck.

Call the first position of P_1 that is free of the puck launcher number one; number the remaining positions successively. Now working backward, number the positions of P_2. Naturally several of these positions will be superposed since P_2 was at rest for about one half of the time the shutter was open. About 15 data points for P_1 are optimal.

Note: This experiment can also be done with non-magnetic pucks. There will be a small energy loss in the system due to tangential friction. This loss, however, affects the results by only 1 to 2 percent.

Plot x and y components of momentum for P_1 and P_2 as a function of time. Also plot the sum of the components. Can you plot the sum of the x and y components directly from the graph? Why? Comments.

Graphically, calculate the motion of the center of mass of this system. What is the velocity of the CM? Comments

Plot the kinetic energy of P_1 and P_2 and also the sum of their kinetic energies. Comments.

Prove that if $M_1 = M_2$ and the initial velocity of P_2 is zero then the angle between the paths of the pucks after collision is 90°. How does this compare to the observed angle in your collision?

If you have time and sufficient equipment try a collision between unequal mass magnetic pucks.

If a simple collision with one of the magnets at rest seems too tame, you may wish to try a collision where both pucks have some initial velocity. This experiment is most interesting if these initial velocities differ by at least a factor of 2. If you do this more complex collision experiment be sure to answer all the applicable questions in the other sections above.

Experiment 10: Partially Elastic Collisions

Object:

To use the concept of coefficient of restitution to organize data on partially elastic collisions. To show that the coefficient of restitution is frequently velocity dependent.

Theory:

A collision is said to be elastic if the kinetic energy of the system is conserved; if not, the collision is termed inelastic. A completely inelastic collision is one in which the colliding particles remain stuck together. Though these definitions are meaningful, they are not quantitative.

The parameter that gives physical meaning to a real collision is called the coefficient of restitution. It is defined as:

$$\gamma=-(v_1'-v_2')/(v_1-v_2) \qquad (1)$$

The primes refer to the velocities after collision and the subscripts 1 and 2 refer to the particles. The velocities used in equation (1) are those components that are parallel to the line connecting the center of the two objects during the collision and not the *x* components of the velocity of the pucks. For a completely inelastic collision, $\gamma=0$ and for perfectly elastic collision, $\gamma=1$. For contact collisions no material has a coefficient of restitution equal to unity, e.g. $\gamma\approx0.98$ for a collision between hardened steel spheres at low velocities.

Applying conservation of momentum to a one dimensional collision one can show that when $\gamma=0$ and $v_1'=v_2'=v'$, then

$$v'=(m_1v_1+m_2v_2)/(m_1+m_2) \qquad (2)$$

if $0<\gamma<1$, then

$$v_1'=(m_2v_2(1+\gamma)+(m_1-\gamma m_2)v_1)/(m_1+m_2) \qquad (3a)$$

and

$$v_2'=(m_1v_1(1+\gamma)-(\gamma m_1-m_2)v_2)/(m_1+m_2) \qquad (3b)$$

When $\gamma=1$, equations 3(a) and 3(b) reduce to:

$$v_1'=2m_2v_2+(m_1-m_2)v_1/(m_1+m_2) \qquad (4a)$$

$$v_2'=2m_1v_1-(m_1-m_2)v_2/(m_1+m_2) \qquad (4b)$$

One can also show that the percent energy lost in the collision is given by:

$$Loss = m_1m_2(1-\gamma^2)(v_1-v_2)^2/2(m_1+m_2) * 100\% \qquad (5)$$

For collisions between two given objects, the coefficient of restitution is not necessarily a constant but may be a function of velocity. When comparing various collisions, one must specify not only the substances involved but also their velocities upon impact. Show that if a mass m_1 is dropped from a height y_1, collides with a mass m_2 ($m_2 \gg m_1$), and rebounds to a height y_2, then

$$\gamma\approx\sqrt{(y_2/y_1)} \qquad (6)$$

If the air table is tilted and a puck is allowed to fall freely and to collide with a fixed wall that is fastened to the table, we expect $\gamma<1$.

Procedure:
Find the coefficient of restitution for a collision involving equal mass magnetic pucks. Use data from a previous experiment if available. Can you use equation (1) above to find γ. If yes, perform the calculation; if no, how can you find γ? Hint - what is the motion of each puck with respect to the center of mass.

Obtain a record of a collision of two non magnetic equal mass pucks. Calculate γ and then compare the observed final velocities to those predicted by equations 3a and 3b. Include an error analysis. Also calculate the percent energy lost and the error involved in finding this quantity.

Place an inelastic collision collar on a small puck (unloaded). Place a strip of wood against the wire wall and just outside it, near the center of the lower edge (opposite the single leveling screw). Clamp it securely but be sure to place a small square of wood or metal between the underside of the table and the C-clamp. To determine the coefficient of restitution as a function of velocity, tilt the table at various angles and measure v and v'. It may be convenient to use the rebound height to compute v'. Compute γ for several values of v.

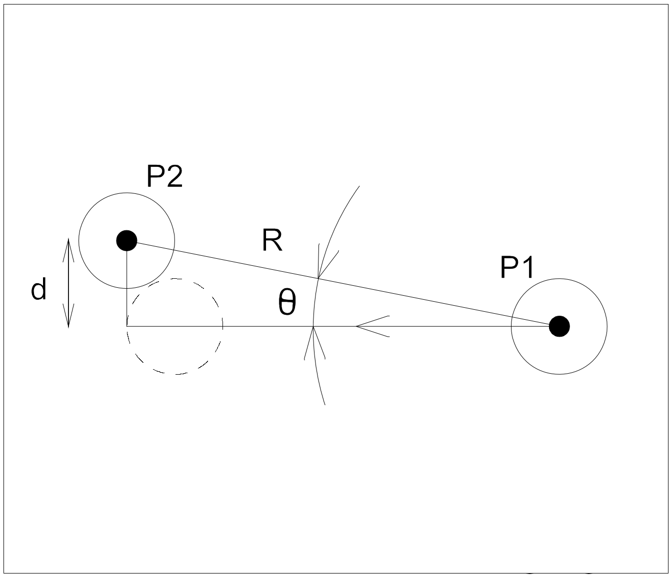
Plot γ versus velocity on linear graph paper. What conclusions can you draw? Now plot the data on semi-log paper. Comments? Try plotting the change in gamma ($\Delta\gamma$) as a function of the velocity. Can you write an equation describing the dependence of γ on velocity? Describe an interaction process that could account for this behavior.

Experiment 11: Inelastic collisions & Angular Momentum

Object:
To show quantitatively that a puck is moving in a straight line has angular momentum with respect to any point not on the line along which the center of mass is moving. To show that both linear and angular momentum are conserved in an elastic collision between 2 pucks.

Theory:
Angular momentum. In the following figure, an inelastic collision is shown reduced to its bare essentials so that the initial angular momentum of the system can be identified.

