Lecture Demonstrations for Mechanics

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Preface

Why lecture demonstrations?

Experience shows that students in the General Physics courses need more than "chalk and talk" lectures to keep them awake, interested, and regularly attending class. Over the years, various approaches for solving this problem have been tried. One venerable solution that still works is the use of "demonstration experiments" to enliven the lectures.

For demonstrations to be effective, a certain degree of showmanship is required; also, some preparation is called for before class to make sure that the required apparatus is on hand and will work properly when the time comes. Often it is a good idea for there to be some element of mystery or surprise concerning what is about to happen and what point it will illustrate.

Another tactic is to use demonstrations that appear to put the instructor at risk of physical harm! Examples include the bowling-ball pendulum, walking on hot coals, having a student hit one on the head through a physics-textbook inertial cushion, and lying on a bed of nails. With the exception of the first, these are not included here, but the interested reader is referred to **Death-Defying Physics** (I forget who wrote this and when it was published — if anyone knows, please tell me).

Here is a collection of demonstrations that have been used successfully in the past. We will endeavor to keep these apparati organized, available, and in working order and to add to them as time and budgets permit. Your comments and suggestions are welcome as to how to make this manual more useful and what other demonstrations to add.

1 Inertia

1.1 Inertia Ball

This is a massive ball hung from a stand by a string with a second string dangling beneath. A sharp pull on the bottom string breaks the bottom string, while a slow pull on it breaks the top string — why?

Inertia m of ball prevents it from accelerating quickly from rest, since (Newton's 2nd Law)

$$a = \frac{F}{m} \,. \tag{1}$$

Thus

- with a sharp pull there is not time for the ball to acquire sufficient velocity to break the upper string.

On the other hand,

- when the force is applied slowly, the top string must withstand both the applied force and the weight of the ball, so it breaks before the bottom string (which feels only the applied force).

WARNINGS: To avoid injury, make sure to hang the ball with the string slightly beyond the edge of the table, so that there is nothing immediately beneath that you might hit with your hand when the bottom string breaks. Wearing a leather glove will protect one's hand from being cut by the string. To be sure that the apparatus does not topple over, the base of the stand should be clamped to the table.

Also, it may be a good idea not to break the top string — the ball is heavy and could dent the floor, hurt one's foot, or bend its bottom screweye. Instead, the point can be made that the top and bottom strings are identical by cutting them off of the same spool in front of the class — then following the demonstration, the question can be posed, why does the bottom string break rather than the top string? If one wants to break the top string without risk to one's feet and the floor, a safety cable can be loosely hung in parallel with the top string, to stop the ball's fall.

An alternative (and more direct) demonstration of the same concept is the Inertia Hammer (Sec. 12.1 under Physics of Carpentry). This has the advantage over the Inertia Ball that no complicated time dependence need be explained.

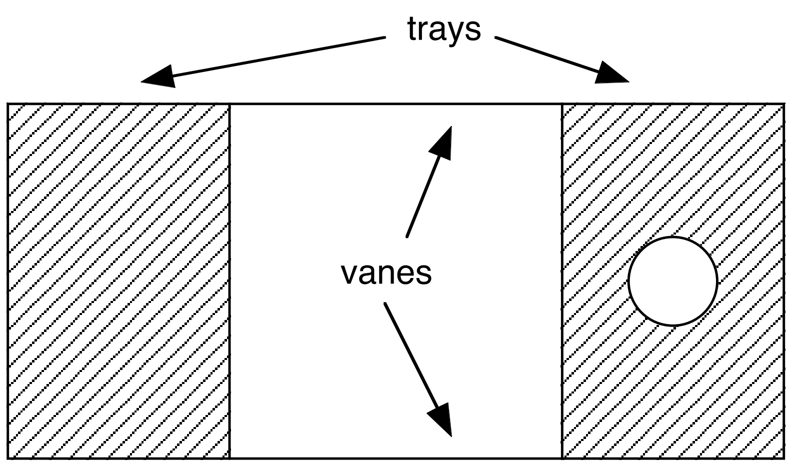

Figure 1: Top view of inertia balance.

