How Things Work

DEMONSTRATIONS

The most effective way to illustrate the physics concepts encountered in a *How Things Work* course is with in-class demonstrations. While many physics departments or schools already have collections of demonstrations that they use with various introductory physics courses, I have found myself using a number of unusual demonstrations in *How Things Work*. Here are some of the demonstrations that I have used over the years. Within this collection, you will find old standards as well as some surprises. In addition to these demonstrations, you should remember that, whenever possible, you should inspect and disassemble the objects that you're discussing so that the students can see for themselves what's inside them and how they work.

Section 1.1 Falling Balls

1. Pulling a Tablecloth Out From Under Dishes

Description: You pull a smooth silk tablecloth out from under a place-setting, leaving the dishes essentially unaffected.

Purpose: To demonstrate that inertia tends to keep stationary objects stationary.

Supplies:

1 silk tablecloth (no hem on at least one side)
1 smooth topped table, just large enough for the place-setting
1 relatively smooth-bottomed plate
1 knife
1 spoon
1 fork
1 short wineglass with a smooth, lip-less bottom
red wine (or disappearing ink: about 1/4 tsp. of phenolphthalein in 1 liter water, with just enough sodium hydroxide—about 1/16 tsp.—to turn it pink. When exposed to air, carbon dioxide gradually deactivates the sodium hydroxide and renders the mixture colorless.)

Procedure: Place the tablecloth on the table and arrange the dishes as you would at dinner. Align the wineglass with the fork and make sure that you have room to pull the tablecloth out and down without hitting anything. Also make sure that there is no hem to catch the dishes as the tablecloth slides out from under them. Grip the edge of the tablecloth firmly so that your right hand is aligned with the knife and spoon and your left hand is aligned with the fork and wineglass. This alignment will help minimize bunching of the fabric as it slides under the objects. Now jerk the tablecloth smoothly and swiftly out from under the dishes. A slight downward motion will help ensure that you don't lift the dishes upward and flip them. Don't pause—every instant is crucial. You want to minimize the time during which the tablecloth is pulling on the dishes. If you move quickly enough, the dishes will barely move.

Explanation: The dishes remain in place because of their inertia. Since they experience only modest frictional forces from the tablecloth, and because the time during which those forces are exerted on them is very brief, the dishes continue doing what they were doing: they remain stationary on the table. The tablecloth leaves them behind.

Follow-up: Students can try this procedure by placing some objects on a sheet of paper and then snapping the paper out from under the objects.

2. A Frictionless Puck on a Flat Surface

Description: A puck glides steadily in a straight line after being pushed.

Purpose: To show that an inertial object follows a straight line path at a steady speed.

Supplies:

1 frictionless balloon- or dry-ice-powered puck (Mattel used to make a battery-powered Air-pro air hockey puck that was perfect for this demonstration, but they dropped it in 1991. I still use it.)
1 flat, level surface

Procedure: Make sure that the surface is as flat and level as possible. Use paper shims to level it until the puck can remain almost stationary when left alone. Then give the puck a gentle push and let it glide. It should travel at constant velocity. Show that, once free of horizontal forces, it always travels at constant velocity.

Explanation: The cushion of gas below the puck allows it to slide virtually without friction. As a result, it can follow its inertia in horizontal directions. It moves at a steady pace along a straight line path, as required by Newton's first law of motion, so long as you aren't pushing on it.

3. Cutting a Banana in Midair

Description: A banana dropped from one hand is cut in half by a knife held in your other hand.

Purpose: To show that an object's inertia can keep its velocity from changing while you work on that object.

Supplies:

1 banana (relatively ripe and easy to cut)
1 sharp kitchen knife

Procedure: Hold the banana in one hand and the knife in the other. Drop the banana and, with a rapid sweeping motion, slice the banana in half with the knife. The two halves of the banana should continue falling almost together to the floor.

Explanation: The banana's inertia keeps it from accelerating horizontally. Although gravity makes the banana fall (and is thus a nuisance in this demonstration), there is nothing to make the banana begin moving horizontally. When you swing the knife through the banana, the banana's inertia keeps it in place. Although the knife does exert a small horizontal force on the banana, that force lasts for such a short time that it causes almost no change in the banana's velocity. The banana is simply sliced in half and continues falling to the floor.

Follow-up: How does this effect relate to mowing the lawn with a rotary mower? or to operating a kitchen blender?

4. Cutting a Banana in Midair II

Description: You throw a banana horizontally at a knife held in your other hand and the banana cuts itself in half.

Purpose: To show that an object's inertia will keep it moving at constant velocity in the absence of outside forces.

Supplies:

1 banana (relatively ripe and easy to cut)
1 sharp kitchen knife

Procedure: Hold the knife upright in one hand and throw the banana at the knife with your other hand. (Don't cut yourself! You can also mount the knife upright on the table if you like.) The banana should be flying freely and horizontally when it encounters the knife blade. If the blade is sharp, the banana relatively soft, and you've thrown the banana hard enough, the banana will smoothly slice itself in half and continue on its way.

Explanation: The banana's inertia keeps it moving steadily forward as it encounters the knife. Since the knife barely pushes on the banana, the banana travels through the knife and is sliced in half.

5. Acceleration with a Frictionless Puck

Description: A puck accelerates in the direction of a force on it.

Purpose: To show that force and acceleration are in the same direction.

Supplies:

1 frictionless balloon- or dry-ice-powered puck (Mattel used to make a battery-powered Air-pro air hockey puck that was perfect for this demonstration, but they dropped it in 1991. I still use it.)
1 flat, level surface

Procedure: Make sure that the surface is as flat and level as possible. Use paper shims to level it until the puck can remain almost stationary when left alone. Give the puck gentle pushes in various directions and show that it accelerates in the direction you push it. You can show that acceleration backward (against its velocity) slows it down. You can also show that making the puck travel in a circle takes a steady inward (centripetal) force.

Explanation: The gas cushion under the puck keeps friction from influencing its motion. It can thus respond to forces in accordance with Newton's second law of motion.

6. Human Animation of Velocity and Acceleration

Description: You perform a series of movements that show the students the differences between velocity and acceleration.

Purpose: To help reduce the confusion between velocity and acceleration.

Supplies:

None

Procedure: One of the best ways I've found to illustrate velocity and acceleration is to walk (and even run) about while pointing in the direction of my acceleration (if any). I start from rest, then accelerate toward the right, then maintain constant velocity, then accelerate toward the left, and come to rest. There are many variations on this idea and I use a variety of them in my lectures. I also show accelerations toward a center, so that I travel in a circle. It's particularly important to show the students that you can accelerate without changing speed (by changing directions instead).

Explanation: Acceleration isn't as easy to see as velocity. However, by watching a person's velocity and the changes in that velocity, the students can begin to perceive accelerations.

Follow-up: Walk around as before and have the students point with their hands in the direction of your acceleration or velocity.

7. Comparing the Accelerations of Different Balls

Description: A bowling ball is much harder to accelerate than a baseball.

Purpose: To show how mass affects acceleration.

Supplies:

1 bowling ball (or another massive ball)
1 baseball (or another low-mass ball)

Procedure: Put each ball on a table and give each a brief horizontal push. Try to exert the same force for the same time in each case. The baseball will accelerate to much higher speed than the bowling ball. Point out that this behavior has nothing to do with weight, since it would happen even in the absence of gravity. It has only to do with the masses of the two balls.

Explanation: The bowling ball has a much greater mass than the baseball. Since an object's acceleration is inversely proportional to its mass, the more massive ball experiences the least acceleration.

Follow-up: Consider cases of objects (e.g., vehicles) that are hard to start or stop because they are quite massive.

8. A Ball Falling Downward

Description: A ball dropped from rest accelerates downward and eventually hits the floor.

Purpose: To show that gravity exerts a downward force on a ball, causing it to accelerate downward. This acceleration continues indefinitely.

Supplies:

1 baseball (or another small ball)

Procedure: Hold the ball still in your hand and let go. The ball will fall, moving downward faster and faster as it accelerates in response to its own weight. Point out the this acceleration continues all the way to the floor. To prove that the students already know that this continuing acceleration takes place, have them consider whether they would mind if you dropped the ball on their hands from 2 centimeters. Then ask them whether it would still be OK from 2 meters. If they think about those questions, they'll realize that they know that the ball continues to pick up speed as it falls and is thus accelerating the whole way down.

Explanation: The earth's gravity gives the ball a weight—that is a gravitational force in the downward direction. When only this downward force acts on the ball, the ball accelerates downward. Its velocity increases in a downward direction from zero when it starts to a rapid downward velocity when it hits the floor.

9. Two Different Balls Fall at the Same Rate

Description: Two different balls, having different masses, are dropped from equal heights at the same time and they hit the floor at the same time.

Purpose: To show that all objects fall at the same rate (in the absence of air resistance).

Supplies:

1 marble (or another very small ball)
1 baseball (or another small ball)
1 bowling ball (optional)

Procedure: Hold both balls (the marble and the baseball) in your hands and drop them simultaneously from the same height. They will hit the floor simultaneously. Discuss what would happen if you dropped a bowling ball as well (it's probably not a good idea to actually drop the bowling ball).

Explanation: Although the baseball has more mass than the marble, the baseball also has more weight. That means that while the baseball is harder to accelerate than the marble, gravity also pulls more strongly on the baseball. In fact, gravity's pull on each ball is exactly proportional to its mass, so that the baseball receives exactly the right pull to make it accelerate together with the marble. No matter what object you pick, its weight (the gravitational force it experiences) will be just right to make it accelerate together with the marble. In short, all objects at the earth's surface accelerate at the same rate, in the absence of air resistance.

10. A Ball Falling Up and Down

Description: A ball tossed directly upward rises and falls, always accelerating downward in response to its weight.

Purpose: To show that a ball that is free in the air is always falling—always accelerating directly downward.

Supplies:

1 baseball (or another small ball)

Procedure: Toss the ball directly upward and catch it as it returns to your hand. Discuss the direction of acceleration (steadily downward the whole time). Discuss what force(s) the ball experiences (only the downward force of gravity…nothing else—a fact that the students will be extremely slow to accept completely). Discuss what drives the ball upward to its peak height (the ball's inertia alone).

Explanation: A ball falls from the moment it leaves your hand, even if it's initially heading upward. While its velocity may be upward, its acceleration is directly downward and caused only by the ball's weight. There is no "force" pushing the ball upward and there is no special change in the ball's acceleration that occurs when the ball reaches maximum height. The falling process is very smooth as the ball's velocity gradually shifts from upward to downward.

11. Rising and Descending Take Equal Times

Description: A ball tossed upward takes the same time to rise to its peak as it does to descend to your hand.

Purpose: To show how symmetric a ball's flight is as it rises and falls.

Supplies:

1 baseball (or another small ball)

Procedure: Toss the ball straight up and catch it as it returns to your hand. Count aloud the time it takes to rise to its peak and the time it takes to descend to your hand. Make sure that you count the time *intervals* during the rising and falling periods and not the beginning and ending moments—if you aren't careful, you will over-count by one on the way up. With a little practice and a high ceiling, you can get to 3 (or even 4) intervals on the way up and the same number on the way down and it can be pretty clear that the time up is the same as the time down. Practice first.

Explanation: The ball's upward speed when it leaves your hand is the same as its downward speed when it returns to your hand. Since the acceleration due to gravity is constant, it takes the same amount of time for the ball to lose its upward speed as it rises as it does for the ball to gain its downward speed as it descends.

12. The Independence of Falling on Horizontal Motion

Description: Two balls fall to the floor simultaneously, even though one ball starts with a horizontal velocity and the other starts from rest.

Purpose: To show that a horizontal component of velocity has no effect on a ball's vertical motion.

Supplies:

2 baseballs (or other small balls)

Procedure: Hold both balls in your hands at the same height. Drop one at the same moment that you throw the other horizontally. If your timing is good and your throw is truly horizontal, the two balls will hit the ground at the same moment. There are commercial gadgets that use springs to drop two balls in this manner, but I've had good results just doing it by hand. You could also make your own gadget from a springy wooded stick that supports one ball while you bend it with your hand and then strikes another ball horizontally when you let go of it. The first ball should lose its support and begin falling while the second ball should be knocked horizontally off its support and also begin falling.

Explanation: Since the force of gravity acts only in the vertical direction, it has no effect on a ball's horizontal component of velocity. Moreover, the ball's vertical component of velocity increases steadily in the downward direction, regardless of its horizontal component of velocity. In short, the two balls fall at the same rate and hit the ground simultaneously because their horizontal components of velocity don't affect their vertical motions.

13. Throwing a Ball as Far as Possible

Description: A ball tossed at several angles travels the farthest downfield when it's thrown at roughly 45 degrees above horizontal (neglecting air resistance).

Purpose: To show that both the horizontal and the vertical components of velocity are important to downfield distance.

Supplies:

1 baseball (or another small ball)

Procedure: Throw the ball directly upward at a particular speed and show that, while it stays in the air a long time, it doesn't travel downfield. Then throw the ball horizontally at the same speed, just above the table, and show that, while it moves rapidly downfield, it doesn't stay in the air long enough to travel downfield very far. Finally, throw the ball at 45 degrees above the horizontal and show that, because it stays in the air for a moderately long time and moves downfield at a moderate rate, it travels downfield rather far.

Explanation: The ball's vertical component of velocity determines how long the ball stays in the air and its horizontal component of velocity determines how effectively it uses that time aloft to move downfield. Given a fixed starting speed for the ball, the throw that moves it downfield most effectively is at 45 degrees above horizontal (although this neglects the effects of air resistance).

Follow-up: Have the students throw water balloons on an open field and get a feel for what initial angle allows them to throw the balloons the farthest (thanks to C. Conover for this idea).

Section 1.2 Ramps

14. Dropping an Egg on the Floor

Description: An egg shatters when it's dropped on the floor.

Purpose: To show that the egg and the floor exert equal but oppositely directed forces on one another.

Supplies:

1 raw egg

Procedure: Hold the egg in your hand and describe what is going to happen when you drop the egg. Point out that at the moment the egg reaches the floor, its inertia will tend to carry it downward and into the floor. Because the floor and the egg can't occupy the same space, they will begin to push against one another very hard—the egg will push downward on the floor to try to move the floor out of its way and the floor will push upward on the egg to try to stop it from descending. The forces will be equal in magnitude but opposite in direction. Now drop the egg.

Explanation: The egg shatters because the force exerted on it by the floor is (1) very large—because the floor must bring the egg to rest very quickly and must give it a large upward acceleration—and (2) exerted on only a small portion of the egg's surface. Since the floor's force on the egg is exert only on one part of the egg, most of the egg doesn't accelerate and continues downward. Only the part of the egg that touches the floor accelerates upward and the rest of the egg soon overtakes it. The egg deforms and shatters.

15. A Tug-of-war

Description: Two people pulling in opposite directions on a book leave that book motionless.

Purpose: To show that objects accelerate in response to net force, rather than in response to individual forces.

Supplies:

1 book (avoid a rope, because its non-rigidity leads to complications.)
2 people

Procedure: Have the two people pull on opposite ends of the book so that the book remains motionless. Note that, since the book isn't accelerating, the net force on it must be zero. The forces from the two people and the force of gravity (the book's weight) are canceling one another perfectly.

Explanation: Anytime an object isn't accelerating, the net force on it must be zero. If you can identify a force pulling that object in one direction, you can be sure that there are other forces pulling it on the opposite direction.

16. An Object on a Spring or Bathroom Scale

Description: Measuring an object's weight with a spring scale.

Purpose: To show that a surface exerts an upward force on an object exactly equal to the object's weight and that a scale reports the upward force it exerts on an object.

Supplies:

1 heavy object
1 spring scale or bathroom scale

Procedure: Put the object on the scale so that the two remain stationary. Point out that the net force on the object is zero—it's not accelerating. Identify the two forces on the object: its downward weight and the upward support force that the surface exerts on it. Since the upward support force on the object must cancel the object's downward weight, they must have equal magnitudes. The scale reports the upward force it's exerting on the object, so it reports the object's weight.

Explanation: It doesn't matter what pushes on the scale—the scale merely reacts to any force exerted on it from above by pushing back with an equal but oppositely directed force. In this case, the downward force on the scale is the object's weight and the scale pushes up with a force that's equal in magnitude to that weight.

Follow-up: What is the scale reporting when you push down on it with your hand?

17. Human Animation of Work and Energy Transfer

Description: You raise, hold, and lower a weight to identify those times when you do work—when you transfer energy.

Purpose: To show that work is done only when a force is exerted on an object and when that object moves a distance in the direction of the force.

Supplies:

1 object (a heavy ball or weight)

Procedure: Hold the object motionless at chest height and then raise it gradually upward over your head. Discuss the direction of the force you are exerting on it and the direction in which it moves (both upward). Point out that you are doing work on the object and that you are transferring energy to the object.

Now hold the object motionless over your head and again discuss the force and direction of motion (upward and none, respectively). Point out that you are doing no work on the object and that its energy isn't changing.

Now gradually lower the object back to chest height and repeat the discussion. This time you are doing negative work on the object (or, equivalently, it's doing work on you) and it's transferring energy to you.

Finally, walk at constant velocity across the room and discuss the fact that you are not doing any work on the object because the force and distance are at right angles to one another. However, be aware that people will wonder about the starting and stopping moments, when you <u>are</u> doing work. Discuss that starting and stopping process.

Explanation: To do work on an object, you must exert a force on it and it must move in the direction of that force. When you do work on the object, you transfer energy to it. Since energy is a conserved quantity, your energy goes down whenever you transfer energy to another object.

Follow-up: People will wonder about why you get tired when you hold a weight motionless above your head, since you aren't doing any work on it. The answer is that your muscles are inefficient and turn food energy into thermal energy even when they do no work on outside objects…in effect, they just burn the food to produce thermal energy. This internal conversion tires you out. They will also wonder what becomes of the energy returned to you when you lower the object back to chest height. The answer is that it becomes thermal energy in your muscles—they just aren't able to turn this energy into a more useful form.

18. Two Types of Energy

Description: Energy you transfer to a ball becomes gravitational potential energy as the ball moves upward. It then becomes kinetic energy as the ball falls.

Purpose: To show two forms of energy: gravitational potential energy and kinetic energy.

Supplies:

1 baseball (or another small ball)

Procedure: Slowly lift the ball upward from a table. Point out that something about it is changing—it's acquiring a stored form of energy: gravitational potential energy. Point out that you are providing this energy. Then drop the ball and let the gravitational potential energy transform into kinetic energy. The ball's height decreases so its gravitational potential energy decreases. However, its speed increases so its kinetic energy increases. Overall, its energy remains constant. By the time the ball reaches the table again, its gravitational potential energy is gone and all of the energy you transferred to the ball has become kinetic energy.