Clearly puck P_1 will strike P_2 rather than passing by freely; however, if it could pass by freely, it would have its closest point of approach when the line joining the 2 pucks is perpendicular to P_1's velocity vector. This point is identified by the drawing of the perpendicular, and at their point the distance



Experiment #11 Figure #1
Identification of the important parameters in a collision.

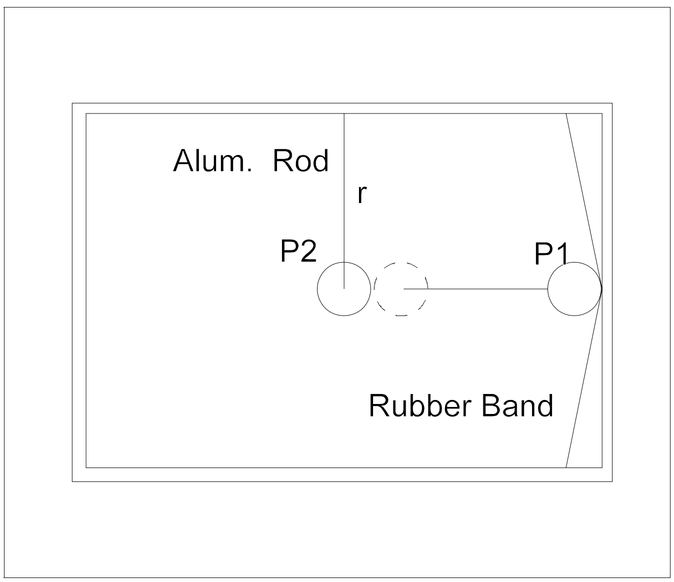
from P_1 to P_2 is d. If you consider the situation at just this point, you are close to an elementary "text book" definition of angular momentum. Just think of P_1 being pivoted about the center of P_2 by a rigid rod of length d. The angular momentum, L, is given in terms of the tangential velocity v_1 by:

$L = m_1 v_1 d$

Check this formula against your own text book using $d=r$ and $\omega=v/r$ as necessary to make it conform.

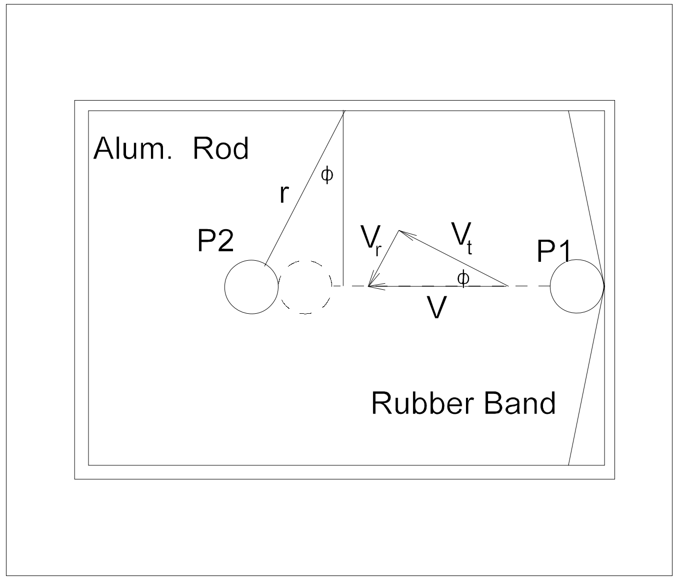
Consider the following unproven statement: The angular momentum of P_1 is $m_1 \cdot v_1 \cdot d$ during the entire time of its approach. Note that, even if the pucks collide before P_1 gets to the point where its path is perpendicular, d is still easy to find. It is just $R \sin(\theta)$, and R and θ can be easily measured at some point prior to collision.

Now restudy the figure 1. The situation is



Experiment #11 **Figure #2**
Setup for converting linear to angular momentum with equal mass pucks.

difficult to keep clear until you have a clear grasp of all aspects of angular and linear momentum, so consider a simpler situation as shown in figure 2. You already know that if P_1 hits P_2 elastically and head on with velocity v_1, and if the pucks have equal mass they will exchange velocity. If P_2 starts out at rest, it will have a velocity v_1 after collision. However, P_2 is constrained by the aluminum rod, so v_1, will be the tangential velocity. Figure 3 is more



Experiment #11 **Figure #3**
Variation of the setup in figure 2 to show the effect of having the collision occur when the rod is not perpendicular to the velocity vector of P1.

complicated. In this case only v_1 "counts" and the angular momentum will be $L=mv_1r$. You should note that this is the same as mvd where d is the "perpendicular" distance as before.

Linear momentum: The trouble with the experiment in figure 1 is that it involves both linear and angular momentum considerations. Unless the pucks touch the table, the collision in the first figure represents a closed physical system. The principle of conservation of linear momentum says that the total linear momentum in this system is the same both before and after the collision. This statement will be impossible to test unless you make use of the concept of the center of mass.

After the collision, the visual picture is complex, but the physics is not. All linear momentum can be accounted for by considering the total mass as m and the velocity of the center of mass as v. In like manner all angular momentum after collision can be accounted of by measuring angular motion with respect to the center of mass.

Equipment:

Setup Problems- As far as the pucks are concerned figures 2,3, and 4 will cover all the setups for this experiment. It is more convenient to have the pucks out in the center of the table, so a long rubber band across the end of the table is the best launcher. You will probably have to "make" a long rubber band by joining three short ones. Join them with a tag hitch (the same knot used to put a tag on a suitcase). Note in figure 4 the string or thread tied to the center of the rubber band. It is easier to shoot the pucks straight if you use the string to release them.

When using the Velcro inelastic collision collars, be sure that they clear the table by about 2mm so that they do not drag during collision.

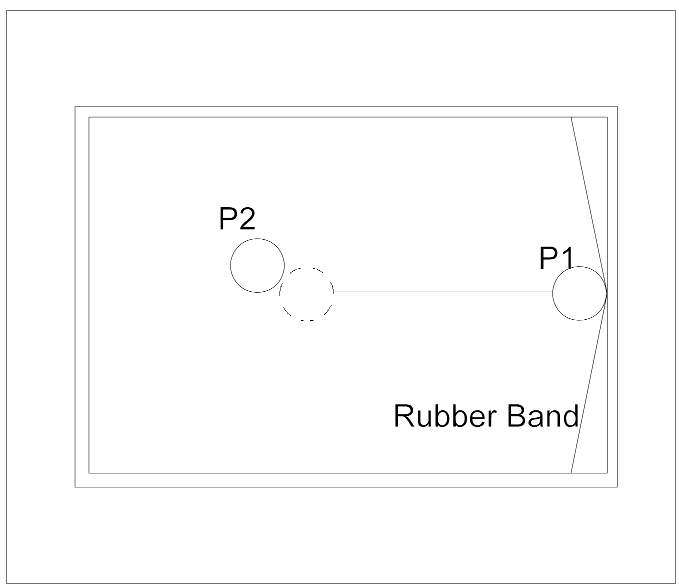
To keep the pucks from drifting out of place before the experiment, first level the table to minimize the motion of the target puck. Then turn off the air until an instant before you are ready to launch the incoming puck. With this technique, the target will not have time to drift before collision.