1.2 Inertia Balance

An aluminum tray about 5 cm × 15 cm supported by two flexible vanes so that it is free to oscillate from side to side (see Fig. 1). The vanes are attached to another aluminum tray that can be clamped to the edge of a table. If the first tray is displaced to the side it oscillates at about 4 Hz. The cantilevered tray has a hole bored through its center into which a massive slug can be inserted. As the mass is increased the oscillation frequency decreases, illustrating that mass has inertia.

The slug can be suspended by a string while still engaged in the hole. This does not affect the oscillation frequency, illustrating that it is the inertia of the slug and not its weight that matters.

Note that no timing need be done for this demonstration — it is quite obvious to the student that the period is longer with mass than without. Further, if the weight of the mass is taken by the string or released while the oscillation is in progress it is obvious that the period does not change.

For this demonstration it is important to have a lecture table with an edge that overhangs its frame! Not all lecture tables satisfy this criterion.

2 Gravitational Acceleration

2.1 Falling Weights

Two strings with split-shot lead sinkers strategically affixed according to linear and quadratic formulae. Each is dropped from a height onto an aluminum pie plate or other resonator. With the sinkers spaced evenly, students hear impacts occurring at an increasing rate. With the sinkers spaced quadratically, impacts are heard at a constant rate, illustrating that the gravitational acceleration g is constant, *i.e.* the time to fall a distance d is proportional to the square root of d,

$$t = \sqrt{\frac{2d}{g}}\,. \tag{2}$$

Note that to get the proper timing of impacts with the quadratically-spaced sinkers, before releasing the string hold it with the first sinker just contacting the surface of the resonator. To get the required initial height it is necessary to stand on the lecture table.

2.2 Acceleration Trolley

A trolley running on pulleys along a cable stretched tightly across the lecture hall (Fig. 2) can be used to measure g. (Rather than steel cable we use a length of 14-lb-test monofilament fishing line.) By adjusting the angle of the cable, the acceleration can be varied according to

$$a = g\sin\theta\,, \tag{3}$$

as can be shown using a free-body diagram. The acceleration can be measured by timing the trolley's traversal of the width x of the lecture hall according to

$$x = \frac{1}{2}at^2\,, \tag{4}$$

or

$$a = \frac{2x}{t^2}\,. \tag{5}$$

(Since θ is small, we have here neglected its effect on distance traveled:

$$d = \frac{x}{\cos\theta}\,. \tag{6}$$

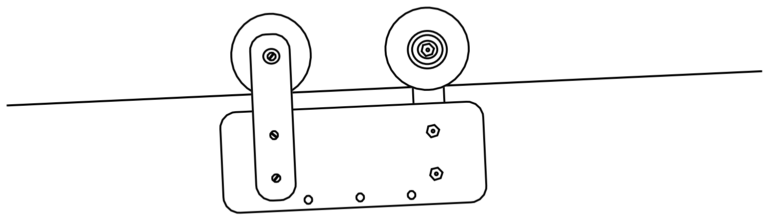

Figure 2: Acceleration trolley shown suspended by its pulleys from a section of cable.

The student may be more comfortable if the $\cos\theta$ factor is explicitly taken into account, or one might choose here to expound the small-angle approximation.)

By hanging weights from the trolley one can show that the gravitational acceleration is independent of mass, since the force is proportional to mass but the acceleration is the force divided by the mass:

$$a = \frac{F}{m} = \frac{mg\sin\theta}{m} = g\sin\theta\,. \tag{7}$$

2.3 Inclined Plane

A simple example of an inclined-plane experiment can be constructed by allowing a coin to slide along the cover of a physics textbook — for visibility in the last row, a quarter is preferable here over smaller coins. One can find experimentally the minimum angle between the textbook and the lecture table to overcome static friction, and thus infer the coefficient of static friction μ_s for these two surfaces. From the free-body diagram for the coin one can readily show that

$$\mu_s = \tan\theta\,. \tag{8}$$

2.4 Air Track

A cart on the air track can also be used to demonstrate and measure the acceleration due to gravity. By using carts of different mass one can show that the acceleration is independent of mass. Since the air track is cumbersome and heavy, the Acceleration Trolley may be preferable fur the purpose.