Explanation: Energy is a conserved quantity. If you don't exchange energy with the ball, then its energy won't change. Thus as it falls, its total energy can't change but the form that energy takes can and does.

19. Forces and Work on a Ramp

Description: A spring scale is used to show that the force needed to keep a cart from rolling down a ramp is much less than the cart's weight.

Purpose: To show that the ramp helps to support the cart's weight so that a small force is needed to support the cart or pull it steadily up the ramp, and that the work done in raising the cart to a certain height doesn't depend on whether the ramp is used.

Supplies:

1 adjustable ramp (or a board and some books)
1 cart
1 hanging spring scale

Procedure: First use the spring scale to weigh the cart. Now place the cart on the ramp and use the spring scale to determine how much force is required to keep the cart from rolling down the ramp. Show that this force is less than the cart's weight and that it becomes even less as the ramp's slope decreases—the ramp is helping to support the cart's weight. Show that the force needed to keep the cart from moving at all is the same as that needed to keep the cart moving steadily up the ramp because in both cases the cart isn't accelerating. Note, however, that only in the latter case are you doing work on the cart. Now discuss how far you must travel along the ramp to lift the cart upward a certain height. Note that while it takes much less force to pull the cart along the ramp than to lift it straight up, you must travel farther along the ramp to reach a certain height than you would were you to lift the cart straight upward.

Explanation: Overall the product of force times distance traveled, in short the work you do on the cart, doesn't depend on how you raise the cart upward. With or without the ramp, you must do the same amount of work to raise the cart to a particular height.

Section 1.3 Seesaws

20. Rotation about Center of Mass

Description: Balls and other objects tossed into the air spinning rotate about their centers of mass while their centers of mass fall.

Purpose: To show that an object's motion can often be separated into its center of mass motion (translational motion) and rotation about its center of mass (rotational motion).

Supplies:

1 basketball (or another large symmetric ball)
1 stick (or, ideally, a juggler's club)

Procedure: Spin each object on the table to show that it naturally rotates about a special point—its center of mass. Then throw each object into the air while spinning to show that it continues to rotate about its center of mass while that center of mass flies through the air like a normal falling object.

Explanation: Gravity effectively acts at the object's center of gravity (which coincides with its center of mass). As a result, the object experiences no torque in flight and continues to rotate freely. At the same time, the object's center of mass falls under the influence of gravity.

21. Wobble Ball

Description: A ball wobbles rapidly back and forth after being thrown upward while spinning.

Purpose: To show that an isolated object rotates about its center of mass.

Supplies:

1 beach ball (or another inflatable ball)
1 rubber balloon filled with sand (not stretched)
1 duct tape

Procedure: Tape the sand-filled balloon firmly to the surface of the inflated beach ball. Now give the ball a spin as you toss it in the air. The ball will wobble wildly back and forth about its center of mass.

Explanation: Putting sand on the ball's surface shifts its overall center of mass toward the sand. When isolated, the ball will no longer rotate about its center—it will rotate about this new center of mass.

22. A Balanced Seesaw Board

Description: A long stick balances when it's supported at its center of mass.

Purpose: To show that being balanced means experiencing zero net torque, and not necessarily being horizontal or motionless.

Supplies:

- 1 long stick with a hole drilled through its center of mass (a meter-stick with a hole through its center is ideal)
- 1 supported shaft that fits reasonably well inside the stick's hole

Procedure: Support the stick by placing it on the shaft. Show that the stick will remain motionless and horizontal if you start it that way. Since it's not undergoing angular acceleration, it's clearly experiencing zero net torque. Now tilt the stick away from horizontal and show that it still balances—it still experiences zero net torque and doesn't undergo angular acceleration. Finally, spin the stick about the shaft and show that it rotates steadily (neglecting friction and air resistance, which gradually slow it down)—so it still balances.

Explanation: Being balanced means only that an object experiences zero net torque. It may or may not be horizontal or motionless. All that you can be sure of is that it will remain motionless if it starts that way and that it will continue to turn steadily if it starts that way.

23. Angular Acceleration of Different Objects

Description: A bowling ball is much harder to spin than a basketball.

Purpose: To show that an object's angular acceleration depends both on the torque it experiences and on its moment of inertia.

Supplies:

- 1 bowling ball (or another massive ball)
- 1 basketball (or another low-mass ball)

Procedure: Place each ball on the table and give it a spin. Discuss the difficulty involved in spinning the more massive ball as compared to spinning the less massive ball.

Explanation: An object's moment of inertia is the measure of its rotational inertia—its resistance to angular acceleration when exposed to a torque. Massive objects usually have large moments of inertia, although moment of inertia also depends on the spatial distribution of that mass. For example, a pizza is harder to spin about its center than a ball of pizza dough is.

24. A Seesaw Board and Some Weights

Description: Two identical weights make a seesaw board balance when they are equidistant from the seesaw's pivot. Two different weights make the seesaw board balance when their distances from the pivot are inversely proportional to their weights.

Purpose: To show how forces produce torques, how two equal but oppositely directed torques can cancel one another, and how the torque that a force produces is proportional to its distance from the center of rotation.

Supplies:

- 1 board (the seesaw board)
- 1 pivot (a pencil or a similar rod)
- 2 identical weights
- 1 weight that is twice as heavy as the others

Procedure: Balance the empty board on the pivot by placing the pivot below the center of the board. Show that the board is balanced—that it experiences no angular acceleration. Now place the identical weights on opposite ends of the board, at equal distances from the pivot. Explain how each weight is exerting a downward force on the board and is thus exerting a torque on the board. Explain that these two torques are in opposite direction about the pivot and thus cancel perfectly so that the board remains balanced. Now replace one of the weights with the heavier weight and show that the balance is spoiled. Finally, move the heavier weight closer to the pivot until the board balances again. Discuss the relationship between force, distance, and torque that allows the heavier weight closer to the pivot to balance with the lighter weight farther from the pivot.

Explanation: Seesaws balance whenever the torques on them cancel perfectly and they experience zero net torque. By placing weights at strategically chosen distance from the pivot, that balance can be achieved.

25. Flinging an Apple with a Stick

Description: An apple is skewered on a stick and then flung at enormous speed by swinging the stick.

Purpose: To show that a lever can help you accelerate a relatively low-mass object (the apple) to enormous speeds.

Supplies:

1 apple (rather firm, so that it grips the stick well)
1 stick (a sturdy elastic stick about 1 to 1.5 m long)

Procedure: Sharpen the end of the stick so that it can pierce the apple without splitting the apple. With the apple firmly attached to the stick, swing the stick very rapidly over your head. When the apple is just about directly overhead, snap the stick downward to pull it out of the apple and the apple will continue forward at tremendous speed. Try this outside in a safe area first because it takes some practice (it helps to have an old apple tree with lots of apples on the ground beneath it). If you choose to do it inside, be careful not to hit anyone or break anything. In my lecture hall, I can fling the apple against a cement wall so that clean-up is relatively easy. But sometimes I miss…

Explanation: The maximum speed at which you can throw an apple is determined largely by the speed at which you can move your arm. The apple's mass is almost insignificant. By putting the apple at the end of a stick, you can accelerate the apple to a much higher speed because you don't have to accelerate your arm to that speed.

26. Breaking an Egg on a Seesaw

Description: An egg sits on one side of a small seesaw and you strike the other side of the seesaw with a mallet. The egg explodes in place.

Purpose: To show that a large unbalanced torque causes rapid angular acceleration and that a large force exerted on the surface of an egg will break that egg.

Supplies:

1 egg
1 small seesaw (a short, sturdy board will do as the seesaw board and a pencil will do as the pivot)
1 mallet (or even a book)

Procedure: Place the egg on one side of the seesaw. You may need to prop it in place so that it doesn't roll off. Ask the students whether the egg will rise up into the air and then smash when it lands or whether the egg will shatter during the launching process. Now strike the other side of the seesaw firmly with the mallet. The egg will explode without rising.

Explanation: When you hit the seesaw board, it experiences a large unbalanced torque and undergoes rapid angular acceleration. The egg, with its inertia, exerts a torque in the opposite direction but can't stop the angular acceleration from occurring. The seesaw board rotates rapidly into the egg, smashing it.

Section 1.4 Wheels

27. Sliding Versus Static Friction

Description: A box pulled by a spring scale initially resists sliding but eventually slides forward.

Purpose: To illustrate the forces of static and sliding friction.

Supplies:

1 box (or a heavy block)
1 string
1 spring scale

Procedure: First show that the box remains at rest on the table, even if you push it gently toward one side. Discuss static friction. Then push harder and show that the box begins to move but that it doesn't accelerate indefinitely, even though you keep pushing. Finally, stop pushing and show that it coasts to a stop. Discuss sliding friction. Use the string to attach the spring scale to the box and show that the force of static friction can range from zero up to some maximum value, depending on how hard you pull the box to one side. Then start the box moving and show that the force of sliding friction is just about constant, no matter how fast you move the box (as long as you move it at constant velocity). Lastly, add weight to the box and show that the frictional forces can become stronger—discuss the microscopic basis of friction.

Explanation: Static friction opposes any relative motion between two surfaces that are at rest with respect to one another. Sliding friction opposes relative motion between two surfaces that are already sliding across one another. Since these two forces are caused by "collisions" between microscopic features of the two surfaces, pushing those surfaces together more strongly increases the frictional forces.

Follow-up: You can also changes the characteristics of the two surfaces and show that rougher surfaces generally experience stronger frictional forces.

28. Using Sliding Friction to Start a Fire

Description: A wooden peg is turned rapidly with a bow. Friction between the peg and a board causes them to heat up and begin smoking.

Purpose: To show that sliding friction converts work into thermal energy.

Supplies:

- 1 wooden peg, about 1 cm in diameter and about 10 cm long. Sharpen one end as though it were a pencil.
- 1 bow (either a commercial bow from an archery set, or an equivalent homemade one)
- 1 wooden block with a hollow greased socket for the peg's flat end
- 1 wooden board with a narrowly drilled hole for the peg's sharpened end
- 1 clamp

Procedure: Clamp the board to the table. Wrap the bow string once around the peg and insert the peg's sharpened end into the drilled hole in the board. Press the peg against the board with the wooden block and move the bow back and forth fairly rapidly. The peg should spin one way and then the other as you move the bow. If you apply the right amount of pressure to the peg and move the bow quickly enough, sliding friction between the sharpened peg and the board will cause them to heat up and smoke. While I have never been able to start a fire this way, it should be possible with the help of some dry tinder or cotton balls.

Explanation: As the peg turns in its hole, the two surfaces slide across one another. They convert the work that you are doing by pushing and pulling on the bow into thermal energy.

Follow-up: Light a match and discuss the role of sliding friction in the ignition process. Have the students rub their hands together until their skin feels warm. They should be aware that they are doing work against sliding friction as they move their hands.

29. A Swinging Pendulum

Description: A pendulum swings back and forth, with its energy transforming from gravitational potential energy to kinetic energy and back again, over and over.

Purpose: To show the conversion of energy from one form to another.

Supplies:

- 1 pendulum (or any large object supported by as long a string as is practical)

Procedure: Start the pendulum from rest by pulling it back and letting it go. Point out that you do work on it by pulling it away from its central position and thus give it its initial energy. As it swings back and forth, note the times at which its energy is all gravitational (at the end of each swing) and all kinetic (at the bottom of each swing). To make it swing harder, push it every time it begins to swing away from you—you are doing work on it. To make it swing less hard, push it every time it begins to swing toward you—it's doing work on you.

Explanation: The pendulum has two forms for its energy: gravitational potential energy and kinetic energy. It naturally transforms its energy from one form to another as it swings. You can add energy to it by doing work on it once each cycle or you can take energy out of it by having it do work on you once each cycle.

30. Pushing a Swinging Pendulum

Description: Pushing on a swing can make the swing move more or less, depending on when the push occurs in the swing.

Purpose: To show that energy is transferred by doing work.

Supplies:

- 1 pendulum (a ball on a string, or something equivalent)

Procedure: Give the pendulum a series of pushes. Time the pushes so that they always occur as the pendulum moves away from you—so that you do work on it. The pendulum should swing more and more. Now repeat the pushes, but time them so that they always occur as the pendulum moves toward you—so that it does work on you. The pendulum should swing less and less.

Explanation: Making a swing travel further requires that you transfer energy to it. You do this by pushing it as it moves away from you—so that the push and the distance the swing travels are in the same direction. Making the swing travel less far requires that it transfer energy to you. You do this by pushing it as it moves toward you—so that the push and the distance it travels are in opposite directions.

Follow-up: Discuss how this applies to pushing a child on a swing.

31. Forms of Energy

Description: A number of objects are shown to contain energy.

Purpose: To show that energy, the capacity to do work, can take many forms.

Supplies:

1 ball
1 wound or compressed spring
1 elastic balloon, uninflated
2 magnets
1 capacitor and charging system (see next demo)
1 battery and light bulb
1 pretend stick of dynamite

Procedure: This demonstration is simply meant to illustrate that energy takes many form. In each case, it's helpful to show that the energy really is the capacity to do work and that the stored energy can cause some work to be done. Use the ball to show that kinetic energy can do work on a target. Use the ball to show that gravitational potential energy can do work on another object. Inflate the balloon and let it fly around the room. Let the magnets jump apart (or together). Use the capacitor to make a spark. Use the battery and light bulb to make electric charges move and heat the bulb's filament white hot. And talk about the pretend dynamite.

Explanation: Energy is the capacity to do work and it can take many different forms.

32. Forms of Energy - Electrostatic Potential Energy

Description: A large capacitor is charged with the help of a string of 9V batteries. It is then discharged with a screwdriver, producing a large spark and a loud pop.

Purpose: To show one of many forms of energy.

Supplies:

1 large electrolytic capacitor (about 10,000 µF, with a rated voltage of about 75 V)
1 string of 9V batteries with a total voltage of no more than the rated voltage of the capacitor. Form the string by clipping the negative terminal of one to the positive terminal of another, and so on.
2 wires
1 old screwdriver
safety glasses

Procedure: Connect the string of batteries to the capacitor, positive end to positive end and negative end to negative end. The batteries will begin to transfer charge from one side of the capacitor to the other, a process that will take a few seconds for new batteries but may take as long as a minute for old batteries. If you want to know how the transfer is progressing, measure the voltage drop across the capacitor with a voltage meter. Be careful, because both the string of batteries and the capacitor have enough voltage to injure you.

Once the capacitor is fully charged, detach the batteries. Now discharge the capacitor by connecting its two terminals with the screwdriver. You should wear goggles or safety glasses while doing this and be prepared for a big spark. Since the discharge will blow chunks of metal out of both the screwdriver and the capacitor's terminals, you should probably extend the capacitor's terminals with bolts if you want to be able to do this demonstration more than a couple of times. This demonstration drains the batteries substantially, so you won't be able to do it more than a few dozen times before you'll have to replace the batteries.

Explanation: The batteries pump charge from one side of the capacitor to the other. One side of the capacitor acquires a positive charge and the other side acquires a negative charge. The attractive forces between these two opposite charges are capable of doing a substantial amount of work. They have electrostatic potential energy. When you connect the two sides of the capacitor with the screwdriver, the charges move toward one another and release their stored energy as heat, light, and sound.

33. A Box and Rollers

Description: A box that slides badly on the table, coasts almost freely when it's supported by rollers.

Purpose: To show that rollers eliminate sliding friction.

Supplies:

1 heavy box (or a large heavy block)
3 dowels (or equivalent rods)

Procedure: Place the box directly on the table and give it a push. Show that it quickly slows to a stop as sliding friction exerts a force on it in the direction opposite its motion. Now support the box on two rollers and place the third roller in front of it. Push the box toward the third roller and show that it coasts smoothly forward as long as it doesn't fall off the rollers. Discuss the fact that the only friction left in the situation is static friction.

Explanation: As the rollers turn, their surfaces don't slide across those of the box or table. As a result, there is only static friction present and nothing converts the box's kinetic energy into thermal energy. The box thus coasts forward indefinitely after you give it a push.

34. Wheels - Free and Powered

Description: A freely turning wheel spins as you pull it across the table. A turning (powered) wheel pushes itself forward across the table.

Purpose: To show that static friction between the ground and the bottom of a wheel can either cause the wheel to turn (in the case of a freely turning wheel) or can propel the wheel across the ground (in the case of a powered wheel).

Supplies:

1 bicycle wheel (or a similar wheel on an axle)

Procedure: Hold the bicycle wheel against the table and begin rolling the wheel across the table. Point out that it is static friction between the table and the wheel that is producing the torque that makes the wheel turn. Now hold the bicycle wheel against the table and begin to twist the wheel with your hand. As the wheel begins to rotate, it will also propel itself across the table. Point out that it is static friction between the table and the wheel that is allowing the wheel's rotation to produce the forward force that propels the wheel forward.

Explanation: The forces of static friction between the table and the wheel affect both the wheel's center of mass motion (its progress forward or backward across the table) and its rotational motion (how it spins).

Follow-up: Show that when a wheel skids, sliding friction appears and some energy is converted to thermal energy.

35. Roller or Ball Bearings

Description: The balls or rollers in a bearing rotate as the inner part of the bearing turns relative to the outer part.

Purpose: To show that the balls or rollers in a bearing experience only static friction—they touch and release as they move past the surfaces. There is no sliding friction in a ball or roller bearing.

Supplies:

1 large ball or roller bearing without aprons (that would cover the internal components)

Procedure: Show that the balls or rollers in the bear touch and release the surfaces of the bearing as the inner and outer surfaces move relative to one another.

Explanation: The balls or rollers in the bearing are equivalent to rollers places between the inner and outer surfaces of the bearing. The balls or rollers move slowly around the inner surface as the two surfaces moves relative to one another. Because the balls or rollers never slide across the surfaces, there is no sliding friction and no energy wasted as thermal energy.

36. A Skidding Wheel Wastes Energy

Description: A spinning grinding wheel makes sparks as it "skids" on a steel surface.

Purpose: To show that a skidding wheel uses sliding friction to turn useful energy into thermal energy.

Supplies:

1 grinding wheel on an axle
1 electric drill
1 steel plate
1 clamp to hold the metal plate to the table

Procedure: Clamp the steel plate to the table. Put the grinding wheel in the drill and start the wheel spinning fairly rapidly. Now touch the wheel to the steel plate and watch the sparks fly. (Alternatively, you can use a bench grinder and hold the steel yourself.)

Explanation: As the grinding wheel slides across the plate, it wears steel away from the plate's surface and ejects the hot wear chips into the air, where they burn up.