Strobe photography - There is nothing special about the camera setup for any of these experiments; however, wasted film is expensive, so concentrate your efforts on perfecting each setup before you photograph it. Make several dry runs and be sure to compute a convenient strobe rate. To avoid overexposing the background in this experiment, use the low intensity strobe or have one person follow the pucks with the center of the stroboscope beam so most of the table is in the "dark" most of the time.

Procedure:

Preliminary experiments- Before you collect any data, do all of the experiments below quickly and simply. Do not worry about using the launchers or keeping to the exact experiments shown in the figures. Launch the pucks by hand and do each experiment several times. Try variants like having the incoming puck spinning. Use 10 to 15 minutes so that you know what to expect from each experiment, then go on and do the sections below that have been suggested by your instructor.

1.) Do the experiment shown in figure 2. Try it with both hard pucks and magnetic pucks, but only collect data for one of the two. Observe what happens if you use inelastic collars on P_1 and P_2. For each case make a general statement about the linear momentum before and after the collision and the angular momentum with respect to the pivot point both before and after. Collect data for one case and make quantitative statements. Observe some collisions that are not head on and comment on them.



Experiment #11 **Figure #4**
Experimental setup for inelastic collisions.

2.) Repeat the same analysis as in part (1), but use the more complicated setup of figure 3. What happens to the momentum represented by the radial component *vr* of the velocity $_v$?

3.) Do the inelastic collision experiment shown in figures 1 and 4. From your data record compute: the linear momentum of P_1 initially; the linear momentum of the center of mass after collision; the angular momentum of P_1 with respect to the center of P_2 initially; the angular momentum of the two pucks with respect to the center of mass after collision. How well are the momenta conserved? If the conservation is poor, the collars dragged during collision. (Avoid repeating the experiment, be sure the collars are right ahead of time). It is tempting to say that the initial angular momentum is with respect to the center of mass - this is wrong. In a physical system the "instantaneous axis" is a point that is stationary for an instant. What is the instantaneous axis one strobe spark after collision? Does this observation help to show why the center of P_2 is the right point for referencing the initial angular momentum?

(4) It is instructive to consider what happens to the energy in any collision. Most text books discuss the head-on inelastic collision of two bodies of equal mass. For this special case one half of the original kinetic energy becomes heat and one half goes on as the kinetic energy of the center of mass. Consider figure 4. If P_2 were moved down so that P_1 hit it head on, would the velocity of the center of mass be the same? Either "prove" your answer theoretically or do so experimentally. In figure 4 as drawn, the collision is "tangential" and the pucks will go off with some "spin". Consider the data from an actual "tangential" inelastic collision and compute the energy involved in angular motion of the pucks with respect to the center of mass. Add this energy to the linear center of mass energy. Is more energy conserved in a tangential inelastic collision or a head on collision? Can you compute how much energy would be lost if the pucks stuck together in a collision where P_1 just grazed P_2? Is it possible to have an "inelastic" collision where no energy is lost? Can you describe such an experiment?

Experiment 12: The Force Potential Relationship

Object:
You will be assigned to do sections of this experiment that have one or more of the following objectives:

- to measure the repulsive force between two magnetic pucks at a number of different distances.

- to determine the potential energy between the same two magnetic pucks at various distances.

- to show graphically that "the force is given by the negative slope of the potential curve"; or on a more mathematical level to show that

$$F(r)=-dU(r)/dr$$

and that when U is given by

$$U=\beta/n*r^{n+1} \quad \text{Then } F=\beta r^n$$

and to find the various exponents and constants in these equations.

- to find the force law that operates when magnetic dipoles interact.

Introduction:
Defining potential energy - Potential energy or energy due to position is usually introduced by discussing the motion of object in a uniform gravitational field. You are assumed to be familiar with the fact that in such a field, potential energy can be converted to kinetic

energy and vice versa.

When more complicated forces are studied, it is frequently useful to know the relation between the force on an object at some point and the potential energy at that same point. Thus many physics courses work out a general relationship that will work for any force that has a power relationship between the force and distance. Such a force has the form $F=\beta r^n$ and the corresponding potential is

$$U=(1/n)\beta r^{n+1}$$

and the relationship is

$$F(r) = -\,\mathrm{d}U(r)/\mathrm{d}r$$

In these relations, r, is the distance between interacting bodies, F is the force, U is the potential energy and β is the constant of proportionality.

Force	β	n
Gravitational (2 point mass)	Gmm'	-2
Electrostatic (2 point mass)	$(q\text{-}q')/4\pi\epsilon_0$	-2
Mechanical Spring	$-k$	+1

Note that the values given for "gravitational" are for point masses. Although it is convenient to assume that local gravitational attraction is uniform, this approximation only works since typical distances are much smaller than the radius of the earth.

What do these operations mean in simple works? Perhaps you can assign more meaning to them if you remember that when you know how fast the potential energy is changing with distance you already *know* the force. Graphically, if you plot the potential energy, you can obtain the force by measuring the slope at a number of points and by plotting this new function. In calculus language, the force is the negative of the first derivative with respect to distance of the potential energy function.

Measuring Potential Energy **-** The argument above assumes that potential energy can be measured. For this we need an operational definition. When studying a 2-body system in the laboratory, first fix the location of one body. After friction and all other forces have been eliminated, one can perform either of two tests for bodies that repel:

(a) Start at some point where there is essentially no force between the bodies and launch the free body directly at the fixed body with a velocity v. The potential energy U at the point P where the first body stops and reverses direction must be equal to the original kinetic energy KE. $U=KE=1/2mv^2$.

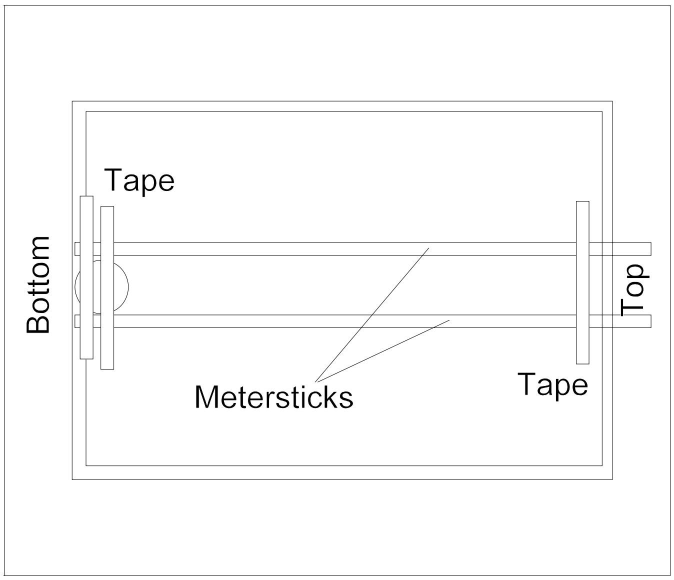
(b) Alternatively, the free body can be released from P and allowed to accelerate until it is moving with velocity in an essentially force free region. The equation is the same.