However, this might be a good opportunity to introduce the air track in a simple situation with the intention of using it later for more complicated demonstrations (*e.g.* collisions).

2.5 Coin and "Feather" Tube

This is a simple apparatus from Pasco including an acrylic tube with corks at each end within which a coin and a less dense object (the "feather") can be placed. A styrofoam packing peanut is used rather than a feather (which, unless very small, could easily get stuck in the tube). With air inside, of course, when the tube is rapidly rotated from the horizontal into the vertical, the coin accelerates more rapidly and reaches the bottom first.

The apparatus includes a large syringe and two check valves, connected up with Tygon tubing such that pumping on the syringe pumps air out of the tube. According to the instruction sheet, it takes 50 or 60 pumping cycles to remove enough air that the two objects accelerate at the same rate and reach the bottom together.

NOTE: During much of the academic year the indoor humidity is low enough that a significant static charge easily builds up inside the tube and impedes the fall of the packing peanut. To prevent this a dampened tissue can be pushed through the tube before pump-down.

3 Projectile Motion

3.1 TekSys "Second Law of Motion" Apparatus

Despite the name given by the manufacturer, this is really a demonstration of the independence of the vertical and horizontal components of projectile motion.

Two identical steel balls are released simultaneoulsy using a spring plunger assembly. The assembly is mounted on a stand and should be carefully leveled so that the balls will not fall off prematurely. The stand should be placed at the edge of the lecture table, so that the plunger assembly is held out beyond the edge of the table.

First insert one ball into the plunger, pushing it in while simultaneously inserting the locking pin until the pin engages. The pin locks the plunger in place. Then slide the other ball over the protruding end of the plunger.

A pull on the the pin will release the plunger, so that one ball falls straight down at the same time that the other is projected horizontally. (To avoid obscuring the students' view, the instructor should pull the pin while standing behind the table.) The students will hear both balls hit the floor at the same time, demonstrating that the vertical motion of the balls is independent of their horizontal motion.

3.2 Hunter and Monkey

Apparatus to demonstrate the independence of horizontal and vertical components in projectile motion.

The "script" that goes along with this demonstration tells of a monkey in a jungle hanging from a tree branch. A hunter aims a gun directly at the monkey and fires; the monkey observes the flash and instantly drops from the branch in order to avoid the bullet. Of course, monkey and bullet have identical downward accelerations, thus the bullet strikes the monkey in mid-air despite the "avoidance maneuver."

The monkey is represented by a tin coffee can, which is suspended by an electromagnet from a tall stand placed on the lecture table. The wooden "bullet" is "fired" by inserting it in a brass tube and blowing on the end of the tube by mouth. (The tube can be disinfected first by wiping its end with alcohol.)

Prior to the lecture, the tube should be carefully aimed at the "monkey" and clamped in place supported by two stands. A strip of aluminum foil should be attached just beyond the exit of the tube to complete the electrical circuit that energizes the electromagnet. When the bullet breaks the foil, the circuit will open and the monkey will fall.

With practice, the can can be oriented so that the bullet lands inside it — this is particularly dramatic.

3.3 Projectile Ball and Cart

A roller cart projects a steel ball upwards from a receptacle by means of a compressed spring. The spring is held compressed by means of a large cotter key attached to a string. A tug on the string releases the spring and projects the ball upward. One can then demonstrate and compare the following two situations:

1. If the cart is at rest when the spring is released, the ball travels straight upwards and downwards and is caught in the receptacle.

2. If the cart is in uniform motion when the spring is released, the ball's trajectory is parabolic. Since the horizontal motion is independent of the vertical motion, the ball still is caught in the receptacle.