37. Throwing an Object—Momentum Conservation

Description: You sit on a cart at rest and throw a heavy object. While the object accelerates in one direction, you accelerate in the other.

Purpose: To demonstrate the transfer of momentum and to show that momentum is conserved.

Supplies:

1 cart with low-friction wheels and bearings
1 heavy (but soft) object

Procedure: Sit on the cart with the heavy object in your lap. The cart should be at rest on a smooth level surface. Now throw the object as hard as possible along a direction that the cart can roll. The cart will begin rolling in the opposite direction, with you still on it.

Explanation: At the start of the demonstration, you and the object have zero total momentum. As you throw the object, you transfer momentum to it in one direction and thus end up with an equal amount of momentum in the opposite direction. Overall, the momentum is still zero, but now the object has momentum in one direction and you and the cart have momentum in the opposite direction.

38. Twisting a Wheel—Angular Momentum Conservation

Description: You sit on a swivel chair and twist the axle of a spinning bicycle wheel. When you change the wheel's direction of rotation, you and the swivel chair also experience a change in your rotation.

Purpose: To demonstrate the transfer of angular momentum and to show that angular momentum is conserved.

Supplies:

1 bicycle wheel with handles attached to the axle (Inserting metal wire into the tire helps by adding mass to the rim and increasing the wheel's moment of inertia.)
1 swivel chair with a low-friction rotational bearing

Procedure: Get the bicycle wheel spinning as rapidly as possible with your hands or with a motor. We use a bench grinder with a polishing wheel replacing its grinding wheel—pressing the bicycle wheel against the spinning polishing wheel gets the bicycle wheel spinning quite rapidly after about 10 or 20 seconds. Now twist the bicycle wheel so that it's spinning horizontally, with its axis of rotation pointing upward (it spins counter-clockwise as viewed from above). Sit on the swivel chair and point out the wheel now has all the angular momentum and that that angular momentum is upward. Now lift your feet off the ground and flip the bicycle wheel upside down, so that it's axis of rotation points downward. You will begin to spin with your axis of rotation upward. The wheel has transferred angular momentum to you. When you flip the wheel back to its original situation, you will stop spinning. The wheel will now have all the angular momentum again.

Explanation: Each time you flip the bicycle wheel, you are exerting a torque on it and it is exerting a torque on you. When you turn the wheel over, its angular momentum reverses and you end up with twice its original angular momentum. Overall, the angular momentum remains the same, but it's distributed differently.

39. A Diablo—Angular Momentum Conservation

Description: You spin a diablo (an hourglass-shaped rubber toy) on its string support and show that, once spinning, it tends to continue spinning steadily about a fixed axis in space.

Purpose: To show that angular momentum is conserved.

Supplies:

1 diablo—an hourglass-shaped rubber toy with a narrow metal waist. This toy is supported from a string that stretches between two sticks.

Procedure: Rest the diablo on the string and begin to snap one of the sticks in a series of quick upward jerks. The string will grab onto the diablo during those jerks and exert a torque on it to start it spinning. Keeping the diablo level requires that you pay attention to the relative positions of the stick ends. It takes some practice to get the diablo to spin smoothly and horizontally. However, once it's spinning nicely, you can walk around it, holding it up by the strings, and it will spin about a fixed axis in space for a long time.

Explanation: The spinning diablo is virtually free from external torques, so its angular momentum doesn't change as you walk around it.

40. Changing Your Moment of Inertia

Description: You spin on a swivel chair with your arms outstretched and weights in your hands. As you pull your hands inward, you begin to spin faster and faster.

Purpose: To show that because angular momentum is conserved, a spinning object that reduces its moment of inertia must spin faster.

Supplies:

- 2 weights for your hands
- 1 swivel chair with a low-friction rotational bearing

Procedure: Sit on the swivel chair and hold the weighs in your outstretched arms. Now push on the ground with your feet to obtain the torque you need to get yourself spinning. Once you are spinning, lift your feet off the floor so that you are isolated from external torques. Now pull in your arms and you will begin to spin much faster than before.

Explanation: Since angular momentum is the product of angular velocity times moment of inertia, decreasing your moment of inertia causes your angular velocity to increase.

41. The Direction of Acceleration

Description: A pendulum that is released from rest always accelerates toward the point below its support—in the direction that reduces its gravitational potential energy as rapidly as possible.

Purpose: To show that objects accelerate in the direction that decreases their potential energies as rapidly as possible.

Supplies:

- 1 pendulum (a ball on a string)

Procedure: Push the pendulum away from its stable equilibrium point and let go. No matter which way you have shifted it from the equilibrium point, it will always accelerate toward that point.

Explanation: Because potential energy and forces are related, it's not surprising that an object accelerates in a direction dictated by its potential energy. In fact, an object always accelerates in the direction that reduces its potential energy as rapidly as possible (because that is the direction of the net force on the object).

Section 2.1 Spring Scales

42. A Spring's Behavior at and near Equilibrium

Description: A coil spring, supported from above, is shown to exert a restoring force that's proportional to how far it's distorted away from its equilibrium shape or position.

Purpose: To illustrate equilibrium and to show that a spring's restoring forces are proportional to its distortion.

Supplies:

- 1 coil spring
- 1 support for the coil spring (above)
- 1 ruler or other measuring device (it should be fixed in place next to the coil spring so that the students can see how the spring's length changes)
- 3 identical objects

Procedure: Suspend the coil spring from the support and align the ruler next to it so that the ruler's zero is next to the spring's free end. Point out that the end of the spring is motionless and not accelerating, so that it must be experiencing a net force of zero—it must be in equilibrium. Now hang first one, then two, then all three objects from the spring. Note that the spring adopts a new equilibrium height after each addition. Since the objects' weights are being exerted downward on the spring, the spring must be pulling upward on the objects with a force that's equal in magnitude to the objects' weights. Point out that the spring has had to stretch in order to exert this upward force on the objects and that the extent of this stretch is proportional to the upward force the spring is exerting on the objects.

Explanation: The spring obeys Hooke's law, exerting an upward force on the objects that's proportional to how far the spring has been stretched downward. Since two objects weigh twice as much as a single object, the spring must stretch twice as far. For three objects, it must stretch three times as far.

43. A Hanging Pan

Description: A hanging pan automatically adjusts its angle so that its center of gravity is directly below its support.

Purpose: To show that a hanging object will tip until its center of gravity is directly below the point from which it's being supported.

Supplies:

1 hanging pan (or any basket that's supported by strings that merge to a single point of support)
1 support for the pan
3 objects to put in the pan

Procedure: Suspend the hanging pan from the support and allow it to settle. Its center of gravity should then be directly below the point from which it's supported. Now begin adding the objects to the pan. Show that the pan tips until its new center of gravity is directly below the support point.

Explanation: When the pan's center of gravity is directly below its support point, the pan is in equilibrium—it experiences no net force and no net torque. But whenever the pan's center of gravity isn't below the support point, it experiences a torque about its support point that restores it to its equilibrium position. This torque is a restoring torque because, just as restoring force of a spring returns it to its equilibrium position, this restoring torque always returns the pan to its equilibrium orientation.

44. A Ruler is a Spring

Description: A flexible ruler that extends from the edge of a table acts as a spring when objects are placed on it.

Purpose: To show that almost everything acts as a spring when deformed slightly.

Supplies:

1 flexible ruler (a clear plastic ruler or a wooden meter stick)
3 identical objects
1 heavy book (or any other anchor for the ruler)

Procedure: Extend the ruler from the edge of a table, using the book to anchor its supported end to the table. Note that the free end of the ruler adopts an equilibrium height. Now add first one, then two, then three objects to the end of the ruler. Point out that the ruler deforms downward with each additional object and that the amount of its deformation is proportional to the weight that it's supporting.

Explanation: The ruler is acting as a spring, deforming downward by an amount that's proportional to the restoring force it's experiencing. This restoring force is supporting the weight of the objects on its end. Since the objects have equal weights, the ruler's restoring force and its deformation are both proportional to the number of objects the ruler is supporting.

45. A Bathroom Scale

Description: As you step on a bathroom scale, its surface descends slightly as the spring inside it deforms. The scale measures this deformation in order to determine your weight.

Purpose: To show that even a bathroom scale is really a spring scale.

Supplies:

1 bathroom scale

Procedure: Step on a bathroom scale and watch the scale's surface descend. Show that the more weight you place on this scale, the farther downward the scale's surface goes. Pick up the scale and squeeze it to show the direct relationship between how far inward you push its surface and the weight that it reports on its dial.

Explanation: The bathroom scale contains a spring that deforms as you step on the scale. This deformation allows the spring to exert the upward support force that keeps you from falling into the scale's surface. The scale's surface descends until the spring's restoring force is just enough to provide its surface with an upward support force that's equal in magnitude to your weight.

46. The Difficulty in Weighing an Astronaut

Description: You jump off a stool while holding a loaded spring scale. The scale reads zero while you are falling.

Purpose: To show that a spring scale only reads the weight of the objects its holding when the objects aren't accelerating.

Supplies:

1 spring scale
1 object
1 short stool

Procedure: Hang the object from the spring scale and stand motionless on the stool. The scale will read the weight of the object. Now jump carefully from the stool and allow the scale and the object to fall with you. Pay attention to your landing so that you don't hurt yourself. During the time that you, the scale, and the object are in free fall, the scale will read zero.

Explanation: When the object is falling, the only force acting on it is gravity. Since the scale doesn't exert any upward force on the object, the scale's spring doesn't distort and the scale reports that it's exerting zero force on the object.

47. An Accelerating Spring Scale

Description: An object hangs from a spring scale as both bounce slowly up and down on the end of a very long spring. The spring scale reads alternately more or less than the object's actual weight.

Purpose: To show that when a scale and the object it's supporting accelerate, the force that the scale exerts on the object isn't equal in magnitude to the object's weight.

Supplies:

1 spring scale
1 object
1 very long spring or elastic cord

Procedure: Suspend the object from the spring scale and then suspend the spring scale from the very long spring. Allow the scale to hang motionless from the spring and note that the scale reads the true weight of the object. Then make the scale and object bounce gently up and down. The scale will alternately read more or less than the object's weight.

Explanation: Whenever the scale and object are below their equilibrium position and the very long spring is stretched downward, the scale and object are accelerating upward. The scale must therefore pull upward extra hard on the object and the scale reads more than the object's weight. Whenever the scale and object are above their equilibrium position, they are accelerating downward and the scale reads less than the object's weight.

Follow-up: Allow the scale and object to bounce so high that they enter free fall. At that point, the scale will read zero! Be careful that the object doesn't fall off the spring scale.

Section 2.2 Bouncing Balls

48. How Different Balls Bounce

Description: Several different balls rebound to different heights after being dropped.

Purpose: To show that different balls have different coefficients of restitution and thus return different fractions of the collision energy as rebound energy.

Supplies:

3 different balls (or more)
1 set of happy and unhappy balls (optional—available from a scientific supply company)

Procedure: Drop the different balls one at a time from a set height. Show that, while none of them return to their original heights, some bounce higher than others. Discuss how energy changes form from gravitational potential energy, to kinetic energy, to elastic potential energy (in the ball), to kinetic energy, and back to gravitational potential energy as the ball bounces. If you can obtain a happy/unhappy ball pair, show how well the happy ball bounces (essentially a superball) and how incredibly poorly the unhappy ball bounces (a remarkably dead ball—it barely bounces at all).

Explanation: As they deform during a collision, different balls have different efficiencies at storing energy. Hard balls that store energy via compression tend to bounce much better than soft balls that store energy via bending surfaces.

49. A Bouncy Ball Transfers More Momentum

Description: A bouncy object swings into a block that's balanced on its end and the block falls over. A less bouncy object of identical mass swings into the block but this time the block doesn't fall over.

Purpose: To show that a bouncy object transfers momentum during a collision both as the object slows to a stop and as it rebounds backward. An object that doesn't bounce transfers momentum only as it slows to a stop and thus transfers less momentum.

Supplies:

1 hard block that can be balanced on its end
1 bouncy ball (such as a happy ball)
1 non-bouncy ball (such as an unhappy ball)
string
1 support for balls

Procedure: Use the string to suspend the two balls from the support. Place the block on end in front of the bouncy ball, pull the ball back, and let it swing into the block. Determine how far back you must pull the ball in order to knock the block over. Now try the same experiment with the non-bouncy ball. You should have to pull it back much farther in order to knock over the block.

Alternative Procedure: Use a metal rod as a battering ram—suspend it on several strings so that it swings forward smoothly and strikes the block. Now put Silly Putty on the block to create a bouncy surface for the metal rod to hit. Determine how far back you must pull the battering ram in order to knock over the block. Now try the same experiment but replace the Silly Putty with a soft, non-elastic putty. You will have to pull the battering ram much farther back in order to knock over the block when the battering ram hits the non-elastic putty.

Explanation: When an object slows to a stop during a collision, it transfers all of its forward momentum to the surface it hits. If that object rebounds, it will then transfer additional forward momentum to the surface so that the object leaves with backward momentum.

50. A Baseball Bat's Center of Percussion

Description: A baseball bat, hanging by its handle from a support, is struck at various places with a rubber mallet. Only when the bat is struck at its center of percussion does the handle remain in place.

Purpose: To show that there is a special point on the bat, its center of percussion, at which you can hit the ball without causing the bat's handle to accelerate.

Supplies:

1 baseball bat
1 rubber mallet
1 support
string
putty

Procedure: Attach the string to the bat's handle and hang the bat from the support. With the bat hanging motionless below the support, strike the bat firmly at various points on its business end. Only when you strike the bat on its center of percussion will the handle remain in place (although the bat's body will accelerate away from the impact and the bat will begin to rotate). If you hit the bat almost at its end, the handle will jerk toward the mallet. If you hit the bat near its middle, the handle will jerk away from the mallet. You can show this jerking motion by sticking the putty to the bat's handle. The bat will fling the putty in the direction of its jerk. When you hit the bat exactly at its center of percussion, the putty may still come off the bat because of vibrations, but it will drop more or less straight down.

Explanation: When you hit the bat, the bat's center of mass will accelerate away from the mallet but the bat will also begin to rotate about that center of mass. If you hit the bat at its center of percussion, these two motions will cancel at the handle and the handle itself won't accelerate.

51. A Baseball Bat's Vibrational Node

Description: A wooden baseball bat, hanging by a string from a support, is struck at several places with a rubber mallet. Only when it's struck at its vibrational node does the bat emit a clear "crack" sound. When struck at other places, the bat emits a buzzing sound.

Purpose: To show that a bat can vibrate and that you can avoid making it vibrate only by hitting it at its vibrational node.

Supplies:

1 wooden baseball bat
1 rubber mallet
1 support
string

Procedure: Attach the string to the handle of the bat and hang it from the support. Strike the bat a sharp blow with the mallet and listen to the buzzing sound it emits. When you hit the bat's vibrational node, there should be a significant change in the sound, with it emitting the sharp "crack" sound we associate with a solid impact. The bat's vibrational node should roughly coincide with its center of percussion.

Explanation: The bat vibrates in much the same way that a xylophone plate vibrates—the middle of the bat moves in the opposite direction from its two ends. That motion is its fundamental vibrational mode. This mode of vibration leaves two points on the bat motionless and these two vibrational nodes are located along its handle and part way along the business end of the bat. When you strike the bat at one of these nodes, you don't excite its fundamental vibrational mode and it thus emits very little sound. Any sound that the bat emits is at much higher frequencies because it involves higher order vibrational modes.

Follow-up: Why is a xylophone plate supported at two points that are each about half way between the middle and end of the plate?

Another Follow-up: Hold an 18" C-Thru plastic ruler horizontally by its middle and flap it up and down rapidly. You'll see that the middle and ends are antinodes and that it has a node part way toward each end.

52. Sending a Croquet Ball

Description: Two croquet balls are touching one another when one of the balls is hit sharply with a mallet. The struck ball immediately hits the second ball head on and comes to a stop. The second ball continues on with the momentum and energy of the first ball.

Purpose: To illustrate the transfers of energy and momentum that occur during a collision.

Supplies:

2 croquet balls
1 croquet mallet

Procedure: Place the two croquet balls side by side so that they almost touch. Now strike the outside surface of one ball firmly and briefly so that the ball travels directly toward the second ball. When the first ball hits the second ball, the first ball will come to a stop and the second ball will take over its motion.

Explanation: Croquet balls are highly elastic, so that when they collide, they exchange both momentum and energy. The first ball pushes on the second ball both as they approach one another and as they rebound. This relatively elastic collision allows the first ball to transfer virtually all of its momentum and most of its energy to the second ball and the second ball takes over the first ball's motion.

Follow-up: Try a similar experiment with pool or billiard balls and a cue stick. Also, experiment with an "executive toy," a toy with several steel balls that are suspended from a wooden frame so that they can swing into one another. If you pull one of the balls back and let it swing into the others, only the last ball in the chain will swing out. You can do this same experiment with a row of identical coins on a tabletop.

53. Rotation and Translation During a Bounce

Description: A spinning basketball that's dropped on the floor leaps forward or backward after it hits.

Purpose: To show that friction between a ball and the surface it hits can cause the ball's rotational and translational motions to interact with one another.

Supplies:

1 basketball (or another large ball)

Procedure: Spin the basketball as you drop it and watch what happens when it hits the floor. It will leap forward or backward, depending on its direction of spin. Point out that the support force from the floor is directly upward, so that this effect must be due to friction between the ball's surface and that of the floor.

Explanation: The frictional force on the ball causes it to accelerate, increasing its translational motion. This same frictional force also produces a torque that slows the ball's rotational motion.

54. A Tennis Ball Bouncing from a Basketball

Description: A tennis ball sits atop a basketball as the two are dropped from a modest height. When they hit the floor, the tennis ball leaps into the air and rises well above its original height.

Purpose: To show that bouncing from a moving surface can lead to counterintuitive results and to show the importance of picking a good inertial frame of reference from which to observe a bounce.

Supplies:

1 tennis ball (or another small, elastic ball)
1 basketball (or another massive, elastic ball)

Procedure: Balance the tennis ball atop the basketball and hold them a few feet above the floor or a firm table. Now drop the pair. The tennis ball should rebound to a height much greater than its original height.

Explanation: The tennis ball effectively completes its bounce from the basketball after the basketball has already bounced off the floor. As a result, the tennis ball is bouncing from a rising surface. Like a ball that's been hit by a rising baseball bat, the tennis ball rebounds with a speed that's larger than its speed before it hit the basketball. If both balls were ideally elastic (coefficients of restitution of 1.0) and if the basketball were infinitely massive, the tennis ball would rebound to 9 times its original height.