These introductory remarks will help you to keep track of the vocabulary in the discussion that follows. Note, that nothing has been proven. Refer to a standard text for proof of the various equations and definitions.

Data Collection:

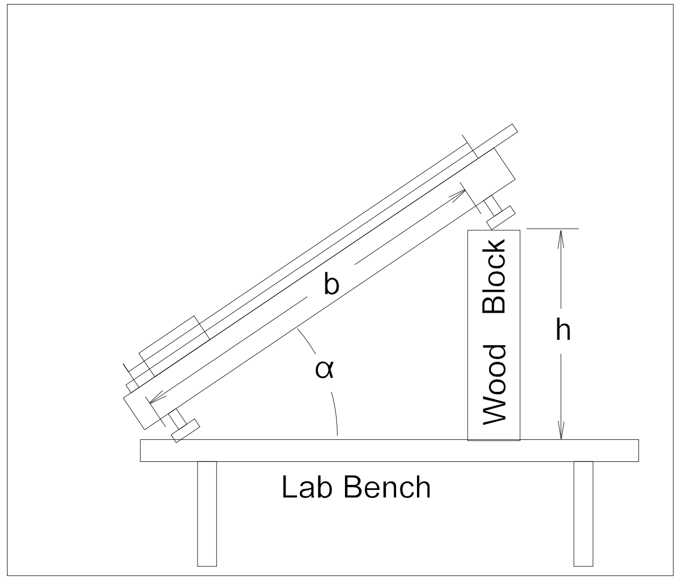
Measure F(r) **-** In this part of the experiment, force is applied by fixing one puck to the table and then tilting the table until the second puck slides as close to it as the magnetic force will allow. The variables are the center to center distance for the pucks and the tilt angle of the table. while this procedure sounds simple, there are a few complications. First, the free puck must be kept “uphill” with respect to the fixed puck. This is too much of a “balancing act” to do without an auxiliary rig, so the following is suggested.

The experimental Setup - Level the table in the usual way except that it will help if the leveling screws are as long as possible. After locking the leveling screws, take a pair of magnetic



Experiment #12 **Figure #1**
Fixed magnetic puck and channel formed by two meter sticks. Note the location of the leveling feet and the leftover ends of the metersticks.

pucks. For this experiment, the end of the table with two leveling screws is the “bottom”, see figure 1. Tape one magnetic puck near the center of the bottom end using masking tape. Next with more tape, place two non magnetic strips up close to the puck. Wooden meter sticks will work well. They should be exactly parallel to each other and run “uphill” parallel to the long dimension of the table. These strips should be spaced so the second magnetic puck can slide freely between them with little friction and little slop. If one side of your table is known to be flatter than the other, place this “channel” on the flat side rather than across the center.

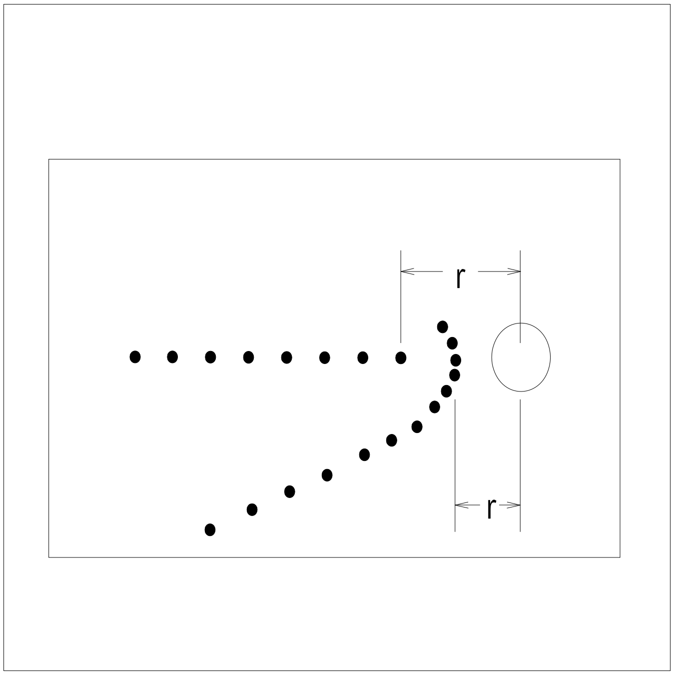


Experiment #12 **Figure #2**
Use a block of wood to achieve the largest tilt angles. By placing the air table almost on the edge of the lab bench, greater angles can be achieved.

Figure 2 shows how you must locate the air table near the edge of the lab bench if you are to use large tilt angles. Do not let the table slide off onto the floor! Note that all measurements will employ the same base line *b*, but that h will change. You will not need to know α or even to compute it. Why?

Measurements - Measure the center to center distance between the pucks for various angles and record your results. The number of measurements you need will depend upon which data analysis section you are told to do. Plan ahead. Remember, when measurements are easy to take, it is easier to take extra data points and skip using them later than it is to redo part of an experiment.

Measure U(r) Using a Strobe - Here, the technique is to shoot a free puck at the fixed puck with some initial velocity *v*. The closest point of approach gives *r*. If the path of the free puck is straight back on itself, the potential is



Experiment #12 **Figure #3**
The minimum collection of data points must include some "far away" where velocity is uniform and some at the turn around point (straight path) or point of closest appraoch (curved path).

just $1/2mv^2$ since all the kinetic energy is magnetic potential energy at the turn around point. If the path is curved then one needs the velocity at the closest point of approach v_f. Figure 3 will help to clarify this point. In this case

$$U = 1/2mv^2 - 1/2mv_f^2$$

By now you should be familiar with the equipment for recording; if not, read the appropriate introductory sections. If you elect to use straight on collisions, you will want high strobe rates, so the turn around point is unambiguous; for the curved path technique, slower rates give a good v_f determination.

You will need to develop a good launching technique for this experiment, since you will want to record approximately the same close approach distances in this part of the experiment as in the force part. By practicing the launch technique ahead of time and by using good strobe technique, you should be able to get all your data on one photograph. If your launch far enough away from the target puck, you will measure the velocity " at a great distance". How can you test whether you are far enough away? Hint - 3 successive data points are all you need.

The bounce method for determining U(r) - This technique for determining $U(r)$ takes the experimenter one step further away physically from the quantity U desired but is nonetheless easy to understand. Consider figure 3. The upper puck is released from rest and allowed to accelerate down the table until it is stopped by the other magnet. It then rebounds back to something approximating its original height, or it may be deflected a bit to one side or the other. In this sequence gravitational potential energy is converted to kinetic energy and then into magnetic potential energy. The principle of conservation of energy allows us to equate the original potential $mg(h_1-h_2)$ to the desired magnetic potential U.