Care must be taken to avoid jerking the cart excessively when pulling the string to release the cotter key, otherwise the ball might miss the receptacle.

4 Springs and Hooke's Law

4.1 Hooke's Law Apparatus

This apparatus demonstrates Hooke's Law for a small spring under tension. The spring is hung from a hook attached to a stand and supports a platform to which slotted weights may be added. A pointer attached to the platform indicates displacement on a scale. The scale may be raised or lowered to zero its offset. A graph of displacement *vs.* spring tension should exhibit the linear relationship which is Hooke's Law.

WARNING: So as not to exceed the elastic limit of the spring, do not exceed 250 g.

The built-in scale has numerals that can be read only at distances up to a few meters. For use in large lecture sections, a scale with larger numerals can be printed on a piece of paper and attached to the apparatus with clips or tape.

4.2 Spring Tester

This apparatus demonstrates Hooke's Law for a stiff spring under compression.

4.2.1 Hooke's Law with mechanical advantage

A stiff spring is constrained by a plexiglas tube so that it can be compressed without bending. It supports a plunger attached to a lever arm. A weight hanger (identical to the plunger) is hung from the end of the arm.

As weights are added to the weight hanger, the compression of the spring can be observed and measured. A convenient approach is to mark the tube with a grease pencil at the successive positions of the top of the spring. A graph of weight *vs.* compression distance will show the linear dependence given by Hooke's Law,

$$F = kx \,, \tag{9}$$

and the spring constant k may be inferred from the slope of the graph. The $\times 2$ mechanical advantage of the lever needs to be taken into account to get the spring constant accurately.

4.2.2 Hooke's Law without mechanical advantage

An alternative method measures the spring constant directly, with no mechanical advantage. For this approach the apparatus should be clamped to a stand using the built-in thumbscrew.

Enclosed by the plexiglas tube, the spring is positioned over the hole in the base plate of the apparatus, with a weight hanger inserted through the spring upside-down (*i.e.* with the hook hanging down through the hole). Various weights can then be hung from the hook end of the weight hanger and the compression of the spring marked and measured as above.

5 Newton's Second Law

5.1 Pulleys and Mechanical Advantage

We have a number of pulleys of various configurations that can be used to illustrate Newtons Second Law and mechanical advantage. The pair of triple tandem pulleys can be configured to give mechanical edvantages ranging from 1 (no advantage) to 6. The mechanical advantage can be measured by hanging unequal weights from the two ends so as to achieve equilibrium. (The free end of the string can be draped over another pulley so that a weight may be hung from it.)

6 Newton's Third Law

6.1 Tennis-Ball Cannon

An impressive demonstration that will wake sleepers in the back row! It can also be used as a demonstration of momentum conservation or, equivalently, that the center of mass of a system does not move under the influence of forces internal to the system.

The cannon is constructed out of three empty Campbell's-soup cans (which happen to be a close fit in diameter to a tennis ball). The tops and contents of the cans have of course been removed. The bottoms of the cans have been shaped so as to form a firing chamber, with a small hole on top to allow fueling and igniting. The structure is held together by duct tape and taped to a wheeled cart.

6.1.1 Procedure

First place bricks at one end of the lecture table.

1. Insert the tennis ball into the open end of the cannon as far as it will go.
2. Inject fuel into ignition hole (1 or 2 cc of ether or a few cc of naphtha lighter fuel works reasonably well).
3. Swirl the fuel around for a few seconds so as to get an explosive mixture of vapor and air.
4. Use a lighter to apply a flame to the ignition hole for a few seconds.

If the mix is right, a loud explosion should propel the tennis ball out of the cannon at impressively high speed, with the cannon recoiling slowly. The bricks at the edge of the lecture table prevent the cannon from falling over the edge.

By estimating the ball and recoil speeds, one can estimate the mass ratio of the cannon and ball. From the known mass of a regulation tennis ball, one can then estimate the mass of the cannon, which can be confirmed by weighing if desired.