55. Bouncing from a Trampoline

Description: A relatively dead ball bounces nicely from an inflated plastic bag.

Purpose: To show that the surface from which a ball bounces can contribute to the rebound.

Supplies:

1 non-lively ball (an "unhappy" ball is ideal)
1 air-filled plastic bag

Procedure: Show that the ball doesn't bounce well from a solid surface. Then show that the ball bounces reasonably well from the surface of the plastic bag.

Explanation: During the collision between ball and surface, the one that deforms the most receives the majority of the collision energy. Since a non-lively ball doesn't return much of the collision energy, its rebound depends critically on how lively the surface it strikes is and on what fraction of the collision energy goes into that surface. Since the plastic bag deforms easily and stores energy well, it allows even an "unhappy" ball to bounce well. While the ball returns no rebound energy, the surface does.

56. Ball Bouncing from a Moving Baseball Bat

Description: A human "animation" of a ball bouncing from a moving bat.

Purpose: To show the importance of inertial reference frame in following a collision between moving objects and to show how a baseball can rebound from a moving bat with a greater speed than it had before it hit the bat.

Supplies:

1 baseball
1 baseball bat

Procedure: Walk the students carefully through a collision between a ball moving at 100 km/h toward home plate and a bat moving at 100 km/h toward the pitcher. Start in the spectators' reference frame with the baseball and bat moving toward one another. Point out that the closing speed between the two is 200 km/h. Then shift to the bat's frame of reference, in which the bat is stationary, the pitcher (and the whole stadium) is heading toward home plate at 100 km/h, and the ball is heading toward home plate at 200 km/h. Allow the ball to bounce from the stationary bat (assume infinite mass for the bat) and rebound at 100 km/h (assume a coefficient of restitution of 0.5). Now the ball is heading toward the pitcher at 100 km/h while the pitcher is heading toward home plate at 100 km/h, so the closing speed between the two is 200 km/h. Finally, shift back to the spectators' frame of reference. The pitcher is stationary again, so the ball must be heading toward the pitcher at a speed of 200 km/h. The ball is now moving faster than anything else in the stadium!

Explanation: The collision appears simple only in the inertial frame of reference of the bat. In the spectators' frame of reference, the ball and bat are both moving when they collide and the result is somewhat counter-intuitive.

Section 2.3 Centrifuges and Roller Coasters

57. Uniform Circular Motion - Centripetal Acceleration

Description: You keep a large ball circling a marker by pushing it toward the marker as it moves sideways around the marker.

Purpose: To show that an object will travel in a circle only if it experiences a centripetal force that causes it to accelerate toward the center of that circle.

Supplies:

1 large ball (a bowling ball is ideal; an air puck will also work nicely)
1 marker

Procedure: Mark the center of your circle on a table or the floor and start the large ball rolling past it at a distance of a meter or two. Show first that without any horizontal force, the ball travels in a straight line. Now repeat the roll, but begin to push the ball toward the marker as it rolls. The ball will begin to "orbit" the marker. While the pushes you give to the ball tend to upset its rolling, the need for a centripetal force is still fairly evident.

Explanation: An object in uniform circular motion around a center is always accelerating toward that center and thus requires a centripetal force. Without that centripetal force, the object will follow inertia and it will travel in a straight line.

58. A Ball on a String

Description: A rubber ball attached to a string circles your head. The only force on the ball (ignoring gravity) is the inward pull of the string.

Purpose: To show that a centripetal force can cause uniform circular motion.

Supplies:

1 rubber ball attached to a string

Procedure: Swing the ball around your head on the string. Point out that the only horizontal force on the ball is the inward pull of the string. Point out that the ball is always accelerating toward your hand (the center of the circle) because of the inward pull of the string (a centripetal force). Ask the students what will happen if you let go of the string. They should recognize that it will immediately begin to travel in a straight line, continuing forward in the direction it was traveling at the moment you let go of the string. Show them that this is the case.

Explanation: Uniform circular motion involves a centripetal acceleration. For an object to travel in a circle at a uniform speed, it must be experiencing a centripetal force.

59. The Experience of Acceleration

Description: You compare the experience of gravity (your weight) to the experience of acceleration, showing that these experiences are indistinguishable.

Purpose: To show why acceleration gives rise to the same feelings that we associate with weight and gravity.

Supplies:

1 chair

Procedure: Stand motionless on the floor and begin to describe the forces that appear within your body to support your various parts. Note that while gravity acts on each part of your body separately, the floor only supports your feet. As a result, your feet are responsible for supporting your ankles, your ankles are responsible for supporting your lower legs, your lower legs are responsible for supporting your knees, and so on all the way to your head. You can feel all of these parts pushing against one another as they provide this support and those compressive forces are how you experience weight. You are particularly sensitive to the internal forces that support your stomach. Now sit in the chair and imagine that you are accelerating forward in a car or train. Begin to describe the forces that appear within your body as you accelerate forward. Note that the only force acting on your body to make it accelerate forward comes to you from the chair pushing on your back. As a result, your back is responsible for pushing your spine forward, your spin is responsible for pushing your lungs forward, and so on all the way to your chest. You can again feel all of these parts pushing against one another as they provide this accelerating force and these compressive forces are how you experience acceleration. Note that this experience of acceleration is identical to the experience of gravity—you can't tell them apart.

Explanation: Whenever you accelerate, you feel a gravity-like sensation that appears to be pulling your parts in the direction opposite the acceleration. What you are really feeling is those parts resisting the acceleration—they are trying to remain inertial.

60. Spin Drying

Description: A wet towel is swung rapidly in a circle, causing the water to leave it and travel in a straight line.

Purpose: To show how a spin dryer works.

Supplies:

1 wet towel

Procedure: Hold one end of the towel in your hand and swing it rapidly around in a circle. Water will spray off the other end of the towel and travel in a straight line (though it will also fall). Swing it both in a horizontal plane and a vertical plane to show that this effect is essentially independent of gravity.

Explanation: For the far end of the towel to travel in a circle, it must experience a centripetal force. This force is provided by your hand and by the tension in the towel. The water, which is not very well attached to the towel, can break free of the towel and travel in a straight line.

61. A Hand Loop-the-Loop

Description: A book held in your open palm remains in your palm as you move it in a vertical circle, even though the book is beneath your palm as you pass through the top of that circle.

Purpose: To show that an object traveling in a circle is experiencing a centripetal acceleration and that that acceleration can exceed the acceleration due to gravity.

Supplies:

1 book (a medium-sized hardback with a non-slippery cover is best)

Procedure: Place the book on top of your open palm. Now move your palm quickly in a large vertical circle so that your palm is always facing the center of that circle. When you finish, your arm will have become twisted one full turn. If you do this motion quickly enough, the book will follow your palm and will remain pressed against it even as your hand travels over the top of the circle and the book is below your open palm. You can then circle backward to untwist your arm.

Explanation: As long as you make the book accelerate toward the center of the circle faster than the acceleration due to gravity, your palm will have to provide at least part of the centripetal force and the book will remain pressed against your palm.

62. Swinging a Wine Glass on a Pizza Pan

Description: A full wineglass remains in place on a pizza pan as you swing that pizza pan in a vertical circle at the end of a rope. (See photograph on Pg. 77 of the book.)

Purpose: To show that when an object on a platter is made to travel rapidly in a circle, the object experiences a large centripetal acceleration and needs a large centripetal force from the platter. If that centripetal acceleration exceeds the acceleration due to gravity, then the platter will have to push inward on the object and the object will push back on the platter. Even a fluid (wine) in the object will push against the platter and remain in the object.

Supplies:

1 wineglass
1 pizza platter
rope
red wine (or disappearing ink: about 1/4 tsp. of phenolphthalein in 1 liter water, with just enough sodium hydroxide—about 1/16 tsp.—to turn it pink. When exposed to air, carbon dioxide gradually deactivates the sodium hydroxide and renders the mixture colorless.)

Procedure: Attach three pieces of rope to the edge of the pizza platter at three evenly spaced locations and join those ropes together about 0.5 m above the platter. Attach a single rope about 1 m long to the three joined ropes. You should be able to hold that single rope and swing the platter in a vertical circle, and the platter's surface should always face the center of the circle. After some practice with non-fragile objects in the platter, particular with a cup of water, try the wineglass. Starting and stopping are much harder than keeping the wineglass going. You must always let the platter swing freely during the starting and stopping—it will lag behind your hand briefly as you start and it will swing past your hand briefly as you stop. If you let it swing properly, the wineglass will remain in place on the platter and everything will go well. Make sure that when you start aggressively enough that you go over the top of the circle the first time at full speed. If you go slowly over the top of the circle, you'll have a disaster.

Explanation: Traveling in a circle requires a centripetal force. The platter exerts that centripetal force on the wineglass and the wineglass exerts that centripetal force on the wine. Since the wineglass pushes inward on the wine, the wine pushes outward on the wineglass and the two remain pressed against one another, even as they pass upside-down over the top of the circle.

63. A Loop-the-Loop

Description: A car or ball rolls down the hill of a track and then around a circular loop-the-loop. It remains pressed against the track, even at the top of the loop-the-loop.

Purpose: To show that an object traveling in a circle is undergoing centripetal acceleration and requires a centripetal force.

Supplies:

1 car or ball
1 toy track with a hill and a loop-the-loop

Procedure: Assemble the track so that you have a hill and a loop-the-loop. Make sure that the hill is high enough (at least 5/2 as tall as the loop-the-loop) that the car or ball will move fast enough to remain on the loop-the-loop. Now roll the car or ball down the hill and let it go around the loop-the-loop. If it's traveling fast enough, it will remain pressed against the track, even at the top of the loop-the-loop. Now repeat this experiment from lower points on the hill and show that without sufficient speed, the centripetal acceleration will be less than the acceleration due to gravity and the car or ball will begin to fall rather than follow the track.

Explanation: As long as the centripetal acceleration of the car or ball exceeds the acceleration due to gravity, the track will have to provide at least part of the centripetal force on the car or ball and the two will push against one another. Even at the top of the track, the car or ball will remain pressed against the track.

Section 3.1 Balloons

64. Blowing up a Balloon

Description: You inflate an elastic balloon.

Purpose: To show how air pressure can exert forces on surfaces.

Supplies:

1 rubber balloon
1 pump (optional)

Procedure: Stretch the balloon to show that it takes outward forces and work to enlarge the balloon. Now inflate the balloon. Point out that the air that you've pushed into the balloon has provided the outward forces and work needed to stretch the balloon to its new size.

Explanation: By adding more and more air molecules to the volume inside the balloon, you are increasing the pressure inside the balloon. A pressure imbalance appears between the pressure inside the balloon and the pressure outside the balloon, and the balloon's skin experiences outward forces and accelerates outward. While the balloon's own elastic forces tend to oppose this outward acceleration, the balloon gradually grows larger.

65. Gas Pressure as the Result of Molecular Collisions

Description: A number of marbles roll down a ramp and collide with a small barrier, pushing that barrier across the table.

Purpose: To illustrate that air pressure is caused by the impacts of countless air molecules.

Supplies:

50 marbles
1 ramp
1 small (pencil-sized) barrier

Procedure: Place the barrier in front of the ramp and then pour the marbles down the ramp so that they collide with the barrier. The barrier will begin to slide across the table, away from the on-rushing stream of marbles. While this demonstration is representing a moving stream of air colliding with a surface, the collision effects it illustrates are also present in stationary air. You can simulate stationary air by stirring the marbles around with your hand. If they hit the barrier only on one side, they will again push it across the table.

Explanation: The marbles represent air molecules colliding with a surface (the barrier). With enough molecular collisions each second, we can ignore the individual collisions and treat them as exerting a steady pressure on the surface.

Follow-up: An ideal demonstration of pressure would be a stream of tiny pellets colliding with a vertical surface that's attached to a spring scale. The pellets would push the surface forward and the scale would report the amount of force the surface was experiencing. You could then show that the force exerted on the surface is proportional to its surface area—thus justifying the whole concept of pressure.

66. An Animation of Pressure in a Box

Description: You stir marbles about in a glass dish. The more marbles there are in the dish and/or the faster you stir them, the more often and the harder they collide with the walls of the dish.

Purpose: To show that gas pressure increases with the gas's density and temperature.

Supplies:

1 glass baking dish
50 marbles

Procedure: Put a modest number of marbles in the dish and stir them gently with your hand. Point out that each time a marble collides with a wall, it exerts a small outward force on that wall and contributes to the pressure that wall is experiencing. Now stir the marbles faster and point out how the "pressure" is increasing—the marbles hit the walls both more often and harder. Finally, add more marbles to the dish and show that, even when you stir them at the original speed, they still hit the walls more often and thus exert more pressure on the walls.

Explanation: The pressure exerted on the walls depends on how often the air molecules hit and on how much momentum they have when they hit. Increasing the gas's density will increase the frequency of the collisions and increasing the gas's temperature will increase both the frequency of the collisions and the momenta of the molecules when they hit.

67. An Object in a Gas at Uniform Pressure

Description: A block placed in the glass dish (see previous demonstration) doesn't accelerate as long as the pressures on all of its surfaces are equal.

Purpose: To show why the objects around us are essentially unaffected by atmospheric pressure.

Supplies:

- 1 glass baking dish
- 50 marbles
- 1 small block that fits easily into the dish

Procedure: Put the block in the center of the dish and stir the marbles evenly about the dish so that they collide uniformly with the block's surfaces. If you balance the impacts pretty well, the block will stay relatively still.

Explanation: Although the block is experiencing inward forces on all of its surfaces, these forces cancel on average and the block doesn't move.

Follow-up: Discuss Brownian motion—if the "block" were small enough, the collisions with air molecules would become relatively rare and they wouldn't always cancel perfectly on a small time scale. The "block" would exhibit small motions that depend on its size and on various characteristics of the air molecules.

68. Air Pressure and Temperature

Description: A metal ball with helium gas inside and a pressure gauge on it is immersed in liquid nitrogen. The pressure in the ball drops.

Purpose: To show that cooling a gas without changing its density slows the gas's molecules and decreases the pressure of that gas.

Supplies:

- 1 hollow metal sphere with a pressure gauge attached and helium gas inside (typical physics demonstration equipment)
- 1 container of liquid nitrogen (or ice water, in a pinch)

Procedure: Observe the pressure of the helium inside the sphere before you cool it. Now immerse the sphere in the liquid nitrogen and observe how the pressure of the helium inside the sphere drops.

Explanation: All of the helium atoms are still inside the sphere—it's just that they're traveling more slowly. They hit surfaces less often and exchange less momentum with those surfaces when they hit. As a result, the pressure of the helium gas is less.

Follow-up: Discuss what would happen if you tried this same experiment with air inside the sphere.

69. Cooling a Helium Balloon

Description: A helium balloon is immersed in liquid nitrogen and shrinks to about a quarter of its normal size. When the balloon is removed from the liquid nitrogen, it reinflates and eventually lifts itself up into the air.

Purpose: To show that cooling a gas slows its molecules so that they must become more dense in order to have the same pressure as before. To show that cooling a gas without changing its pressure causes the gas's density to increase.

Supplies:

- 1 latex rubber helium balloon
- 1 container of liquid nitrogen (wide enough to accommodate the balloon)

Procedure: Show that you have a helium balloon by letting it float briefly. Now immerse the balloon carefully into the liquid nitrogen (don't freeze your skin) and observe how the balloon becomes much smaller. The balloon will eventually reach about a quarter of its original size. Now remove the balloon from the liquid nitrogen and allow it to warm up on the table. Once the balloon is almost back to its original size, it will become buoyant enough to rise up into the air.

Explanation: Cooling the helium gas slows its atoms so that its pressure begins to fall and the surrounding atmosphere compresses the balloon. The result is that the balloon's volume decreases while the pressure of the cooling helium inside it remains nearly constant. The helium gas becomes more and more dense. When you then warm up the helium gas, its pressure increases and it pushes the walls of the balloon outward. The balloon's volume increases so that the pressure inside the balloon remains nearly constant.

70. Cooling an Air-filled Balloon

Description: An air-filled balloon is immersed in liquid nitrogen and shrinks to very small size. When the balloon is removed from the liquid nitrogen, it reinflates.

Purpose: To show that cooling air slows its molecules so that they must become more dense in order to have the same pressure as before. When the molecules have slowed sufficiently, they condense into a liquid, with a dramatic decrease in volume.

Supplies:

1 latex rubber balloon
1 container of liquid nitrogen (wide enough to accommodate the balloon)

Procedure: Inflate the balloon, tie it off, and immerse the it carefully into the liquid nitrogen (don't freeze your skin). The balloon will become much, much smaller. Now remove the balloon from the liquid nitrogen and allow it to warm up on the table. It will eventually return to its original size.

Explanation: Cooling the air slows its molecules so that its pressure begins to fall and the surrounding atmosphere compresses the balloon. The result is that the balloon's volume decreases while the pressure of the cooling air inside it remains nearly constant. Below a certain temperature, the air inside the balloon begins to condense—the molecules begin to stick to one another to form a liquid. When that happens, the volume of material inside the balloon drops dramatically. When you then warm up the air in the balloon, it converts back into a gas, its pressure increases, and it pushes the walls of the balloon outward. The balloon's volume increases so that the pressure inside the balloon remains nearly constant.

71. Overfilling a Balloon with Air

Description: You repeatedly add air to a balloon and liquefy that air in liquid nitrogen. After finally tying off the balloon, you allow it to warm up on the table and it eventually explodes.

Purpose: To show that, when its density and pressure are sufficiently high, a gas can exert enormous pressures—and cause things to explode.

Supplies:

1 uninflated latex balloon (a long, thin one works well)
1 container of liquid nitrogen (wide enough to easily accommodate the balloon)
safety glasses

Procedure: Blow up the balloon and pinch the nipple to keep the air inside. Now carefully immerse the other end of the balloon in the liquid nitrogen and allow the air inside it to liquefy. Quickly remove the balloon from the liquid nitrogen and blow more air into the balloon. Return the end of the balloon to the liquid nitrogen so that the added air liquefies. Repeat this procedure a total of about 10 times. Finally, tie off the balloon and place it on the table. It will inflate itself to giant size and eventually burst.

Explanation: Cooling the air inside the balloon removes much of its thermal energy. Exposed as it is to atmospheric pressure, the balloon collapses as it cools. The air inside the balloon first becomes denser and then begins to liquefy. Because liquid air occupies so much less volume than gaseous air, even at lower temperatures, you can put a considerable number of air molecules into the balloon as liquid air. When this liquid air turns back into gaseous air and the temperature of this gaseous air returns to room temperature, the molecules will either occupy a very large volume (if their pressure is roughly atmospheric) or have an enormous pressure (if the volume they can occupy is very limited). In this case, the air's volume and pressure both increase until the balloon's skin rips.