There are a number of ways to measure the Δh between release and turn around. Feel free to improve on the one described here. First establish a reference line parallel to the top edge of the table and corresponding to the lower edge of the free puck just before it is released. If a T-square is available, use it; otherwise use a ruler. Next, observe approximately how far the puck falls before it rebounds, and tape a reference string in place as shown by the solid line. Make several trials to insure the correct location of the string. A T-square will enable you to get the string square with the edge of the table edge. The distances h_1 and h_2 are measured from the reference lines to the lab bench if it is horizontal, or to a surface leveled ahead of time if the bench is tilted.

Note that it is important to have a good release technique. A thread around the puck or its center peg can be suddenly released with more precision than can the puck itself. Note also the reference string running lengthwise above the pucks. This string will help you to center the puck so it rebounds approximately straight up.

If you are clever, you can get both the potential and the force measurements from one set of manipulations using the bounce technique.

A second student should be stationed in front of the air table especially at high tilt angles. He can keep the table from being accidentally knocked on the floor and can catch the puck after rebound.

Data Analysis:

Linear plot analysis **-** The object of this technique is to show by direct graphical analysis that the force curve $F(r)$ is given everywhere by the slope of the potential function curve $U(r)$. Both functions are rapidly changing so the more data points the better. Remember, however, the more data, the more computing.

Plot $U(r)$ and make the best possible smooth curve through the points. Next determine the slope of this smooth curve at a number of points. Either use the familiar $m=(y_2 - y_1)/(x_2 - x_1)$ formula or find the slopes graphically as described in the appendix on graphical analysis.

Plot $F(r)$ on the same piece of graph paper as you used to plot the slopes from the $U(r)$ curve. There should be reasonable agreement between these two curves. Is there?

Log-Log Plot Analysis **-** Review the appendix on graphical techniques where log-log plots are discussed. You will need the section where a straight line on log-log paper is shown to indicate a power law of the form $y=\beta x^n$. Since the ceramic magnetic pucks are not point dipoles but are a collection of distributed dipoles, there is no reason to assume that they act as if all the dipoles were collected together at the center. In fact, one can argue strongly that magnetic dipoles are much weaker at a distance than the r^2 forces like gravitational and electrostatic force and that therefore only the parts of the magnets close to one another count. Thus one suspects *a priori* that the *effective* distance between two magnetic pucks is not the center to center distance. It will come as no surprise then if a log-log plot of the force versus distance fails to yield a straight line. Does some effective distance exist such that the plot is straight? It would seem legitimate to subtract some distance δ from all the center to center distances to find the effective "dipole-dipole" distances. If by subtracting the same distance from each measurement the line can be made to plot straight, one can feel confident that the magnets are interacting like point dipoles.

Procedure for finding δ empirically - Plot your force data on 2x2 cycle log-log paper. Relate these points by the best smooth curve possible. To find δ, pick 3 data points that happen to lie close to or on the smooth curve. Two should be at or near the ends and one in the middle. You know that δ must be some distance between zero and r, the radius of the puck. Try subtracting a trial δ from each of the center to center distances corresponding to the 3 chosen points and replot them. If the new points are not on a line but still "bend" the same way as before try a larger δ. If the line curves the other way, your δ was too large. Four or five trial δ's will put you close enough. Apply the best value of δ to all your readings. When you plot all the corrected points, you should find that the curve is a straight line.

Naturally, you will have to use the same δ when working with your potential measurements. Plot the potential measurements on the same piece of graph paper after correcting for δ.

The final step in the analysis is also the most elusive. You are more likely to make a mistake when taking the slopes of your two curves than anywhere else. Be sure you understand why the slope of the force curve is given by

$\beta=(\log(F_2) - \log(F_1))/(\log(r_2)-\log(r_1))$

$\beta=\log(F_2/F_1)/\log(r_2/r_1)$

$\beta= - \log(F_1/F_2)/\log(r_1/r_2)$

Where the points (r_1, F_1) and (r_2, F_2) are from the best fit curve.

What is the slope of the *F* curve? Of the *U* curve? Are the slope's integers within experimental limits. Write the equation for $F(r)$ and $U(r)$ where *r* is the dipole-dipole distance. Do the slopes differ by exactly one? Is $F = -dU/dr$ within the limits of error in your experiment?

Experiment 13: Simple Harmonic Motion The Spring-Mass Oscillator

Object:

To build a spring-mass oscillator by placing a puck between two weak springs on an air table and to study the relationship between the following variables: spring constant, puck mass, amplitude of vibration, table tilt and period of vibration. An optional section investigates the energy in the spring-mass system.

Theory:

Harmonic motion, the most familiar type of vibration, is illustrated by the motion of a pendulum or a mass hanging from a spring. It is a to and fro or vibrating motion of objects stretched or bent from their normal positions and then released. Such an object moves back and forth along a fixed path and returns to each position and velocity after a definite period of time. This type of motion is produced by a varying force; hence the object experiences varying accelerations.

Simple harmonic motion requires a restoring force *F* acting on an object that is proportional to and in the opposite direction from the displacement *x* of the object.

$$F=-kx \qquad (1)$$

In this equation, *k*, is the force constant of the spring. Equation 1 is the defining equation for *k*. The negative sign in the equation is used to indicate that the restoring force is in the opposite direction to the displacement of the object.

In general, the force constant for a spring is measured by hanging the spring vertically and adding weights while the displacement is recorded. Most coil springs are constructed of carefully selected steel so that the *k* remains constant for large displacements of the spring. If the spring is overstretched, however, it may have a new force constant and will certainly have a new starting point before any weights are hung on it. The springs supplied with the air table can be safely stretched to 20 times their original length. If a plot of force *versus* displacement yields a straight line, then the spring is said to obey Hooke's law. This relationship was first discussed by Robert Hooke in 1676.

Equipment:

The spring mass setup- You will be provided with an air table and a selection of springs along with pucks with various masses. Timing is to be done with stop clocks if available; otherwise use the sweep second hand of your watch or an electric clock. The springs are attached to the table by using the small pegs in the holes along the edge of the table. These springs can be stretched to 20 times their original length. Do not overstretch the springs.

Your instructor will tell you ahead of time what pucks are available, but you will probably be able to work with fully assembled pucks as well as the separate plastic parts. You are expected to “make do” with what is available.

Since rather large forces are generated just as a puck reverses direction, the pucks will tend to tip and drag unless the spring is attached to the center of mass. Another source of trouble is the springs dragging on the tops of the pucks. Before gathering data, try various puck attachment methods. Try stacking two pucks with a peg in between. Try stacking parts of pucks and try placing loading weights near the spring attachment point. You may even wish to place a loop of thread through the medial plane before assembling the puck. In any case, for each mass of puck, you should be able to devise a way to attach the springs that minimizes drag. For most of the experiments you will want heavy pucks, so be sure to devise at least one good heavy puck configuration.