According to www.tennisserver.com, a regulation tennis ball is "more than two ounces (56.7 grams) and less than two and one-sixteenth ounces

(58.5 grams) in weight.” (Note the confused state of non-metric units — Ohanian isn’t the only one who is confused!)

7 Center of Mass

7.1 Fish with Lights

A large irregular form cut from foam plastic vaguely resembling a fish. Holes have been cut in the foam to accomodate two AA penlight cells and light bulbs with receptacles. Screw a bulb in all the way to complete the circuit.

1. When the fish is tossed through the air, its center of mass describes a parabolic trajectory, as can be seen if the bulb located at the center of mass is illuminated.

2. If the other bulb is illuminated and the fish is tossed spinning slowly around an axis perpendicular to its plane, students can see that the bulb rotates about the center of mass as the fish flies.

(May want to dim room lights to make light bulb more easily visible.)

8 Conservation of Energy

8.1 Inclined Plane with Loop-the-Loop

A steel ball rolls down an inclined track with a loop-the-loop section at the end. By conservation of energy, in the absence of friction, the ball should traverse the loop-the-loop without falling off if the initial height is sufficiently greater than the height h at the top of the loop-the-loop (note that h is the diameter of the loop).

How much greater than h must the initial height be? This comes from the requirement that at the top of the loop the centripetal acceleration equal in magnitude the gravitational acceleration, *i.e.*

$$\frac{v^2}{R} = g\,, \tag{10}$$

where the radius of the loop $R = h/2$. The analysis can be carried through either taking into account or ignoring the rotational energy of the ball, depending on when in the semester this demonstration is employed.

Ignoring for now the rotational energy,

$$mgy_0 = mgh + \frac{1}{2}mv^2 \tag{11}$$

$$= \frac{1}{2}mgR\,, \tag{12}$$

or

$$y_0 = 1.25\,h\,. \tag{13}$$

(The rotational energy of the ball is a small effect and leads to $y_0 = 1.45\,h$.)

In fact one observes that rolling friction does a surprisingly large amount of work, such that the minimum initial height for successful loop-the-loop traversal is approximately $2h$. The amount of work done by friction can thereby be estimated as the difference in energy between the initial height and that neglecting friction:

$$W_f \approx 2\,mgh - 1.45\,mgh \tag{14}$$

$$\approx 0.55\,mgh\,. \tag{15}$$

8.2 KE-PE Track

A track bent into a hill-and-valley shape along which a ball may be rolled. In order for the ball to get over the hump in the middle of the track, it must be started out at a height somewhat greater (due to friction) than the height of the hump.

8.3 Bowling-Ball Pendulum

Most effective with a high ceiling, so that the pendulum has a long period.

A bowling ball is suspended by a steel cable from a hook in the ceiling. The instructor stands with back against a wall, holding the bowling ball lightly against nose with the cable taught. The ball is carefully released — the instructor must avoid giving it even the slightest push! The pendulum swings across the lecture hall and back towards the instructor, who will not flinch if belief in conservation of energy is sufficiently strong!

(Given the slight frictional energy loss at the suspension hook and due to air resistance, the pendulum in fact only approaches, but does not touch, one's nose on return.)

8.4 Work Requires Motion

The bowling-ball pendulum can also be used to demonstrate that work requires a force to act on an object as it *moves over a distance*, contrary to most students' intuitive notion of work (*e.g.* energy expended by a person holding a heavy weight at rest).

If two students (or the instructor and one student) hold a broom handle (or other stiff object) firmly in the path of the pendulum cable, such that the cable bends around the object without the object moving, the students can clearly see that the pendulum loses very little energy per cycle. In contrast, if the students allow the cable to push the object some distance on each cycle, the pendulum quickly slows down and loses amplitude.