72. Magdeberg Hemispheres - Atmospheric Pressure

Description: Two half-spheres are joined together and the air is removed from between them. With no air inside the sphere, its halves can't be separated by hand.

Purpose: To show that atmospheric pressure exerts enormous forces on large surfaces.

Supplies:

1 set of Magdeberg hemispheres
1 vacuum pump

Procedure: Show that the two hemispheres don't normally stick to one another when you simply touch them together. Then touch them together and remove the air from inside the overall sphere with the vacuum pump. Point out that you are removing the air by allowing the air molecules to bounce out through a hole in the spheres and into a machine that prevents them from returning (i.e. you aren't "sucking" the air out of the sphere). Once there is a vacuum inside the sphere, seal off the sphere and allow two students to try to pull the hemispheres apart. Note that the two hemispheres are being pressed together so strongly by the surrounding air pressure that they are inseparable. Now allow air to reenter the sphere and show that the hemispheres separate easily.

Explanation: When there is no air inside the sphere, the enormous inward forces exerted by air pressure on the outer surfaces of the hemispheres aren't balanced by outward forces exerted by air inside the hemispheres. Only when air is allowed to reenter the sphere do the outward forces reappear and make it easy to separate the hemispheres.

73. Bubbles in a Vacuum

Description: Balloons, marshmallows, and shaving cream expand to enormous sizes in a vacuum chamber.

Purpose: To show a bubble's size depends on a balance of forces and that when the pressure around the bubble is reduced, the bubble's size increases.

Supplies:

- 1 air-filled balloon
- 1 marshmallow (we put several marshmallows on a wire frame to create a person-shaped object known as "marshmallow man.")
- 1 sandwich filled with marshmallow cream
- 1 small container filled with shaving cream
- 1 bell jar and vacuum pump

Procedure: First put the balloon in the bell jar and gradually remove the air from around the balloon. As the pressure surrounding the balloon falls, the unopposed pressure inside the balloon will cause it to grow in size. Eventually, the balloon will burst. Now repeat this same experiment with the other objects (each of which contain many tiny bubbles). Each will grow to giant size before its bubbles begin to burst. This bursting is most noticeable for a marshmallow—after growing steadily for a while, its size will abruptly shrink. Once this shrinkage has occurred, let the air return to the bell jar. The object will shrink dramatically as its bubbles are crushed by the surrounding air pressure. Marshmallows become withered, ancient-looking things.

Explanation: When you remove the air from around a bubble, only the bubble's elastic character remains to oppose the outward pressure of the gas inside the bubble. The gas inside the bubble pushes its walls outward until they burst.

74. Buoyancy and Archimedes Principle

Description: A cylindrical weight is suspended from a cylindrical container of the same size, which is itself suspended from a spring scale. When the cylindrical weight is submerged in water, the weight reported by the scale decreases. But when the cylindrical container is then filled with water, the weight reported by the scale returns to its original value.

Purpose: To show that an object that is displacing water in a container experiences an upward buoyant force that's equal in magnitude to the weight of the water it's displacing.

Supplies:

- 1 cylindrical weight
- 1 cylindrical container of exactly the same volume (it should be able to fit around the weight exactly—so that it's internal volume is equal to the overall volume of the weight)
- 1 spring scale
- 1 support for the spring scale
- 1 container of water (large enough to hold the cylindrical weight under water)
- 1 support for the container of water
- 1 cup of water (for filling the cylindrical container)

Procedure: Suspend the spring scale from the support, suspend the cylindrical container from the spring scale, and suspend the cylindrical weight from the cylindrical container. Observe the weight of the two cylindrical objects on the spring scale. Now raise the container of water so that the cylindrical weight is entirely immersed in the water and place the support under the container of water. The scale will now read less than the weight of the two cylindrical objects. Point out that the water in the container is exerting an upward buoyant force on the cylindrical weight so that the scale doesn't have to pull upward as hard to support the cylindrical weight. Now fill the cylindrical container with water. The scale will report the original value. Evidently, the upward buoyant force on the cylindrical weight is exactly equal in magnitude to the weight of an equal volume of water.

Explanation: The buoyant force experienced by an object immersed in water is equal in magnitude to the weight of the water it displaces.

75. A Hot Air Balloon

Description: Hot air from a heat gun is directed into a large, thin-walled plastic bag. The bag inflates and, when released, floats upward to the ceiling.

Purpose: To show that hot air is less dense than cold air at the same pressure.

Supplies:

1 hot air balloon—a very thin-walled plastic bag. Scientific supply companies sell a solar-heated hot air balloon (a dark, ultra-thin bag that rises when sunlight heats the air it contains) that works very well, but even a dress-sized (full length) dry cleaning bag works adequately.
1 powerful hairdryer with several heat settings

Procedure: Insert the hairdryer into the mouth of the plastic bag and begin to inject hot air into the bag. Use a medium power setting until the bag is fairly fully inflated so that you don't melt the plastic. Once the bag is relatively inflated, switch to the highest heat setting. Continue to blow hot air into the bag until all the air inside the bag is hot. If you're using a dry cleaning bag, you can seal the bottom of the bag around the neck of the hairdryer and allow air to flow out of the small hanger hole at the other end of the bag. If your using a solar hot air balloon, leave some space so that cold air can escape as hot air enters the balloon. Once the bag is completely full of hot air, let it go and it should rise up into the air. The solar hot air balloon will float all the way to the ceiling, while a dry cleaning bag will rise several meters upward before it collapses. Point out that the pressures inside and outside the bag are equal—if they weren't, air would accelerate toward the lower pressure.

Explanation: The hot air inside the bag is less dense than the cooler air around it. Because there are fewer air molecules in the bag than there would be if the bag were full of cooler air, the bag's overall weight is less and it's pushed upward by the buoyant force.

76. A Helium Balloon

Description: An elastic balloon is filled with air, tied off, and released. It slowly sinks downward. A second balloon is filled with helium. This balloon floats upward.

Purpose: To show that helium gas is less dense than air at the same pressure.

Supplies:

1 tank of helium
2 balloons

Procedure: First fill a balloon with air, tie it off, and release it. It will sink because its average density is slightly greater than that of air. Now fill the second balloon with helium, tie it off, and release it. It will float upward.

Explanation: The number of helium atoms in the second balloon is the same as the number of air molecules in the first balloon. However, helium atoms weigh much less than the average air molecule, so the overall weight of the helium balloon is much less than that of the air-filled balloon. While the air-filled balloon's average density is slightly higher than that of air—the balloon's skin contributes much of this excess density—the helium balloon's average density is well below that of air.

77. A Helium Balloon in Helium

Description: A helium balloon is floating at the top of a clear jug that's only open at the bottom. When helium gas is introduced into the jug and the air is expelled, the helium balloon no longer floats.

Purpose: To show that the buoyant force exerted by helium gas is less than the buoyant force exerted by air.

Supplies:

1 helium-filled balloon
1 large transparent container
1 tank of helium

Procedure: Invert the container, so that the closed end is on top, and put the helium balloon inside it. The balloon will float to the top of the container. Now spray helium gas into the container from below. The air will be displaced and the container will soon be full of helium. The helium balloon will sink to the bottom of the container.

Explanation: The buoyant force on the helium balloon depends on what gas it's displacing. When the balloon is displacing air, the buoyant force is relatively large and is large enough to support it against gravity. But when the balloon is displacing helium, the buoyant force is much smaller and the helium balloon sinks.

Follow-up: Discuss what would happen to a hot air balloon if it were to drift into a region of very hot air? Why do balloonists prefer to fly in cold weather?

78. Helium-filled Soap Bubbles

Description: Soap bubbles filled with air sink slowly to the ground. But soap bubbles filled with helium rise rapidly.

Purpose: To show that the upward buoyant force on a helium bubble greatly exceeds its downward weight.

Supplies:

- 1 tank of helium
- 1 small plastic funnel
- 1 container of soap solution (a mixture of 1 part Joy detergent, 2 parts glycerin, and 3 parts water works well)
- 1 hose
- 1 plastic ring for blowing bubbles

Procedure: First dip the plastic ring in the soap solution and blow some normal bubbles (air-filled bubbles). In calm air, they will slowly settle downward. Now use the hose to attach the funnel to the helium tank and dip the wide end of the funnel in the soap solution. Lift the funnel out of the soap and observe that a film has formed across its mouth. Turn on a gentle flow of helium so that the soap film gradually inflates. With a flick of your wrist, break off a helium-filled bubble and watch it float upward to the ceiling.

Explanation: While a helium-filled bubble and an air-filled bubble of the same size contain the same number of particles, the helium atoms in the helium-filled bubble are much lighter than the air molecules in the air-filled bubble. While the air-filled bubble has an average density just slightly greater than that of the surrounding air, the helium-filled bubble has an average density that is substantially less than that of the surrounding air.

79. Methane-filled Soap Bubbles

Description: Soap bubbles filled with methane (natural gas) rise rapidly until they are ignited. They then burn with a large orange flame.

Purpose: To show that the upward buoyant force on a methane bubble exceeds its downward weight.

Supplies:

- 1 small plastic funnel
- 1 source of methane gas (natural gas—*not* propane!)
- 1 hose
- 1 container of soap solution (a mixture of 1 part Joy detergent, 2 parts glycerin, and 3 parts water works well)
- 1 stick about 1 meter long
- 1 spring-loaded clothespin (optional)
- 1 small (birthday) candle
- 1 large candle
- 1 base for large candle
- tape

Procedure: Be careful—do this experiment only in a room with a high ceiling and no flammable materials around! Use the hose to attach the funnel to the source of methane. Mount the large candle on its base and light the candle. Attach the clothespin to the stick with tape and use it to grab the small candle (or simply tape the small candle to the stick). Light the small candle with the big candle.

Now turn on a gentle flow of natural gas, but keep the two candles well away from the gas flow. Dip the wide end of the funnel briefly into the soap solution and allow a methane-filled bubble to form. When the bubble is reasonably large, flick your wrist to break the bubble free from the funnel. It will float upward rapidly. When it's a safe distance from you, the funnel, and any flammable materials, ignite the bubble with the small candle on the stick. It will burn with a surprisingly large, orange flame. Be sure that the bubbles always fill with essentially pure methane and never a mixture of methane and air—such a mixture can be explosive.

Explanation: A methane molecule (CH_4) is lighter than the average air molecule. Thus a methane-filled bubble has an average density that is well below the density of air.

Section 3.2 Water Distribution

80. Water in a Horizontal Straw

Description: When you hold a water-filled straw horizontally, the water remains stationary.

Purpose: To show that when a fluid in a horizontal pipe experiences equal pressures at both ends, it doesn't accelerate.

Supplies:

1 clear drinking straw
colored water

Procedure: Fill the straw with water by dipping it in the colored water, sealing one end with your finger, lifting it out of the colored water, turning it horizontally, and finally releasing the seal. The water will remain motionless in the horizontal straw.

Explanation: With the water's weight being supported by the wall of the horizontal straw, the water's acceleration is determined only by the pressures at its two ends. Since those pressures are equal, the forces on the two ends of this little column of water cancel one another perfectly and the net force on the water is zero. It doesn't accelerate.

81. Water in a Vertical Straw

Description: When you hold a water-filled straw vertically, the water falls downward. Only when you seal the bottom or top of the straw, thereby allowing a pressure imbalance to develop, does the water stop falling.

Purpose: To show that when a fluid in a vertical pipe experiences equal pressures at both ends, it's weight causes it to accelerate downward and to show that it can only be prevented from falling by allowing the pressure at the bottom of the water to become greater than the pressure at the top of the water.

Supplies:

1 clear drinking straw
colored water

Procedure: Fill the straw with water by dipping it in the colored water, sealing one end with your finger, lifting it out of the colored water, and turning it so that your finger is at the bottom of the vertical straw. After holding it there for a second, release the seal that your finger is making and allow the water to fall out of the straw. Point out that the pressures at the top and bottom of the column of water are the same, so that the water experiences no overall force due to pressure, but that the water's weight causes it to fall. Now show that as long as you seal either the top or the bottom of the straw, the water won't fall. Note that when you seal the bottom of the straw, the weight of the column squeezes the water at the bottom of the straw so that the pressure there rises above atmospheric pressure. A pressure imbalance develops between the top and bottom of the water column so that there is just enough upward force due to pressure to support the column's weight. Then note that when you seal the top of the straw, the water initially begins to fall but as it does, the pressure at the top of the column of water drops below atmospheric pressure. Again, a pressure imbalance develops between the top and bottom of the water column so that there is just enough upward force due to pressure to support the column's weight. But whenever you release the seal, whether at the bottom or the top of the straw, the pressure imbalance vanishes and the water falls.

Explanation: To support a column of water in a vertical pipe, the pressure in the column must increase by 10,000 Pa for each meter of depth. Without such a pressure increase, the water will fall.

82. Water Seeks Its Level

Description: A collection of oddly shaped water containers (Pascal's vases), that are connected at their bottoms, is gradually filled with colored water. The water always flows through the connections so that the water levels in each container are exactly equal.

Purpose: To show that water will naturally flow until its surface is uniformly at the same height.

Supplies:

1 set of Pascal's vases (alternatively, several containers that are connected together with hoses at their bases)
1 pitcher of colored water

Procedure: Slowly pour the colored water into one of the vases. As the height of water in that vase rises, the pressure at the bottom of that vase will also rise and the water will begin to flow through the connections to the other vases. If you proceed slowly enough, the water levels in all the vases will remain essentially equal. When you stop pouring, the water levels will soon become exactly equal.

Explanation: If the water level in one of the vases is higher than in the others, the pressure at the bottom of that vase will exceed the pressures in the other vases. Water will accelerate toward the less deeply filled vases and their water levels will soon rise. Only when the water levels are exactly equal will there be no pressure imbalances and no flow between vases.

83. Simulating a Water Cooler

Description: A full bottle of water is inverted and its mouth is placed in a shallow container of water. The water remains inside the bottle of water. Only when an air bubble is allowed to enter the bottle of water will the level of water in that bottle descend.

Purpose: To show that water falling out of an inverted bottle causes a natural pressure imbalance to develop and to support that water.

Supplies:

1 narrow-mouthed bottle, full of water
1 shallow pan of water

Procedure: Invert the bottle of water and immediately put its mouth below the surface of the water in the shallow pan. The water won't descend out of the bottle because the pressure inside the top of the bottle quickly drops below atmospheric pressure. The resulting pressure imbalance supports the water against the force of gravity. But when you lift the bottle high enough to allow an air bubble to enter its mouth, the water will descend and some of it will flow out of the bottle.

Explanation: The number of air molecules trapped between the water and the top of the bottle is limited and as the water falls downward in the bottle, those air molecules spread out into a greater volume. As the gas's density drops, its pressure also drops and soon the pressure inside the top of the bottle is significantly below atmospheric pressure. With atmospheric pressure pushing upward on the water at the mouth of the bottle and less than atmospheric pressure pushing downward on the water at the top of the bottle, the water is experiencing enough upward force due to pressure to prevent it from descending further. But whenever an air bubble is allowed to enter the bottle, these additional air molecules increase the pressure at the top of the bottle and allow more water to descend out of it.

84. A Siphon

Description: Two containers of water are connected by a water-filled tube. When one container is raised so that the levels of water are different in the two containers, water flows from the higher container to the lower one until their water levels are again equal.

Purpose: To show that the tendency of water to level its surface even applies when the water must flow upward a short distance to flow between two containers.

Supplies:

1 clear plastic hose
2 containers
color water
1 support block

Procedure: Fill both containers with colored water. Now fill the hose with water and insert its ends in the two containers. Water will flow through the hose until the water levels in the two containers are equal. If you now raise one of the containers by placing the block under it, water will flow out of that container through the hose and into the lower container until their water levels are again equal.

Explanation: The top surface of the water in each container is at atmospheric pressure. When those surfaces are at the same height, the water at the highest point in the hose isn't experiencing any pressure imbalance. That's because its heights above the atmospheric pressure levels in the two containers are equal. But when one surface is lower than the other, the pressures on opposite sides of the highest point of the hose are no longer balanced and water accelerates toward the side with the lower water level. Even though the hose may meander up and down on its way between the two containers, what matters most is the height difference between the atmospheric pressure water at the top of one container and the atmospheric pressure water at the top of the other container.

85. Sucking Water up a Straw

Description: You suck water up a straw.

Purpose: To show that when you remove the air from the top of a straw, the atmospheric pressure at the bottom of the straw pushes the water up the straw.

Supplies:

1 clean, clear drinking straw
1 clean container

food-colored water (potable) or a colored beverage

Procedure: Insert the straw into the container of colored water and suck the water into your mouth. Point out that you aren't "attracting" the water toward your mouth—you are reducing the pressure inside the top of the straw so that the pressure at the bottom of the straw can push the water upward toward your mouth.

Explanation: By expanding the volume inside your mouth and the top of the straw, you reduce the density of the air trapped inside that volume and reduce its pressure. Since the atmospheric pressure at the bottom of the straw doesn't change, there is a pressure imbalance. This pressure imbalance exerts enough upward force on the column of water in the straw to lift it upward to your mouth.

86. Sucking Water up a Giant Straw

Description: You suck water up a very tall hose and have great difficulty raising it more than about 8 m. (This experiment requires a tall lecture hall, with access to the upper space at the front of the hall.

Purpose: To show that because atmospheric pressure is limited, it can't support a column of water that's taller than about 10 m, even when there is no pressure above that column.

Supplies:

1 clean, clear plastic hose, about 10 m long
1 clean container
food-colored water (potable) or a colored beverage

Procedure: Hang the hose vertically from the upper space of the room and insert the bottom of the hose into the container of colored water. Go up to the top of hose and suck the water toward your mouth. Again, point out that you aren't "attracting" the water toward your mouth—you are reducing the pressure inside the top of the hose so that the pressure at the bottom of the straw can push the water upward toward your mouth. As the water column gets taller, you will have more and more trouble making it rise. While you may be able to draw a column 8 m high, you won't be able to reach or exceed 10 m.

Explanation: By expanding the volume inside your mouth and the top of the straw, you reduce the density of the air trapped inside that volume and reduce its pressure. Since the atmospheric pressure at the bottom of the hose doesn't change, there is a pressure imbalance. This pressure imbalance exerts enough upward force on the column of water in the straw to lift it upward to your mouth. But the highest that atmospheric pressure can lift the water is 10 m, even if you remove all of the air molecules from above the water column. Since your mouth isn't capable of reaching a complete vacuum, you can't suck the water upward even 10 m.