Timing - Since you will be working with only a stop clock or clock you should time a number of oscillations so that the effect of timing errors is reduced. Typically it is convenient to time 10 oscillations and then to divide by 10.

Procedure:

This experiment has been written with many short sections, some easy, some hard. You are not expected to do all sections. Which sections are to be done will depend on your instructor. If some members of the class “cover” each part, then a class discussion of the entire experiment will prove beneficial to everyone. Consult your instructor to learn how to organize the reporting of results.

1 - Period versus Maximum Displacement and Table Tilt: The object of this section of the experiment is to investigate the effect of initial displacement and table tilt on the period of a simple harmonic oscillator. First level the table and lock the screws. Then set up the oscillator by placing a puck between the two ends of the table using the pair of 5cm springs. Establish the equilibrium position of the puck. To determine the effect of initial displacement, measure the period of oscillation for initial displacements from equilibrium of 5, 10, 15, and 20 cm. Compare and discuss the results. For these measurements you may wish to tape a meter stick down next to the puck, or you may “suspend” it just over the puck center post.

Without altering the oscillator, Place several books or a block under the end of the table. Then repeat all or part of the pervious experiment to see whether the shift of equilibrium position due to gravity has altered the period. If necessary, try more than one tilt angle.

What effect does displacement have on the period? What is the effect of tilting the table? Do your measurements suggest any generalizations about simple harmonic motion or spring mass oscillators? How would you propose to test your generalizations on some other system?

2. Period Versus Puck Mass - The object of this section of the experiment is to determine the functional relationship between the period of oscillation and the mass of the puck. First, measure the period of oscillation for a lightweight puck. Next, measure it for three heavier masses. One of these should be the heaviest puck you can conveniently float and the others should lie in between. In each of these measurements use a constant initial displacement from the equilibrium position. From the data make a plot on log-log paper of the period in seconds versus the mass in grams.

Find the slope of the curve. If you are unfamiliar with log-log plots, read the appendix section entitled "The log-log graph", where the technique for calculating the slope of such a graph is given.

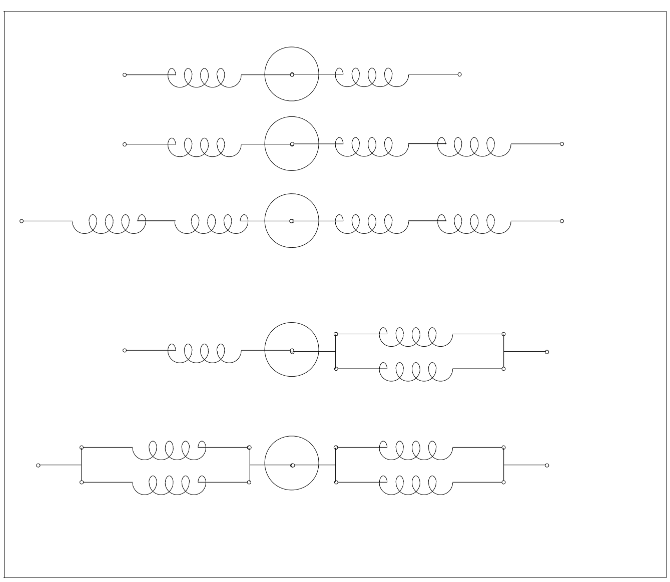
In this experiment you can determine the relationship between the period and mass of an oscillator. Start by assuming that the period varies as some power p of the mass with a constant of proportionality A. Thus $T=Am^p$

Taking the logarithm of both sides of this equation gives a new equation

$$\log(T)=\log(A)+p*\log(m)$$

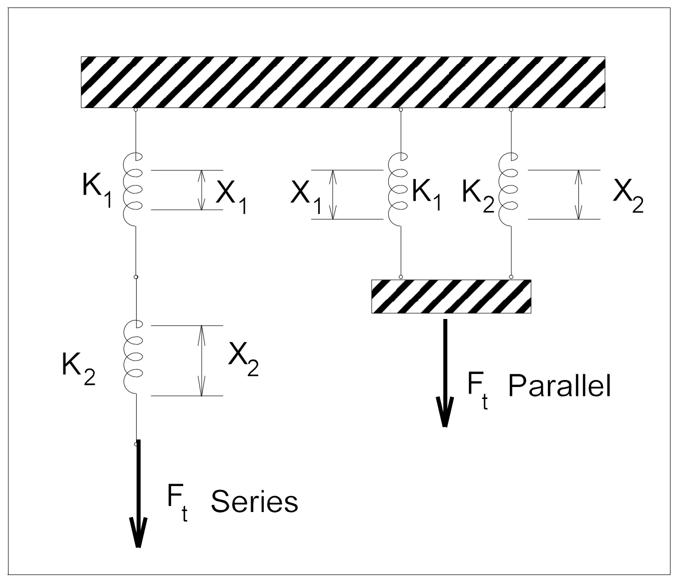
which is the equation of a straight line with p being the slope. Note that the variables are (log T) and (log m), not T and m. Therefore, the value of the constants p and A can be determined from the log-log plot. If your plotted curve is a straight line, then your assumption of a power law was justified.

3. How Spring Constants Combine **-** the object of this section of the experiment is to study how the spring constant varies as two or more springs are "added" together in series or parallel. The constants of the individual springs will be measured by the "static" method while the "total"constant for the springs in a spring mass system will be measured in two ways, static and dynamic, to see if the same answer results. Figure 1 shows some spring configurations that can be tested.



Experiment #13 **Figure #1**
Some typical spring mass systems you may wish to study.

In the "static" method the puck is displaced by adding weights to a string attached to the puck centerpost and passed over a pulley, or the puck is displaced by tilting the table. In the "dynamic" method the spring constant is determined from the period of oscillation.



Experiment #13 **Figure #2**
Series and Parallel configurations.

Derivations **-** To derive laws for the way spring constants combine, first note that there are two important configurations, series and parallel, as shown in figure 2. All configurations that are more complex can be thought of as a combination of these two. In either of the simple cases, you can write three equations $F_1=-k_1x_1$, $F_2=-k_2x_2$, $F_t=-k_tx_t$.