8.5 Simple Harmonic Motion

8.5.1 Pendulum oscillator

The bowling-ball pendulum can also be used to demonstrate simple harmonic motion. By timing the period one can show that it is independent of the amplitude for small amplitude and verify that it is given by

$$T = 2\pi\sqrt{\frac{L}{g}}\,, \tag{16}$$

where L is the length of the bob. This is an approximation good to a percent or so even for amplitudes as large as 30°.

One can also show that for amplitudes considerably larger than 30° the period increases.

8.5.2 Hooke's Law oscillator

The Hooke's Law Apparatus can be used to demonstrate simple harmonic motion. Load it to the middle of its range (about 100 g), displace it by a few cm, and release. By timing the period one can verify that it is given by

$$T = 2\pi\sqrt{\frac{m}{k}}\,. \tag{17}$$

where the spring constant k was determined in the Hooke's Law demonstration.

9 Collisions and Conservation of Momentum

9.1 Newton's Pendulum

A pendulum structure with several steel balls, each suspended from two cords such that all swing in the same plane.

Quiescently the balls are all in contact with each other. If n balls are pulled back and released to collide with the remainder, conservation of momentum and mechanical energy dictate that their momentum will be transferred to an equal number of outgoing balls. This appears intuitive if one or two balls are released, but looks quite surprising when more than half are!

This behavior demonstrates the simultaneous conservation of momentum and mechanical energy. For example, momentum conservation would be satisfied if two balls incident at v caused one ball to emerge at $2v$. This does not happen since it would violate conservation of mechanical energy.

An alternative demonstration of the same concept is Hammer Momentum Transfer (Sec. 12.2 under Physics of Carpentry).

9.2 Softball and Basketball

With the help of a student volunteer, an 12-inch-diameter softball is held centered just above a basketball and both are dropped simultaneously. The basketball collides with the floor, bounces up, and collides with the softball, which recoils to a surprising height.

Can also be performed "solo," but watch out — make sure your face is out of the recoil path!

This behavior illustrates an interesting feature of the equations for elastic collisions in one dimension. We have from conservation of momentum and kinetic energy

$$v_{1f} = \left(\frac{m_1 - m_2}{m_1 + m_2}\right) v_{1i} + \left(\frac{2m_2}{m_1 + m_2}\right) v_{2i}\,. \tag{18}$$

In the present case to good approximation

$$v_{1i} = -v_{2i}\,, \tag{19}$$

assuming that the basketball collides elastically with the floor and its velocity vector is thereby reversed in direction but unchanged in magnitude. Thus

$$v_{1f} = \left(\frac{m_1 - m_2}{m_1 + m_2}\right) v_{1i} - \left(\frac{2m_2}{m_1 + m_2}\right) v_{1i} \tag{20}$$

$$= \left(\frac{m_1 - 3m_2}{m_1 + m_2}\right) v_{1i} \,. \tag{21}$$

If $m_1 = 3m_2$ (as is approximately the case for a basketball and 12-inch softball), object 1 will be brought to rest upon collision with object 2, and thus all of its momentum will be transferred to object 2. The softball thus recoils upwards at twice the downwards velocity it acquired due to gravitational acceleration!

9.3 Happy and Sad Balls

Two rubber balls largely identical in weight and appearance. The "happy" ball bounces normally and can be used to demonstrate elastic collisions if dropped on the floor or thrown against the wall. The "sad" ball is made of a special rubber with a small coefficient of restitution; it will collide almost totally inelastically when dropped or thrown.

A similar demonstration can be made using a normal ball and a lump of putty or clay.

9.4 Recoil Apparatus

A curved ramp down which a happy or sad ball may be rolled and launched into the air to strike a 2 cm × 8 cm × 25 cm wooden block standing on end. With the exit end of the ramp adjusted to be about 10 cm above the table, and the block about 10 cm from the end of the ramp, the impact of the sad ball causes the block to wobble but not to tip over. In contrast, the happy ball tips the block over, illustrating that the momentum transfer in an elastic "brick-wall" collision is twice that in a totally-inelastic one.