87. Turning Pressure Potential Energy into Kinetic Energy

Description: You squeeze a water-filled eye-dropper and a jet of high-speed water sprays out of its nozzle.

Purpose: To show that pressurized water converts its pressure potential energy into kinetic energy as it speeds up in flowing through a nozzle.

Supplies:

1 eyedropper (or better still, a rubber bulb with a pipet attached to it)
water

Procedure: Fill the eyedropper completely full with water. Hold the eyedropper horizontally and squeeze its bulb hard. The pressurized water will flow slowly through the eyedropper until it enters the narrow nozzle. There its speed will increase and its pressure will decrease—it will exchange pressure potential energy for kinetic energy—and it will spray across the room.

Explanation: As it flows slowly through the eyedropper, the water is under substantial pressure and has considerable pressure potential energy. But as it flows through the nozzle, its speed must increase in order for enough water to make it through the narrowing each second. As the water's speed increases, its pressure decreases—as required by Bernoulli's equation, it's exchanging pressure potential energy for kinetic energy. The water spraying through the air is at atmospheric pressure, so all of its pressure potential energy has become kinetic energy.

Follow-up: Spray the water straight up. Now its kinetic energy will gradually become gravitational potential energy!

88. Turning Gravitational Potential Energy into Kinetic Energy

Description: Water stored in an elevated container flows down a hose to a narrow nozzle. It sprays upward from the nozzle, almost returning to the height of the container.

Purpose: To show that a flowing fluid can convert its energy between gravitational potential energy, pressure potential energy, and kinetic energy.

Supplies:

1 water container with a spigot at the bottom
1 hose
1 nozzle (an eyedropper tube will do nicely)
1 tall support for the water container
1 low support for the nozzle
1 pitcher of water

Procedure: Use the hose to connect the nozzle to the water container's spigot. Elevate the water container and support the nozzle so that it points straight upward. Now pour water into the water container and allow it to flow downward to the nozzle. Water will begin to spray upward from the nozzle and will rise almost to the height of the water container.

Explanation: The water in the container has gravitational potential energy. The water's gravitational potential energy decreases as the water descends through the hose, but its pressure and pressure potential energy increase. By the time the water reaches the nozzle, its pressure is relatively high. As the water flows through the nozzle, its pressure drops to atmospheric pressure and its speed and kinetic energy increase to compensate for the decrease in pressure potential energy. The spraying water then rises upward, exchanging its kinetic energy for gravitational potential energy. The fact that the water doesn't quite reach its original height reflects the total energy lost by the water as it flows through the system. Because the water flows relatively slowly through the hose, it doesn't lose very much energy to friction with the walls. However, it loses enough in flowing rapidly through the nozzle and the air that it can't rise back to full height.

Follow-up: Try the same experiment, but with a very long hose and a water container that's 8 or 10 m above the nozzle. The height of the spray from the nozzle is impressive.

89. The Absence of a Pressure Gradient in Free Fall

Description: A large cup of water has two holes in its lower sides through which water squirts. But when the cup is dropped, the water stops squirting out of the holes.

Purpose: To show that the elevated pressure at the bottom of a cup of water disappears when the cup of water is falling.

Supplies:

1 plastic or Styrofoam cup with two small holes pierced on opposite sides about a centimeter from the bottom of the cup
1 stool or ladder
water

Procedure: Cover the two holes with your fingers and fill the cup with water. Climb onto the stool or ladder. Now uncover the holes and water will begin to squirt out of the holes. Point out that this water is propelled outward by the elevated pressure near the bottom of the water. Now drop the cup. As it falls, the pressure inside the cup will be uniform—all the water will be at atmospheric pressure. With no elevated pressure inside the cup, water will no longer squirt out of the holes.

Explanation: When the cup is motionless, an elevated pressure develops at the bottom of the cup as the water there acts to support the water above it. It's this elevated pressure that causes the water to accelerate toward the holes and squirt out into the air. But when the cup is in free fall, the water at the bottom of the cup no longer has to support the water above it. No pressure gradient develops and the water is uniformly at atmospheric pressure inside the cup. Without any pressure imbalance between the atmospheric pressure water near the bottom of the cup and the atmospheric pressure air outside the holes, the water doesn't accelerate toward the holes as the cup falls. No water squirts out into the air.

Section 4.1 Water Faucets

90. A Vortex Cannon

Description: A large cylinder with a small circular opening in front has a flexible rubber diaphragm on its back. When the diaphragm is pushed inward rapidly, a vortex of air leaps out of the circular opening and travels across the room. When smoke is introduced inside the cylinder, the vortices appears as giant smoke rings.

Purpose: To show that even air has remarkable and interesting dynamics.

Supplies:

1 5-gallon plastic paint or other liquid container (although even a cardboard box will do)
1 flexible rubber sheet, large enough to seal the open end of the cylinder

1 clamping system to hold the sheet across the open end of the cylinder (or use tape)
elastic bands (optional)
smoke generator (optional—we use a hand-operated balloon pump to push air first through a bottle containing a small quantity of hydrochloric acid and then through a bottle containing a small quantity of household ammonia; when the air emerges from the second bottle, it's filled with tiny particles of ammonium chloride and makes a dense, white smoke)

Procedure: Carefully cut a circular opening about 10 cm in diameter in the center of the plastic container's bottom. Stretch the rubber sheet across the open end of the cylinder and clamp it into place. (We have done this by cutting out the center portion of the container's top and then forcing the top onto the container so that it clamps the rubber sheet in place.) If you now hold the container horizontally and strike the rubber sheet firmly, it will emit vortex rings that travel across the room. We have attached several rubber bands to the rubber sheet in our device, so that these rubber bands pull the sheet toward the circular opening. To create vortex rings, you pull the rubber sheet out of the cylinder and let go. The rubber bands pull the sheet back into the cylinder and a vortex ring emerges from the cylinder. If you fill the vortex cannon with smoke before making vortex rings, they will appears a beautiful smoke rings.

Explanation: As air flows out of the relatively small hole in the vortex cannon, friction with the opening causes the air to form a twisting ring—a vortex ring.

91. Water Flow through Tubes of Different Diameters

Description: Water flowing out of a wide pipe attached to the bottom of a water container flows much more quickly than water flowing out of a narrow pipe attached to that same container.

Purpose: To show that the diameter of a water pipe dramatically affects the rate at which water flows through that pipe, for a given pressure imbalance.

Supplies:

1 container with a hole in the side, about 1 cm above the bottom (a plastic cup, for example)
2 corks that fit into the hole
1 narrow tube about 10 cm long
1 wider tube about 10 cm long

Procedure: Fit the two tubes into the two corks. Insert the wider tube into the hole in the container and fill the container with water. Water will flow rapidly through the wide tube and the container will drain quickly. Now insert the narrow tube into the container and refill the container. The water will flow much more slowly and the container will drain very slowly.

Explanation: In both cases, there is a specific pressure imbalance between the elevated pressure inside the container and the atmospheric pressure at the end of the tube. But since the amount of water that can pass through a tube experiencing laminar flow depends on the 4^{th} power of the tube's diameter, the narrower tube carries far less water than the wider tube.

92. Laminar vs. Turbulent Flow - Reynolds Number

Description: A cylindrical stick is drawn slowly through a container of water and leaves no visible wake. But when the stick is drawn quickly through the water, the water swirls behind it.

Purpose: To show the onset of turbulent flow when the Reynolds number exceeds about 2000.

Supplies:

1 cylindrical stick about 1 or 2 cm in diameter
1 container of water
1 overhead projector (optional)

Procedure: First move the stick slowly through the water. Below about 10 cm/s, the Reynolds number will be below 2000 and the flow around it will be laminar. You will see little disturbance in the water. Now move the stick more rapidly—about 50 cm/s. The water will become turbulent behind the stick because the Reynolds number will have reached 5000 or more.

Explanation: The flow around the stick is laminar below a Reynolds number of about 2000 and turbulent above a Reynolds number of about 5000. The faster the stick moves through the water, the higher the Reynolds number and the more likely the flow is to be turbulent.

Follow-up: You can also do this experiment by putting a shallow circular dish of water on a turn-table and lowering the stick into it on a support. The faster you spin the water dish, the faster the water moves past the stick and the more likely it is to exhibit turbulent flow. However, getting the water to spin with the dish isn't so easy. Special rheological fluids are also available that help in flow visualization.

93. Water Hammer Demonstration Toy

Description: When you shake a water-filled glass object, it emits a sharp ping sound, as though it were struck with a solid object.

Purpose: To show that water can exert a sudden impact on a solid surface.

Supplies:

1 water hammer demonstrator from a scientific supply company

Procedure: Hold the demonstrator vertically, with the long tube end down and the air bubble end on top. Accelerate the demonstrator downward rapidly and then stop abruptly. The water will strike the bottom of the demonstrator and emit a sharp ping sound when it hits.

Explanation: When you accelerate the glass container downward, the water is left behind. It drifts toward the air bubble on top and compresses the air in that bubble. When the glass container stops accelerating downward, the pressure imbalance around the water—high pressure above and almost zero pressure below—propels the water downward until it overtakes the bottom of the container. The water strikes the bottom of the container hard enough to create the ping sound.

94. Knocking the Bottom out of a Bottle with Water

Description: A root beer bottle full of water is held upright in your hand while you strike its cap with a rubber mallet. The bottom of the bottle drops out with a loud pop, and water and glass drop into a bucket.

Purpose: To demonstrate the effects of water hammer.

Supplies:

1 glass root beer bottle, filled to the base of the neck with water and sealed on top with either the original cap or with plastic wrap and a rubber band
1 rubber mallet
1 bucket or trash receptacle

Procedure: Hold the root beer bottle upright in one hand, gripping it around the body of the bottle, and strike the top of the bottle firmly with the mallet. A gentle hit will cause the bottle to emit a loud ping sound. A strong hit will knock the bottom out of the bottle. Hold the bottle over the bucket, so that the broken glass and water have somewhere to go.

Explanation: When you strike the top of the bottle, the glass container accelerates downward very suddenly. The water, which is not directly attached to the container, remains essentially in place and enters the neck of the bottle as the bottle shifts downward. Since there is air already in the neck of the bottle, that air becomes compressed. When the bottle stops accelerating downward, the elevated pressure in the neck of the bottle and the near absence of pressure at the bottom of the bottle cause the water to accelerate downward, toward the bottom of the bottle. When the water reaches the bottom of the bottle, the pressure at the bottom surges upward and the enormous force on the bottom of the bottle exceeds its breaking strength. The bottom of the bottle tears away for the sides and the water pours out into the bucket.

Section 4.2 Vacuum Cleaners

95. Speed and Pressure of Air Flowing in a Tube

Description: The pressure of air flowing through a tube changes as the tube's diameter changes—dropping as the tube becomes narrower and rising as the tube becomes wider.

Purpose: To show that air's pressure drops when it speeds up to pass through a narrow channel and that its pressure rises when it slows down to pass through a wide channel.

Supplies:

1 Bernoulli demonstrator—a pipe with a narrow channel near its middle and several pressure monitoring points along its length
compressed air

Procedure: Attach the compressed air to the Bernoulli demonstrator and allow that air to flow through the tube. Observe that the pressure inside the demonstrator rises at any wide portion of the tube and drops at any narrow portion of the tube. Note also that the pressure in the wide portions before and after a narrow channel are different—the pressure is higher before the narrow channel than after the narrow channel (due to energy loss in the channel).

Explanation: Whenever air flows through a narrow channel, it speeds up to allow the same volume of air to flow through the narrow channel each second as flows through the wider portions of the tube each second. When the air speeds up, its pressure drops so that most of its total energy can become kinetic energy. When the air in the narrow channel then enters the wider portion of the tube, it slows down and its pressure rises as its kinetic energy becomes pressure potential energy. The pressure doesn't reach its original value because the high speed air in the narrow channel loses a substantial amount of its energy through friction with the walls of the narrow channel.

96. Two Plates Stick to One Another as Air Flows Between Them

Description: Compressed air is allowed to flow out of a hole in the center of a plastic plate. When a second plate is placed a short distance away from the hole, it's blown away from the hole. But when the second plate is touched to the first plate, the two plates are suddenly pressed together by the surrounding air.

Purpose: To show that when air speeds up to flow through the narrow gap between two plates, its pressure drops dramatically and can even fall below atmospheric pressure.

Supplies:

2 flat plastic plates, about 20 cm on a side. One should have a hole drilled in it and a hose attached to the hole. The other should have a metal pin inserted into it.
compressed air

Procedure: Attach the hose to the compress air and allow the air to flow out of the hole. Show that as the second plate approaches this hole, it's blown away by the rushing air. Now touch the two plates together and allow the pin of the second plate to enter the hole in the first plate. This pin keeps the second plate from sliding off the first plate. The two plates will remain together despite the continued flow of air out of the hole in the first plate. In fact, the two plates will "stick" together!

Explanation: When the air in the hose flows into the narrow gap between the two nearby plates, it speeds up and its pressure drops below atmospheric pressure. The atmospheric pressure on the outside surfaces of the two plates then squeezes the plates together. The spacing between the plates self-regulates so that the pressure between them is just low enough to keep the second plate from moving closer or farther from the first plate. The two plates stay together even when the second plate is hanging below the first plate. In that case, the pressure between the plates drops below atmospheric pressure, providing a pressure imbalance that supports the weight of the second plate.

97. A Ping Pong Ball Suspended by Air in an Inverted Funnel

Description: An inverted plastic funnel is attached to a compressed air source and a Ping Pong ball is inserted into the wide opening of the funnel. The Ping Pong ball hangs suspended in the funnel as air flows downward around its sides.

Purpose: To show that air's pressure drops as it speeds up to flow through a narrow channel.

Supplies:

1 small plastic funnel
1 hose
1 Ping Pong ball
compressed air

Procedure: Use the hose to attach the funnel to the compressed air. Hold the funnel upside down and start the compressed air flowing. Push the Ping Pong ball upward into the wide portion of the funnel. The ball will remain suspended in the funnel.

Explanation: As the air flows through the thin region between the funnel and the upper edge of the Ping Pong ball, its speed increases dramatically. As the air's speed increases, its pressure drops. With low pressure air on part of its upper surface, the ball experiences a net upward pressure force that's sufficient to support it against gravity.

98. Suspending a Ping Pong Ball in an Airstream

Description: A Ping Pong ball remains suspended in a jet of air emerging from a pipe.

Purpose: To show that air's pressure changes as its speed changes.

Supplies:

1 hose
1 Ping Pong ball
compressed air

Procedure: Attach the hose to the compressed air and direct a stream of air upward into the room. Carefully lower the Ping Pong ball into the airstream and it will remain suspended above the hose opening indefinitely.

Explanation: The ball is pushed upward by pressure drag (a topic discussed in Section 4.3). What keeps the ball stable near the center of the airstream is Bernoulli's effect. Whenever the ball drifts away from the center of the airstream, the airflow on the side of the ball nearest the center of the airstream becomes stronger than anywhere else. While the air pressure in the unperturbed airstream is atmospheric, the ball's presence can change that pressure. Since this airstream must speed up as it flows around the sides of the ball, effectively passing through a narrow channel at the sides of the ball, its pressure there drops. Since this pressure drop is strongest on the side of the ball nearest the center of the airstream, the ball experiences a net pressure force toward the center of the airstream.

99. A Paint Sprayer

Description: Compressed air is sent through a narrow channel above a drinking straw. This straw rises from a container of water. The water flows up the straw and into the airstream, creating a mist of atomized water.

Purpose: To show that the air pressure in a narrow channel can drop below atmospheric pressure, even when compressed air is delivered to that channel.

Supplies:

1 eyedropper
1 hose
1 drinking straw
1 container of water
compressed air

Procedure: Use the hose to attached the eyedropper's tube to the compressed air. Insert the straw in the container of water. Start the compressed air flowing and align the eyedropper's nozzle over the top of the straw. Use your fingers to create a moderate seal around the straw and to extend the narrowing at the end of the eyedropper. Be carefully not to direct the airflow down the straw, or you'll get wet. When you have the narrow channel extending all the way across the straw, the pressure in the straw will drop below atmospheric pressure and water will begin to rise up into the airstream. When it reaches the airstream, the water will be atomized into a mist and will spray out into the room.

Explanation: Even though you begin with compressed air at one end of the eyedropper, the pressure of the air flowing out of the eyedropper can drop below atmospheric pressure if its speed become sufficiently high. When this happens, the low pressure can allow atmospheric pressure air to push liquids into the narrow channel containing the fast moving air.

100. A Water Aspirator Pump

Description: A small gadget is attached to a water faucet and water is sent through it. The pressure in a hose attached to the side of the gadget suddenly drops below atmospheric pressure and begins to suck colored water out of container.

Purpose: To show that water's pressure can drop below atmospheric pressure when it passes through a narrow channel and its speed increases substantially.

Supplies:

1 water aspirator pump
1 hose
1 container of colored water
water source

Procedure: Attach the water aspirator pump to the water source and attach the hose to the side arm of the pump. Turn on the water flow and immerse the other end of the hose in the container of water. The water will begin to flow up the hose and into the pump.

Explanation: The water flowing through the pump is entering a very narrow channel. As it does, its speed increases dramatically and so does its kinetic energy. To provide this kinetic energy, the water's pressure and pressure potential energy drop precipitously. A small hole in the side of the channel connects to the hose. When the pressure in the channel becomes very low, water flows up the hose toward the channel.

101. A Fan in a Pipe

Description: A small fan located between two sections of pipe causes the pressure to rise in one pipe and drop in the other.

Purpose: To show that a fan increases the total energy of the air passing through it.

Supplies:

1 small "boxer" fan (a computer fan)
2 segments of pipe that fit tightly against the outer edges of the fan
2 pressure gauges (manometers) for the two pipe segments

Procedure: Attach the two segments of pipe to the two sides of the fan and note that both pressure gauges read atmospheric pressure. Now start the fan. The upwind pressure gauge will drop, showing that the air in that portion of pipe has converted some of its pressure potential energy into kinetic energy so that it can flow toward the fan. The downwind pressure gauge will rise, showing that the air in that portion of pipe has an increased total energy—both its kinetic energy and its pressure potential energy are greater than they were before you turned on the fan.

Explanation: The fan does work on the air that passes through its blades and increases the total energy of that air. This increased total energy is reflected in a rise of both the air's pressure and speed.

102. Chalk Dust in the Air

Description: Two chalk erasers are pounded together, releasing a cloud of dust that hangs in the air. A piece of chalk is released and drops quickly to the table.