Consider the first parallel case. Clearly the displacement is the same for both springs so you can call it x. Further the total force F_t must be made up of the contributions from the two springs. Thus $F_t=F_1+F_2$. First, substitute for each of these forces to give

$k_t x_t=k_1 x_1+k_2 x_2$

Then add the condition $x_1=x_2=x_t=x$ to give

$k_t x=k_1 x+k_2 x$

Upon factoring out the variable x

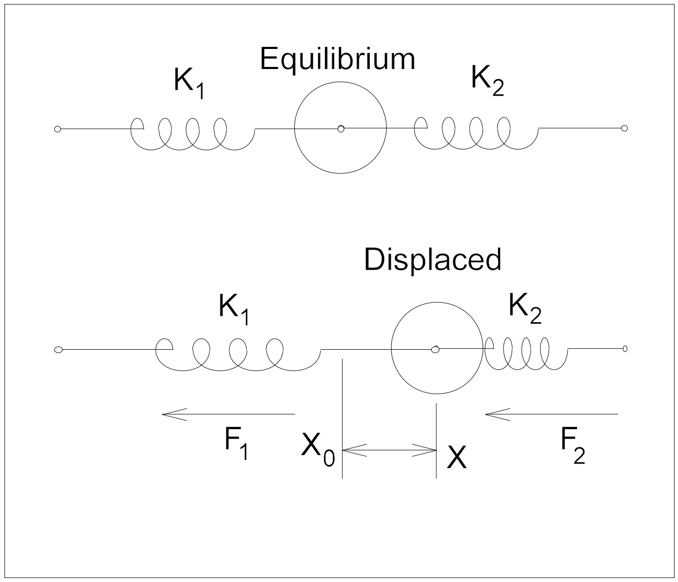
$k_t=k_1+k_2$

The procedure for the series case is similar. First Finally decide what variable remains the same, then what variable has two contributions. Finally write the appropriate equations and complete the derivation yourself.

Now consider a third configuration, the one shown in figure 3. This is the typical setup for a mass on a frictionless surface. Look at the physical quantities. What variable remains constant as the puck is displaced? Which of the previous cases does this resemble? Do not be misled by the fact that the springs happen to be “in line”. Write the appropriate equation relating k_t to k_1 to k_2 for this case. For this part of the experiment, you may use the following equation relating the period of oscillation to k: $k=m/(2\pi T)^2$

A value of k determined by measuring T will be known as a “dynamic spring constant” while if you add weights or tilt the table to obtain a displacement you may call the value obtained the “static spring constant”.

Experimental Arrangement - Use the heaviest mass you can conveniently float and set up the simple configuration of figure 3. If the mass drags at maximum displacement, use less displacement or less mass. Compare the dynamic spring constant with the static spring constant. Compute kt from measurements of k_1 and k_2. Test some or all of the other configurations shown in figure 1. Be sure to do a least one trial involving series springs and one involving parallel springs. Try the lightest mass available for some spring combination. Do the dynamic and static spring constants agree as the mass of the springs becomes comprable to the mass of the moving weight?



Experiment #13 **Figure #3**
Typical configurations used on an air table.

Conservation of Energy (optional) - The object of this part is to investigate the total energy of a system oscillating in simple harmonic motion and to determine whether the forces acting are conservative.

A spring-puck-spring system has practically no external forces acting upon it. Under these conditions the total energy of the system is “conserved” and remains sufficiently constant that the equation E=Ek+Ep holds where total energy equals kinetic energy plus potential energy.

$E=1/2mv^2+1/2kx^2$

During each oscillation, there is a continuous exchange of kinetic and potential energy, so the two terms in x and v change while the total energy, E_t, remains essentially constant.

In moving away from the equilibrium position, potential energy increases at the expense of kinetic energy, and the reverse happens when the particle moves toward the equilibrium position. Such energy relationships may be evaluated by determining the velocity versus displacement during a complete oscillation. The fact that the kinetic energy is maximum at the equilibrium point and zero at the extremes of oscillation makes this study easier. There are two alternate procedures below for measuring the velocity. In either case, you are asked to plot values for the potential energy $E_p=1/2kx^2$. This requires you to know the spring constant k for the system. If you use the same setup as in part (3) you will already know this constant. If you omitted part (3), go back and read the section on measuring k.

Experiment 14: The Physical Pendulum

Object:
To study the period of an air table pendulum made with a disk whose moment of inertia is not negligible and to correlate it with table tilt and length of the support rod.

Introduction:
An ideal pendulum is defined as a point mass on the end of a rigid, massless rod. The rod is supported on a frictionless pivot and it is free to swing when displaced from its vertical equilibrium position. For displacements less than 15°, the period T of this pendulum is adequately given by:

$$T=2\pi(L/g)^{1/2} \qquad \text{(Eqn 1)}$$

where L is the length of the rod and g is the acceleration of gravity.

If the pivoted body is extended, then the period is:

$$T=2\pi(I/(MgL_{cm}))^{1/2} \qquad \text{(Eqn 2)}$$

Where I is the moment of inertia of the body, M is its mass, and L_{cm} is the distance from the center of mass to the pivot point. The system we will be studying consists of a large puck on the end of an aluminum tube. The moments of inertia of interest are given by:

$$I_p=1/2M_pr^2$$

Disk shaped puck of mass M_p, radius r.

$$I_r=1/3M_rL^2$$

Rod of mass M_r, length L pivoted about one end.

By substitution of the appropriate values of the moment of inertia, equation (2) can be recast to account for the various possible ways for setting up a physical pendulum.

$T=2\pi(L/g)^{1/2}$
$r=0$, $M_r=0$ (Point mass on a massless rod)

$T=2\pi[(L^2+r^2/2)/(L_{cm}g)]^{1/2}$
$r\neq0$, $M_r=0$ (disk on a massless rod)

$T=2\pi[(L^2(M_p+M_r/3))/(M_p+M_r)L_{cm}g)]^{1/2}$
$r=0$, $M_r\neq0$ (point mass on a rod with mass)

$T=2\pi\{[L^2(M_p(1+r^2/2L^2)+M_r/3)]/[(M_p+M_r)L_{cm}g]\}^{1/2}$
$r\neq0$, $M_r\neq0$ (Disk on a rod with mass)

Naturally one only uses the simplest equation that will give a theoretical period within the limits of error of actual experimental measurements.

Procedure:

A large puck with one loading disk will be used for the pendulum mass; aluminum tubing with loop terminations on each end will be used for the rod. It is suggested that the tubes be approximately 15, 30, 45, and 65 cm long. Place a rubber grommet in the hole of the pivot assembly that fits over the pucks center post; this prevents the puck from rotating with respect to the rod. Use a pop rivet on the edge of the table for the pivot.

1) Determine the effect of the tilt of the air table on the period of a pendulum; use the 45 or 65 cm rod for this step. Graphically, show that $T \alpha (g)^{½}$.

2) Graphically, show that $T \alpha (L_{eff})^{½}$ where L_{eff} is the effective length of the pendulum. Use a 2 or 3 inch spacer block to tilt the table.

3) Derive the equations (4b), (4c), and 4(d). Use the actual values for the masses and lengths in one of your setups in part 2 and substitute them in equation (4c). Show why equation (4c) can be used for calculating the theoretical period of the four pendulums.

4) Is there a systematic deviation between the observed and theoretical periods? Do a complete error analysis to determine if this deviation can be attributed to your measurement of the various parameters. Compare the importance of the various terms in the equation for the period by ignoring those terms that make a small contribution and seeing how much the value of T is changed.