9.5 Experiments with Air Track

Carts may be collided on the air track with negligible friction. Some carts possess springs at their ends so that they collide elastically. Features of elastic collisions in one dimension may be illustrated by using carts of equal or unequal mass. Carts without springs can be collided with a loop of Scotch tape or a lump of clay or putty attached to one of them to illustrate inelastic collisions.

10 Rotational Motion

10.1 Centripetal Force Apparatus

A string threaded through a cylindrical plastic handle with masses hung at both ends. The mass (m_1) at one end consists of a single large metal washer, while that the other end (m_2) is 10 washers hung on a large paper clip. A second paper clip marks a point on the string between the handle and m_2. If the apparatus is held up, the students can easily see that m_2 outweighs m_1 and so falls to the bottom.

If m_1 is swung overhead by the instructor in a circle of about 1 m radius, an equilibrium can be found at which the point marked on the string by the second paper clip hangs at a constant distance of several cm below the handle — why?

At equilibrium, the centripetal force on m_1 must equal the weight of m_2. We then have

$$m_1 \frac{v^2}{r} = m_2 g \,, \tag{22}$$

where v is the velocity of m_1 and r is the radius of the circle. Since the mass of the two paper clips approximates the mass of a washer, the ratio $m_2/m_1 \approx 11$, giving a period $T \approx 0.6\,\mathrm{s}$ at $r \approx 1\,\mathrm{m}$. One can easily time several periods of the rotation with a stopwatch to verify this.

10.2 Moment of Inertia

Two aluminum tubes, one red and one blue, with closed ends, of equal dimensions and weight but differing moments of inertia. One tube has internal weights distributed towards the ends; the other, weights located near the center.

Students can have trouble getting used to the idea of moment of inertia and appreciating it on an intuitive level. Their appreciation can be helped by passing around the pair of tubes. Ask the student to twirl each one about its center, observing that despite their similarity in size, shape, and weight, one is considerably easier to accelerate rotationally than the other.

Thus size, shape, and mass or weight are not the only fundamental properties of an object that are relevant for mechanics; one must also specify the moment of inertia, which depends on the *distribution* of mass with respect to an axis of rotation.

10.3 Maxwell Wheel

A disk of about 25-cm diameter mounted on an axle and hung from a horizontal rod by two threads. The rod is supported between two stands. The axle can be leveled beforehand by adjusting a knurled nut at the center of the rod. The wheel has a large moment of inertia and thus accelerates very slowly when (carefully and neatly) wound to the top and released.

10.4 Hoop/Disk/Sphere Race

A hoop, a disk, and a sphere can be released simultaneously to roll down an inclined plane. The winner of the race will be the object with the smallest ratio of moment of inertia to mass, since it will convert the least fraction of its initial potential energy into rotational energy and the largest fraction into translational energy.

We have two versions: One is a small inclined plane made of plexiglass with a door that can be lifted to release three small rolling objects simultaneously (the two end compartments can accomodate a hoop and disk of equal diameter, the center compartment can hold a ball of somewhat smaller diameter). The other is a large steel hoop, a disk, and (for the ambitious!) a bowling ball that can be rolled down a wooden plank, released from rest simultaneously by rapidly sliding a meter stick out of the way.

One can show that the time to reach the bottom depends only on shape and is independent of diameter, though to second order diameter may matter if a smaller-diameter object is released first as the door is slid open.

10.5 Soda/Soup Race

A related question is whether a can of soda or a can of cream-of-mushroom soup would win a race down an inclined plane. The answer can easily be found experimentally. Can the students correctly predict the outcome? And explain why?

11 Angular Momentum

11.1 Bicycle-Wheel Gyroscope

This consists of a bicycle wheel with a lead hoop attached to its rim to increase its moment of inertia. One can spin it up by hand or with a rubber head attached to an electric drill. The wheel can then be supported by resting one end of its axle on a stand or on one's hand or by suspending the end of the axle with string.