Purpose: To show that chalk dust isn't supported by buoyant forces—it's supported by viscous drag forces.

Supplies:

2 chalky erasers
1 piece of chalk

Procedure: Smack the two erasers together and observe the cloud of chalk dust that hangs in the air. Now drop a piece of chalk and observe that it falls quickly. Note that the chalk is far more dense than the air it displaces, so that neither the piece of chalk nor the chalk dust is support by buoyant forces. Note instead that the chalk dust is supported by viscous drag forces—as the chalk begins to descend through the air, the air molecules exert an upward viscous drag force on it and support it against the force of gravity.

Explanation: Chalk dust has so much surface area relative to its volume that its motion is dominated by air resistance. Because of the dust's small size, the air flow around it is generally laminar and the only drag force it experiences is viscous drag—the molecular friction that occurs when the dust moves relative to the air. In effect, the dust pulls the surrounding air with it because of viscous interactions in the air. This pulling of the air slows the dust's decent and limits its downward speed to only a few millimeters per second (its terminal velocity).

Section 4.3 Balls, Birdies, and Frisbees

103. Throwing a Balloon - Pressure Drag

Description: You throw a balloon forward and it comes to a stop almost immediately.

Purpose: To show the slowing effects of pressure drag.

Supplies:

1 inflated balloon

Procedure: Throw the balloon forward and observe how quickly it slows to a stop (and begins descending slowly to the floor).

Explanation: The air flow around the balloon becomes turbulent at any significant speed. The pressure in front of the balloon rises above atmospheric pressure, the pressure at the sides of the balloon drops below atmospheric pressure, and the pressure behind the balloon begins to rise above atmospheric pressure. However the air flow separates from the back of the balloon shortly after rounding the sides of the balloon, leaving a large turbulent air wake behind the balloon. Since the air pressure behind the balloon doesn't rise very high, the high pressure in front of the balloon is unbalanced and the balloon experiences the slowing force of pressure drag.

104. The Decreased Pressure Drag of a Golf Ball

Description: Two balls of equal diameters and weights hang from long strings in the airstream leaving a fan. One ball is smooth and the other is dimpled—a golf ball. The smooth ball is deflected outward farther by the airstream than the smooth ball. (Note that this demonstration is hard to do convincingly because the balls tend to dither about in the uneven airstream.)

Purpose: To show that the pressure drag experienced by a dimpled golf ball is less than that experienced by a smooth ball of equal size and weight.

Supplies:

1 golf ball
1 very smooth ball with the same diameter and weight as a golf ball
1 tall supporting arm
2 strings, approximately 2 meters long. Woven thread that doesn't untwist is helpful.
1 powerful fan

Procedure: Use the strings to suspend the two balls from the support. Attaching the strings to the balls with tiny screws works best. Let the balls come to rest and mark their starting positions with a line on the table or floor. Now expose both balls to the strong airstream from the fan. They will both swing outward away from the onrushing air. But the smooth ball will swing outward farther, reflecting its greater pressure drag.

Explanation: The dimples on the golf ball delay the flow separation from its rear surface and reduce its pressure drag. As a result, it's pushed on less strongly by the wind from the fan and swings outward less far.

105. A Badminton Birdie Flies Bumper First

Description: A badminton birdie supported at its center of mass on a string flies bumper first as you swing it around in a circle.

Purpose: To show that a birdie has dynamic stability because its center of aerodynamic pressure (its center of drag) is located in its feathers. The feathers naturally drift behind its center of mass.

Supplies:

1 badminton birdie
string
tape

Procedure: Attach the string to the birdie near its center of mass (near its bumper). When the string is properly positioned, the birdie will remain level when you support it with the string. Now swing the birdie around in a circle overhead. It will always fly bumper first.

Explanation: As the birdie flies through the air, the air slows the feathers more than the bumper and the feathers drift to the rear of the moving object. Whenever the feathers begin to drift forward, the birdie experiences an aerodynamic torque that turns its feathers back to the rear.

106. An Arrow Always Flies Point First

Description: An arrow, supported by a string at its center of mass, flies point first as it's swung around in a circle.

Purpose: To show that an arrow has dynamic stability because its center of aerodynamic pressure (its center of drag) is located in its feathers. These feathers naturally drift behind its center of mass.

Supplies:

1 target arrow (we found that enlarging the feathers with sheets of thin cardboard improves this demonstration)
1 target arrow without any feathers
string
tape

Procedure: Attach the string to the arrow's center of mass with the help of the tape. Now swing the arrow around in a circle overhead. It will always fly point first (if it doesn't, increase the size of the feathers). Now create a similar arrow, but without any feathers at all. When you swing it around your head, it will fly with any end forward—it has no dynamic stability.

Explanation: As the arrow flies through the air, the air exerts a torque on its about its center of mass whenever the feathers begin to drift forward. This torque always returns the feathers to the rear of the flying object.

107. Curve Balls

Description: A Styrofoam ball curves in flight when you throw it with spin.

Purpose: To show that a spinning ball experiences a lift force that causes it to curve in flight and to show that lift forces aren't always in the upward direction.

Supplies:

1 Styrofoam ball (or any low-mass but large ball)

Procedure: Throw the ball forward with as much spin as you can manage. The ball should curve in flight toward the side that's heading back toward you as the ball spins. With some practice, you can make the ball curve in different directions by adjust its axis of rotation. Discuss the fact that the lift force that causes these curves isn't always upward. It can even be downward!

Explanation: As the ball spins, it experiences both the Magnus force and the wake deflection force, which both push it toward the side that's heading back to the pitcher. Because of the Styrofoam ball's low mass, it accelerates easily and curves substantially. A more massive ball, such as a baseball, won't curve as dramatically.

108. The Flight of a Frisbee

Description: When you throw a Frisbee across the room, the airflow around its upper and lower surfaces creates a lift force that supports it against its weight.

Purpose: To show that the airflow around an object can exert enough lift force on it to support its weight.

Supplies:

1 Frisbee

Procedure: Explain how the airflow around the Frisbee will develop during the throw. That flow will initially involve air moving at equal speeds above and below the Frisbee. However, the initial pattern of flow is unstable because it involves air flow up and around the trailing edge of the Frisbee. A few moments into the throw, this unstable airflow will blow away from the trailing edge of the Frisbee as a vortex, leaving a new pattern of airflow around the Frisbee. In this new pattern of airflow, the air moving over the top of the Frisbee will travel faster than the air moving under the bottom of the Frisbee. Since this faster moving air has more kinetic energy, it must have less pressure and pressure potential energy. The pressure above the Frisbee is thus less than the pressure below it and there is a net upward pressure force on the Frisbee. Having explained this airflow, throw the Frisbee across the room and observe how it hangs in the air. It descends remarkably slowly and may even rise at first because the magnitude of its upward lift force can equal or exceed the magnitude of its weight.

Explanation: The Frisbee is an airfoil that experiences upward lift when the speed of the air flowing over its top exceeds the speed of the air flowing under its bottom.

Follow-up: Perform a similar analysis for an Aerobee, an even more efficient flying disk. Because of its thin profile, the aerobee experiences less pressure drag and flies farther than the Frisbee.

Section 4.4 Airplanes

109. Blowing Air Across a Sheet of Paper

Description: You hold one edge of a sheet of paper so that it forms an arc in front of you. When you blow across the top of this arc, the paper rises.

Purpose: To demonstrate the upward lift force that appears when a stream of air speeds up as it flows over a convex surface.

Supplies:

1 sheet of paper

Procedure: Hold one edge of the sheet of paper so that it arcs slightly upward at first and then drapes downward on the end farthest from your fingers. Bring the edge that you're holding close to your lips and blow air across the bump in the sheet. The paper will experience an upward lift force and will rise.

Explanation: As the air leaves your lips, its pressure drops to atmospheric pressure. In passing through your lips, it has converted most of its pressure potential energy into kinetic energy. When it then encounters the bump in the sheet of paper, it speeds up still further—in effect, it's going through a narrow channel with only one curved wall: the bump in the sheet. As the air speeds up, its pressure drops below atmospheric pressure. With atmospheric pressure below the sheet and less than atmospheric pressure above it, the paper experiences an upward lift force and rises.

110. A Toy Plane in Flight

Description: A large toy plane glides through the air after being thrown forward.

Purpose: To show the upward lift force that's obtained by the wings of an airplane.

Supplies:

1 large toy Styrofoam airplane

Procedure: Hold the airplane in your hand and discuss how the air will flow around its wings as you throw it forward. Point out that the initial airflow will involve air moving at equal speeds above and below the wings—creating no lift. However, this initial pattern of flow will have air from under the wings turning upward around the trailing edges of the wings. This pattern of airflow is unstable and will blow away from the trailing edges during the throw. It will form a vortex of swirling air behind the plane and will leave a new pattern of airflow around the wings. In this new pattern, the air flowing over the wings will travel faster than the air flowing under the wings and the wings will experience lift. Having discussed how the wings develops an upward lift force, throw the plane forward and watch the lift in action.

Explanation: The plane's weight is at least partially balanced by the upward lift force created by its wings. The wings develop a lower air pressure above them than below them and thus experience an upward pressure force—an upward lift force.

Follow-up: Hold the plane upside down and then throw it forward. It still flies because the wings still develop an upward lift force. However, now it's their angles of attack rather than their asymmetric curved shape that creates this lift. As before, the air flows faster above the inverted wings than below them and it experiences an upward pressure force.

111. Steering a Toy Airplane

Description: By adjusting the surfaces of a toy plane, you can cause its flight to become curved.

Purpose: To show how a plane's surfaces can exert torques on the plane that curve its flight.

Supplies:

1 toy Styrofoam airplane
1 piece of thin cardboard about 20 cm by 5 cm
tape

Procedure: Crease the cardboard about 5 cm from one end and bend it to form about a 135° angle. Use the tape to brace the angle by running a strip of tape through the air from one surface to the other. Now tape the small surface of the angle to the top of the right wing tip, with the angled flap of cardboard leaning upward and toward the rear of the plane. When you throw the plane this time, the right wing tip will experience less upward lift than before and the plane will tip so that its right wing is lower than its left wing. As it flies, the plane will now curve toward the right.

Next, tape the small surface of the paper angle to the top of the elevator surface of the tail (either side of the horizontal tail winglet), again with its angled flap leaning upward and toward the rear. When you now throw the plane, the elevator will experience less upward lift than before and the plane will tip nose upward. It may even stall in flight!—if it does, discuss the resulting loss of lift and onset of severe drag.

Finally, tape the small surface of the paper angle to the right side of the tail rudder (the vertical tail winglet), with the angled flap leaning rightward and toward the rear. The rudder will now experience a leftward horizontal lift. When you throw the plane this time, it will rotate horizontally and will slip sideways through the air.

In each situation, you can discuss the effect of the paper angle on the lift forces, the resulting torque on the plane, the plane's change in orientation, the altered aerodynamic forces that accompany this changed orientation, and how these altered aerodynamic forces affect the plane's trajectory.

Explanation: The paper angle spoils the symmetry of the forces on the plane's surfaces and exposes the plane to aerodynamic torques. When the plane tips toward the right or left, its overall lift stops being vertical and it accelerates toward the right or left respectively. When the plane tips nose high or nose low, its wings' angles of attack change and so do the lift forces they experience. When the plane turns sideways in its flight through the air, it doesn't fly very well and can lose lift in one or both of its wings, initiating a tailspin.

112. A Wind-Up Airplane

Description: A toy balsa airplane with a rubber band motor pulls itself through the air and flies around the room.

Purpose: To show how a propeller can push a plane forward.

Supplies:

1 toy balsa airplane with a rubber band motor

Procedure: Observe the shape and motion of the plane's propeller and discuss how it's essentially a rotating wing. Point out that the lift force this rotating wing experiences is in the forward direction and is renamed "thrust" as a result. Now wind up the propeller, noting that you are doing work on it as you wind it, and release the airplane. The propeller will turn and pull the airplane through the air.

Explanation: The air flowing over the propeller blades speeds up as it flows over the forward surfaces of the blades. Because it converts pressure potential energy into kinetic energy, this air experiences a drop in pressure. With higher pressure behind it than in front of it, the propeller experiences a net forward pressure force—a thrust force. The propeller pulls the plane forward through the air.

113. A Fan on a Cart

Description: A powerful fan propels a small cart across the room.

Purpose: To show how a propeller can push a plane forward.

Supplies:

1 powerful fan
1 cart with very low friction wheels

Procedure: Put the fan on the cart and turn it on. With the fan aligned to push air along the path that the cart can roll, the air will accelerate in one direction and the cart will accelerate in the other.

Explanation: The air flowing over the fan blades speeds up as it flows over the forward surfaces of the blades and the pressure in front of the blades drops below atmospheric pressure. Air also slows down as it flows over the rearward surfaces of the blades and the pressure behind the blades rises above atmospheric pressure. This imbalance in pressures creates a forward pressure force on the fan that propels it and the cart forward. The air accelerates backward, from the higher pressure behind the blades to the atmospheric pressure behind the cart.

114. A Toy Helicopter

Description: You launch a toy helicopter and it flies around the room.

Purpose: To show that when a propeller spins about a vertical axis, its thrust can be directed upward and it can support its own weight.

Supplies:

1 toy helicopter or an equivalent spinning-blade toy

Procedure: First observe that the rotating blades of the helicopter are actually rotating wings that obtain lift in the upward direction as they turn through the air. Then launch the helicopter and watch it lift itself into the air. Note that the blades slow down as it rises, as must occur in order to conserve energy.

Explanation: As the blades of the helicopter turn through the air, the air speeds up to flow over them and slows down to flow under them. With the air pressure lower above the blades than beneath them, the blades experience an upward lift force that initial raises the toy helicopter into the air and then slows its descent.

Section 5.1 Rockets

115. Propulsion by Throwing Away Objects

Description: You sit motionless on a cart with a heavy ball in your lap. When you throw the ball in one direction, the car begins to roll in the opposite direction.

Purpose: To show that the act of pushing an object away causes you to accelerate in the opposite direction and to show that, while the momentum of an isolated system can't change, that momentum can be redistributed among the pieces of the system.

Supplies:

1 cart with very low friction wheels
1 heavy ball (a medicine ball or another massive non-fragile and non-dangerous object)

Procedure: Sit motionless on the cart with the heavy ball in your lap. Point out that your present momentum, including the cart and ball, is exactly zero. Discuss what will happen when you throw the ball in one direction—how you will have to push the ball away from you, how it will accelerate in the direction of your push, and how it will end up with momentum in that direction. Note also that it will push back on you, that you will accelerate in the direction of its push on you, and that you will end up with momentum in the direction of its push. Point out that the total momentum of you, the cart, and ball will still be zero, but that it will now be rearranged. At this point, throw the ball as hard as you can in one direction and you will begin rolling in the opposite direction (make sure that you throw the ball in a direction the cart can roll). Point out that the ball didn't have to hit anything for you to begin moving. The very action of pushing it away was all that was needed—it pushed on you as you pushed on it.

Explanation: You roll in the direction opposite to the ball's motion because it pushes on you as you push on it. The ball didn't have to hit anything for you to accelerate in the opposite direction.

116. Propelling an Air Track Cart with a Balloon

Description: A balloon attached to a cart on an air track accelerates in one direction as the air it contains accelerates in the opposite direction.

Purpose: To show that the act of pushing gas in one direction causes the device pushing that gas to accelerate in the opposite direction.

Supplies:

1 air track
1 air track cart
1 balloon
1 nozzle for the balloon (a plastic hose barb works well)
tape

Procedure: Attach the balloon to the nozzle and then tape the nozzle to the top of the air track cart. Inflate the balloon, pinch it closed, and put the cart on the operating air track. Without pushing the cart, release the cart and balloon. As the balloon deflates, the cart will accelerate in the direction opposite the air stream.

Explanation: The balloon squeezes the air out of the nozzle and pushes that air in one direction. The air pushes back on the balloon and this reaction force causes the cart to accelerate in the other direction.

117. A Water Rocket

Description: A toy water rocket is partly filled with water and attached to the launcher. After pumping air into the rocket, the rocket is released. It flies into the air as it ejects a stream of water in the opposite direction.

Purpose: To show that ejecting a stream of water from the exhaust nozzle of a rocket can cause that rocket to accelerate in the opposite direction.

Supplies:

1 toy water rocket with pump/launcher
water

Procedure: Partially fill the water rocket with water, according to the instructions. Attached the rocket to the launcher and pump air into the region of the rocket above the water. Describe what will happen when you release the rocket—the compressed air will push the pressurized water downward through the rocket nozzle. The water's pressure potential energy will become kinetic energy as it flows through the narrow nozzle and the water will leave the rocket at atmospheric pressure but with a large downward velocity. The rocket will have pushed the water downward to give it this velocity and the water will have pushed back, lifting the rocket into the air. Note that ejecting water from the rocket is more effective than ejecting air because the water has more mass and is harder to accelerate. The rocket pushes harder on the water than it would on air and the water pushes back harder on the rocket. You can make a similar analysis in terms of momentum—the water carries away more momentum because of its greater mass.

Explanation: As the rocket pushes the water downward and that water accelerates downward, the water pushes the rocket upward and the rocket accelerates upward. While gravity introduces an additional force which causes the entire system's center of mass to fall, the rocket's upward acceleration is so great that it rises into the air.

118. A Fire Extinguisher Rocket Cart

Description: You sit on a cart with a modified carbon dioxide fire extinguisher attached to it. When you squeeze the release lever, a jet of gas emerges in one direction and you rocket across the room in the other direction.

Purpose: To show that pushing a stream of stored gas in one direction produces a force of equal magnitude in the opposite direction.

Supplies:

1 full carbon dioxide fire extinguisher
1 cart with very low friction wheels
1 large pipe, bolted to the cart, to keep the fire extinguisher in place (optional)

Procedure: Unscrew the conical diffuser from the carbon dioxide fire extinguish and expose the outlet holes that are connected to the main valve. The gas flowing out of the main valve hits the end of this outlet structure and then turns to flow in all directions through a set of six outlet holes. Carefully! cut off the very end of this outlet structure—just the last fraction of a centimeter—so that the gas no longer turns to flow out of the holes. Without the surface at the end of this structure to deflect the gas flow sideways, the jet of gas leaving the main valve will travel in a straight path at enormous speed. Under no circumstances should you ever cut into the fire extinguisher anywhere but after the main valve! Safety first!

If you have a pipe bolted to the cart, insert the modified fire extinguisher into it and wedge the fire extinguisher as necessary so that it will remain in the pipe when gas is flowing out of it. Then sit on the cart. If you don't have a pipe to hold the fire extinguisher, sit on the cart and hold the fire extinguisher tightly in your lap. It will push rather hard when gas is flowing out of it, so you should be prepared to hold on to it and to stop releasing gas if you find the reaction force uncomfortable.