Experiment 15: Collisions

In experiment 8, we analyzed the momentum changes in pucks which were "exploded". Since both pucks were initially at rest, the total initial momentum of the system was zero. In this experiment we will study two pucks moving toward each other so that the initial momentum of the system has a value other than zero.

Place an unloaded puck, *A*, at the center of the table, there may be some slight drift but this will not affect the results, and launch a second unloaded puck, *B*, from the end of the table.

What is the momentum of *A* before the collision?
What is the momentum of *B* before the collision?
What is the total momentum of the system before the collision?
What is the momentum of *A* after the collision?
What is the momentum of *B* after the collision?
What is the total momentum of the system after the collision?
Double the mass of the stationary puck and repeat the experiment. Double the mass of the moving puck and repeat the experiment. Place an unloaded puck in the center of the table and project pucks of varying mass at it.

Answer the same questions as above for each situation.

In part 1, one puck was stationary at the start of the experiment. In this experiment you will work with two moving pucks. Place unloaded pucks at each end of the table and project them toward each other at low velocities. Determine their velocities before and after the collision. Increase the mass of the puck and repeat the experiment.

Place opposite pieces of Velcro on each puck. When the pucks are projected at each other, they will stick together on collision becoming one object after the collision. Repeat the experiments of parts 1, 2, and 3 using the Velcro.

Tilt the table and try some of the previous experiments with and without Velcro. Do you think momentum will be conserved?

In the previous experiments you have studied only the momentum of the system. No analysis has been made of the energy of the system. Is energy conserved in these experiments? Using the data you have collected in parts 1 to 4, answer the following questions: What is the kinetic energy of the system before and after the collision? Is energy conserved in these collisions?

Experiment 16: Energy

Raise one end of the air table 2 or 3 cm. Release a puck from the raised end of the table so that it moves down the table. Record its motion until it strikes the bottom bumper. Compute the potential and kinetic energy of the puck at six points in its path. Calculate the sum of the potential and kinetic energy at each point. Can you draw any conclusions from your results? Repeat this experiment for various angles of table tilt.

From a puck launcher project a puck from the lower end of the table. Repeat Experiment 1. Remember that the initial velocity is not zero as it was in experiment 1.

Experiment 17: The Pendulum

In this experiment you will study the motion of the pendulum. Normally one constructs a pendulum using a mass such as a steel ball hung from a long thin string. We will duplicate these conditions using a puck as the mass tied to a piece of heavy thread as shown in figure 1.

Tilt the table about 5 cm. Set up your equipment as shown in experiment 2. Pull the puck back to a labeled position and release. With a stop watch, time one complete oscillation (from release to return). Do this several times and find the average time (the period) for a complete oscillation. What happens to the period as we increase the mass hanging from the string? Determine the period of the pendulum for several different puck masses. What effect does changing the mass of the pendulum have on its period?

Set up your equipment to answer each of the following questions: What happens to the period if you change the length of the string? What happens to the period if you change the angle of tilt of the table? What happens to the period if you change the amplitude of the motion?

Look up the formula for the period of a pendulum in a physics text. Can you determine the value of "g" in the formula by performing an experiment on the air table? How would you modify this formula so that it would be valid under all conditions on the air table?

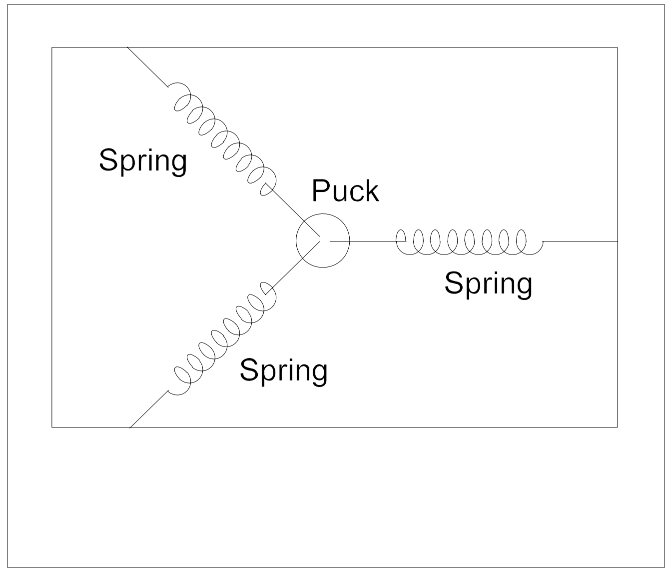
Explain how you could model the behavior of a pendulum on the moon using the air table.

Attach a mini strobe or Blinky to the end of a string and (or use strobe photography). Take a photograph of the pendulum swinging from one extreme position to the other, but not returning. Determine from the record of the motion the point at which the speed of the pendulum bob (that is the puck or Blinky) is a maximum. Determine the point where the speed is a minimum. Determine the point at which the tangential acceleration is a maximum. Where is it a minimum?

Experiment 18: Vectors

The air table may be used at a force table.

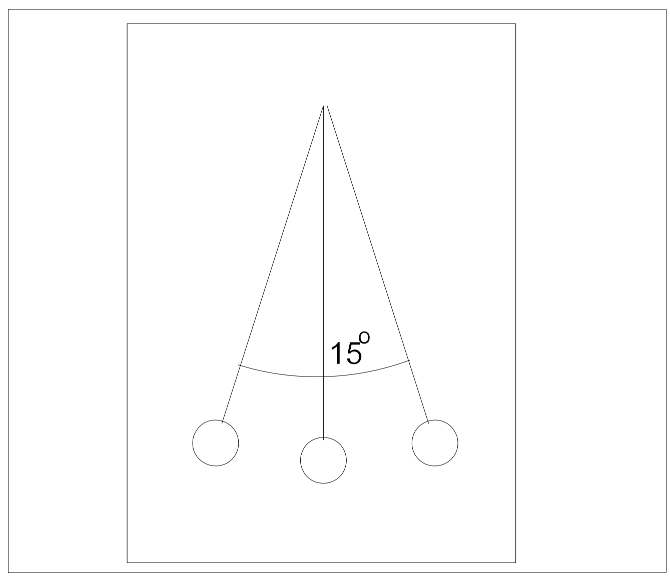
Calibrate three springs as explained in experiment 13. Using any convenient screw locations set up the experiment as shown in figure 1. The three springs will stretch to various lengths until equilibrium is attained. Since the system is in equilibrium the vector sum of all the forces is zero. The force exerted by any spring must be equal to the forces exerted by the other two springs (remember force is a vector). The magnitude of the force exerted by each spring can be determined from the previous calibrations. The angles may be measured using protractors.



Experiment #18 **Figure #1**
Experimental setup for studying vectors.

Move the springs to other positions on the table and draw vector diagrams of the forces acting on the puck.

How would your results be affected if a more massive puck were used? What would be the effect of carrying out the experiment on a tilted table? Could you carry out this experiment using two springs with gravity as the third force component? Try it.



Experiment #17 **Figure #1**
Experimental setup for studying pendulum motion.