Why does the wheel thus supported precess? This can easily be analyzed in terms of the direction of the gravitational torque vector $\boldsymbol{\tau}$ acting on the wheel's angular-momentum vector:

$$\boldsymbol{\tau} = \mathbf{r} \times m\mathbf{g}\,. \tag{23}$$

Note that the torque direction is non-intuitive to the beginning student!

11.2 Experiments with Rotating Stool

These experiments should be done with a volunteer who does not easily get dizzy!

1. A stool with ball-bearing mount turns freely with little friction with a student or instructor seated upon it. The rotating person can hold dumbbells and observe the effect of changing moment of inertia by holding the dumbbells closer in or farther out from the body. (If the student starts to feel dizzy the experiment should quickly be terminated.)

2. A student seated at rest on the stool can be handed a spinning bicycle-wheel gyroscope. The student can then change state of rotation by exerting a torque on the gyroscope in various ways:

   - change gyroscope spin direction
   - increase rate of gyroscope spin
   - decrease rate of gyroscope spin

12 Physics of Carpentry

12.1 Inertia Hammer

An alternative to the Inertia Ball. When a carpenter needs to tighten the head of a hammer on its handle, advantage is taken of the hammerhead's inertia. Simply hold the hammer with the head down and strike the end of the handle with another hammer. Since the head has much more mass than the handle, the handle is thereby driven into the head.

If this demo has already been used in a previous lecture, the head will have to be loosened beforehand. This can be accomplished by alternately striking the claw and hammer ends with the other hammer, being careful to aim the head away from one's feet and other nearby objects, in case it falls off!.

To make the motion of the handle into the head more visible, a stripe has been marked around the handle in red nail polish. When the handle is all the way in, there will be no gap between the stripe and the head.

12.2 Hammer Momentum Transfer

Occasionally a carpenter needs to hammer a nail into a flimsy wooden structure. This is difficult since the momentum transfer from the hammer tends to cause the piece of wood to bounce away rather than driving the nail. The solution is have a helper hold a second hammer (of equal mass as the first) against the other side of the piece of wood. (This can be the same hammer as used in the previous demonstration once its head has been wedged on fairly tightly.) Then when the nail is struck by the first hammer, the second hammer carries away the transferred momentum, leaving the piece of wood stationary so that the nail is driven in. (The second hammer should be held lightly to allow it to recoil freely.)

12.3 Plumb Bob

(Not strictly speaking a demonstration.) A good rotation problem in Halliday and Resnick is to figure out the (nonzero) angle a plumb bob makes with the vertical at (say) 40° north latitude due to the earth's rotation. Unfortunately, most General Physics students don't know what a plumb bob is! The solution is to show them one.

13 Miscellaneous

This is well known as a classic experiment. But what exactly does it demonstrate, and how might it be used in General Physics???

13.1 Hinged Board and Ball

Two "one-by-two" sticks connected together at one end by a hinge. The top stick has a tee at the end opposite the hinge and a plastic cup mounted 1/3 of the way towards the hinged end. With the bottom stick resting on the lecture table, a 30-cm-long 12-mm-diameter dowel is used as a prop rod to support the top stick at a 45° angle above the bottom stick. The prop rod is held in place by friction between felt pads affixed to the inner surface of each stick. A ball is placed on the tee.

When the prop rod is quickly snatched away, the ball falls into the cup. (A ball of clay should first be stuck to the end of the bottom stick away from the hinge to cushion the fall.)

Why does the stick fall faster than the ball if both accelerate at g?

Analysis in terms of rotational acceleration under the influence of the torque due to gravity shows that the initial downward acceleration of the end of the stick is

$$a_y = \frac{3}{2} g \cos^2 \theta \tag{24}$$

$$= \frac{3}{4} g \,. \tag{25}$$

So in fact the stick initially accelerates at *less than* g. But as θ decreases, the acceleration increases, and for $\theta < 35°$ the acceleration exceeds g.

Does the tee then fall out from under the ball, or has the ball already slid off the tee because the tee is moving transversely as well as vertically?