Once you are seated on the cart and the fire extinguisher is pointed along a direction in which the cart can roll, squeeze the release handle and allow the gas to flow. When you're sure that you can handle the reaction forces, squeeze the handle completely so that the flow of gas is vigorous. The gas will stream out in a roaring torrent of white "smoke" and you and the cart will accelerate in the opposite direction. Be prepared to stop releasing gas and to stop your motion before you hit anything. You may want to have someone to "catch" you before you crash, just in case. A full fire extinguisher will last about 6 to 10 seconds at full thrust. I can usually get 2 trips across the front of the lecture hall before running completely out of gas.

Explanation: As the carbon dioxide in the fire extinguisher turns the corner in the main valve and accelerates out of the modified opening, the valve structure pushes on it and it pushes back. This reaction force causes the fire extinguisher, the cart, and you to accelerate in the direction opposite the gas flow.

119. Match Rockets

Description: An aluminum foil-wrapped match, tipped almost upright against a bent paper clip, is heated with another match until it ignites. The jet of gas flowing out from under the aluminum foil and heading down the match stick pushes on the match and sends it flying into the air.

Purpose: To show that when a fuel burns to form a high pressure gas and this gas flows in one direction, the gas's container accelerates in the opposite direction.

Supplies:

- 2 matches (matchbook matches work well)
- 1 paper clip
- aluminum foil
- safety glasses

Procedure: Cut a small piece of aluminum foil and wrap two layers of it around the head of a match. The aluminum foil should extend about 5 mm beyond each end of the match head. Fold the free end of the aluminum foil to seal it—the only direction in which gas should be able to flow is down the stick. Now bend the paper clip so that it forms a prop for the match. The match should be about 20° from vertical. Now light the other match and carefully bake the aluminum wrapper with the flame. When the wrapped match head ignites, the torrent of gas flowing down the stick should push the match into the air. Experiment with different types of matches or wrapping techniques to obtain the best results.

Explanation: When the wrapped match head burns, it creates a large volume of hot gas that flows down the stick. The aluminum foil pushes the gas down the stick and the gas pushes back, propelling the match into the air.

120. Ion Rockets

Description: A set of metal vanes, resembling a whirlybird water sprinkler, is attached to a static electric generator. As the voltage of the static generator builds, the metal vanes begin to spin.

Purpose: To show that pushing ions in one direction causes them to push back, propelling the source of those ions in the direction opposite the ion's velocity.

Supplies:

- 1 set of metal vanes on a low-friction bearing (we use a commercial vane assembly, but a metal rod that has been bent into a "Z" shape and has had its tips sharpened to points should also work)
- 1 metal pin bearing for the metal vanes (the vane should sit on the pin and turn freely in a horizontal plane)
- 1 static electric generator
- 1 wire

Procedure: Set the vanes on the metal pin bearing so that they can turn freely. Use the wire to connect the metal pin to the static generator. Now turn on the static generator so that charge begins to flow onto the vanes. When the charge becomes large enough, the vanes will begin to turn in the direction opposite the direction in which the sharpened points are directed.

Explanation: As charge accumulates on the vanes, it begins to leave the sharpened points and flow onto passing air molecules. These molecules become charged and are repelled by the remaining charges on the vanes. The ionized air molecules accelerate away from the points and the points accelerate away from the ionized air molecules. The vanes turn as the result of torques from these repulsions.

121. Stable, Unstable, and Neutral Equilibrium

Description: A plastic track is first bent to form a valley and a marble rolls into the bottom of the valley. The track is then bent to form a mountain and a marble is carefully balanced on top of the peak but rolls off it at the slightest disturbance. Finally, the track is made flat and level, and the marble is remains wherever it's left along this track.

Purpose: To show the different types of equilibria.

Supplies:

1 plastic track
4 blocks to support the track
1 marble

Procedure: Use the blocks to bend the plastic track into a valley and put the marble at the bottom of the valley. Point out that the marble is in equilibrium because it's not accelerating and thus must be experiencing zero net force. Then disturb the marble and show that it always rolls back to the bottom of the valley—it's in a stable equilibrium.

Now rebend the track so that it forms a mountain rather than a valley. Carefully balance the marble on the top of the mountain. It will again be in equilibrium, but now this equilibrium is unstable. Show that the slightest disturbance of the marble will start it rolling down the mountain.

Finally, place the track flat and level on the table. The marble will now remain in equilibrium no matter where you put it along the track—it's in a neutral equilibrium.

Explanation: A stable equilibrium is one to which the displaced object will return when released—the displaced object experiences a restoring force that pushes it back toward the equilibrium position. An unstable equilibrium is one to which the disturbed object won't return when released—the displaced object experiences a force that pushes it away from the equilibrium position. An object that is displaced from a neutral equilibrium experiences no force either toward or away from the original equilibrium position.

122. Stability on the Ground - Center of Gravity

Description: An object's center of gravity is slowly shifted until it's no longer above the object's base of support. The object then tips over.

Purpose: To show that when an object's center of gravity can descend as it tips, that object will tip over.

Supplies:

1 center of gravity demonstrator or a block with a weight that can be shifted so that the overall center of gravity of the block/weight system can be placed either above the block's base of support or not above that base of support.

Procedure: Start with the demonstrator's center of gravity located above the demonstrator's base of support. Show that no matter which direction you tip the demonstrator, its center of gravity rises. Point out that because there is no direction in which the demonstrator can tip and lower its gravitational potential energy, the demonstrator will not tip. It's in a stable equilibrium—it naturally returns to its original position after begin tipped slightly.

Now shift the demonstrator's center of gravity gradually until it's no longer above the demonstrator's base of support. It will tip over. Point out the once the demonstrator's center of gravity is outside its base of support, there is a direction in which the demonstrator can tip and lower its center of gravity. Since an object accelerates in the direction that lowers its potential energy as quickly as possible, the demonstrator accelerates in the direction that lowers its center of gravity, and its gravitational potential energy, as quickly as possible.

Explanation: While gravity really acts throughout the demonstrator, it effectively acts at the demonstrator's center of gravity (which coincides with the demonstrator's center of mass). If that center of gravity rises, then the demonstrator's gravitational potential energy rises and if that center of gravity falls, then the demonstrator's gravitational potential energy falls. Since objects accelerate in the direction that reduces their potential energy as quickly as possible, the demonstrator will only tip over if doing so will reduce its gravitational potential energy. Thus it will only tip over if doing so will immediately lower its center of gravity. For geometrical reasons, that lowering will occur only when the center of gravity is not above the demonstrator's base of support.

123. Stability on the Ground - Tipping Over a Chair

Description: When you sit in the middle of a chair, it remains upright, even as you jiggle about. But if you lean far away from the center of the chair and its base of support, you and the chair will tip over.

Purpose: To show that an object will tip over when its center of gravity is no longer over its base of support.

Supplies:

1 chair

Procedure: Sit in the chair and roughly locate the center of gravity of you and the chair. Show that tipping the chair slightly won't cause it to tip over because the overall center of gravity will rise and you and the chair will naturally accelerate back toward your original situation—you and the chair are in a stable equilibrium. Now begin to lean far out to one side until the overall center of gravity is no longer above the base of support (the area bordered by the chair's legs). The chair will tip over.

Explanation: As long as the overall center of gravity is above the chair's base of support, tipping the chair raises the center of gravity. But once you begin leaning and the overall center of gravity is no longer above the chair's base of support, tipping the chair lowers the center of gravity. It begins to tip farther and farther so as to lower its gravitational potential energy.

124. Stability in the Air - A Balloon Runs Wild

Description: You inflate a balloon and release it. While it experiences substantial thrust from the gas it's ejecting, it travels in random directions because it's aerodynamically unstable.

Purpose: To show the importance of aerodynamic stability for a rocket.

Supplies:

1 elastic balloon

Procedure: Inflate the balloon and release it. It will fly around randomly until it runs out of air.

Explanation: The balloon's center of aerodynamic pressure is located near its front while the forward thrust of its gaseous exhaust is exerted near its rear. The front of the balloon tends to be slowed by air drag and the back of the balloon tends to be sped up by the thrust. As a result, the balloon tends to turn around in flight, over and over, and wanders almost randomly about the room until its air is used up.

Follow-up: Repeat the stability demonstrations from Section 4.3: the badminton birdie in flight and the arrow in flight. Early rockets used the same techniques to ensure that they flew nose first, tail last.

Section 5.2 Bicycles

125. A Tricycle - Static Stability, Dynamic Instability

Description: A tricycle is stable against tipping while stationary, but it tips over during a sharp turn at high speed.

Purpose: To illustrate the difference between static and dynamic stabilities.

Supplies:

1 tricycle

Procedure: Sit on the tricycle (assuming that you can fit and that your pride will allow you to do so). Show that as long as your center of gravity remains over the base of support (within the triangle bounded by the three wheels), the bicycle is in a stable equilibrium—after small tips, it will return to its original situation. Then ride the tricycle rapidly across the floor and make a sudden sharp turn. The tricycle will tip over (be prepared to stop yourself from falling so that you don't get injured). Note that while the tricycle is statically stable, it's dynamically unstable.

Explanation: Tipping the stationary tricycle raises its center of gravity, so it experiences a restoring force when tipped and naturally returns to its upright orientation. But when the tricycle is moving and you execute a sudden sharp turn, the friction between the ground and the wheel not only causes the tricycle to turn in the direction you want, it also exerts a torque on the tricycle about its center of mass. If this torque is large enough, the tricycle's static stability isn't enough and the tricycle begins to rotate. The wheels rotate in the direction of the turn and your head rotates in the opposite direction. You and the tricycle tip over.

126. A Bicycle - Static Instability, Dynamic Stability

Description: A bicycle is unstable against tipping while stationary, but can avoid tipping over even during a sharp turn at high speed.

Purpose: To illustrate the difference between static and dynamic stabilities.

Supplies:

1 bicycle

Procedure: Sit on a bicycle and show how difficult it is to keep it upright while it's stationary. Unless you are extremely talented, you will be unable to keep it upright for more than a second or two. Then ride the bicycle forward across the floor and show how easy it is to keep it upright while it's moving forward. Make a turn (if you have room) and show that by leaning into the turn, you keep it from tipping over. This holds true no matter how fast you are going or how sharp the turn, as long as the wheels don't skid across the ground. Note that while the bicycle is statically unstable, it's dynamically stable.

Explanation: When you and the bicycle are stationary, your overall center of gravity descends whenever the bicycle tips to one side. As a result, the upright bicycle is in an unstable equilibrium and tips over at the slightest perturbation. But when it's moving, at least two factors contribute to its dynamic stability (the next two demonstrations). Moreover, during a turn, you lean into that turn and the overall force exerted on the wheel by the ground—a combination of an upward support force and a horizontal frictional force—points directly at the overall center of mass. As a result, you and the bicycle don't begin to rotate and the bicycle remains stable throughout the turn.

127. A Bicycle's Tendency to Steer Under Your Center of Gravity - the Front Fork

Description: You straddle the upright bicycle and then tip it to its left. The front wheel spontaneously turns toward the left so that the bicycle is poised to drive under your center of gravity if you were moving forward.

Purpose: To show one of the origins of the bicycle's enormous dynamic stability.

Supplies:

1 bicycle
1 2-meter stick or another long, straight stick

Procedure: Straddle the upright bicycle and make sure that its front wheel points straight ahead. Point out that if you were to sit on the seat that it would be in an unstable equilibrium—your overall center of gravity would be directly above the line between the two wheels; a minimal base of support. Now align the 2-meter stick with the stem of the front wheel and show that the axis of rotation about which the front fork turns intersects the ground in front of the contact point between the front wheel and the ground. Note that this arrangement causes the front wheel to steer toward the left as the bicycle tips toward the left. Now tip the bicycle to its left and show that the front wheel steers toward the left. Point out that this steering effect causes the bicycle to drive itself under your center of mass and thus returns the bicycle to its unstable static equilibrium. As long as the bicycle is moving forward, the unstable equilibrium is actually a stable equilibrium; a dynamically stable equilibrium.

Explanation: If dynamical processes act to return an object to its unstable static equilibrium, then that equilibrium is dynamically stable. In this case, the automatic turning of the front wheel returns the moving bicycle to its upright position—an unstable static equilibrium.

128. A Bicycle's Tendency to Steer Under Your Center of Gravity - the Front Wheel is a Gyroscope

Description: A gyroscope mounted in gimbals acts like the front wheel of a bicycle, turning in the direction the wheel would when the bicycle is rolling forward. When a weight is attached to the left side of the gyroscope's axle—simulating a lean to the left—the gyroscope/wheel begins to turn to the left. This gyroscopic precession would cause the bicycle to drive under the rider's center of gravity and would return the bicycle to its upright, unstable static equilibrium.

Purpose: To show how an unstable static equilibrium can be made stable by dynamic processes and to demonstrate gyroscopic precision.

Supplies:

1 gyroscope, mounted in gimbals to isolate it from external torques
1 weight

Procedure: Spin the gyroscope in such as way that it resembles the front wheel of a bicycle moving forward. You might prop a bicycle next to it so that everyone can see that the gyroscope wheel is turning in the direction that the front wheel of the bicycle would turn. Now hang the weight from the left side of the axle supporting the gyroscope wheel. The gyroscope wheel will turn toward the left—it will precess. This direction of turning would cause a bicycle moving forward to drive itself under the rider's center of gravity and return the bicycle to its upright unstable static equilibrium orientation. Thus the front wheel's gyroscopic character causes the bicycle to be dynamically stable.

Explanation: When the gyroscope wheel is spinning like the front wheel of a bicycle (its top surface is turning forward and away from you when you are standing as though you were riding the bicycle), the wheel's axis of rotation points horizontally to your left (according to the right hand rule). When you add the weight to the left side of the axle, it exerts a torque on the gyroscope that points horizontally rearward (toward the rear wheel of the hypothetical bicycle). The resulting angular acceleration slowly shifts the gyroscope's axis of rotation from leftward to rearward—i.e. the wheel turns toward the left.

129. Gears on a Bicycle

Description: You turn the pedals of an inverted bicycle by hand. Changing the gears allows you to vary the number of turns the rear wheel makes for each complete turn of the pedals.

Purpose: To show that gears, belts, and chain drives allow you to vary the mechanical advantage between two rotating systems.

Supplies:

1 multispeed bicycle (with several sprockets and derailleurs)

Procedure: Flip the bicycle upside down and prop it on its handlebars. Turn the pedals by hand and show that the number of turns that the rear wheel makes for each turn of the pedals depends upon the choice of gears. With the chain going around the largest crank sprocket and around the smallest freewheel (rear wheel) sprocket, one turn of the pedals causes the rear wheel to turn several times. With the chain going around the smallest crank sprocket and around the largest freewheel sprocket, one turn of the pedals causes the rear wheel to turn only about one time. Discuss how, in the first case, your pedaling exerts relatively little torque on the rear wheel—which is why it's difficult to climb a hill in this gear; the frictional torque on the rear wheel stops it from turning. Also discuss how in the second case, your pedaling exerts a relatively large torque on the rear wheel—which is why its easy to climb a hill in this gear; the frictional torque on the rear wheel is easily overcome by pedaling. Of course, you don't get something for nothing: in the hill climbing gear, you must turn the pedals many times to make any reasonable progress up the hill. You're doing the work needed to lift yourself up the hill by exerting modest forces on the pedals but making them move long distances (many turns) in the directions of those forces.

Explanation: The gear system on the bicycle provides mechanical advantage. When you are on level pavement, you need relatively little torque to turn the rear wheel. By using a large crank sprocket and a small freewheel sprocket, you can make the rear wheel turn as rapidly as possible. Your pedaling exerts relatively little torque on the rear wheel but that rear wheel turns many times for each turn of the pedals. When you are climbing a hill, you need a relatively large torque to turn the rear wheel—friction with the ground is acting to slow the wheel's rotation. By using a small crank sprocket and a large freewheel sprocket, you can exert a large torque on the rear wheel although it will turn relatively slowly. You must turn the pedals many times to climb the hill a reasonable distance.

130. Keep the Tire Mass Small

Description: Lights show that a wheel's rim moves at different speeds from the rest of the bicycle.

Purpose: To show why it's important to keep the mass of the tires low.

Supplies:

1 large wheel (we use a Styrofoam disk)
2 small flashlights

Procedure: Attach one flashlight to the center of the disk and the other flashlight to the disk's rim. Turn on the flashlights and dim the room lights. Roll the wheel across a long table or the floor and observe the lights. The light at the center of the wheel will move steadily forward, but the light at the wheel's rim will execute cycloidal motion. It will briefly stop moving altogether when it's at the bottom of the wheel and it will move forward at twice the speed of the wheel's center when it's on the top of the wheel. While the rim light's average speed is still equal to that of the center light, the rim light's average kinetic energy is twice that of the center light.

Explanation: Kinetic energy depends on the square of speed. Although the rim light's average speed is equal to that of the center light, the rim light spends half its time moving at more than this average speed and its kinetic energy during that time is quite large. When the rim light is at the top of the wheel and moving forward at twice the speed of the center light, its kinetic energy is four times as large as that of the center light. Overall, the rim light's average kinetic energy is twice as large as that of the center light. Because you must provide the work that gives this increased energy to the tire of your bicycle, you want as little mass in that tire as possible.

Section 5.3 Elevators

131. A Jackscrew Elevator

Description: A person stands on a metal plate that's supported from a jackscrew automobile jack. Another person furiously turns the crank that rotates the nut that supports the jackscrew and the metal plate slowly rises upward.

Purpose: To show that, while a jackscrew elevator is possible, it isn't very practical.

Supplies:

1 jackscrew automobile jack, rigidly attached to plates at its top and bottom and equipped with a crank to turn the nut that lifts the screw

Procedure: Place the jackscrew elevator on the floor and have someone stand on the upper plate. Then have another person turn the crank so that the screw slowly rises upward. Point out that the person turning the crank is doing work on the crank (pushing it in the direction that it's turning) and that this work is lifting the person on the plate. A small force exerted over a long distance is providing a large force exerted over a short distance. Note, however, that it takes a long time to lift the person on the plate, making this jackscrew elevator rather impractical.

Explanation: The jackscrew and the nut that lifts it are really inclined planes (ramps) that are wrapped into cylinders. The person turning the crank is effectively sliding one inclined plane across the other and causing the inclined plane that is the jackscrew to rise upward. They are obtaining mechanical advantage—a small force exerted over a long distance is providing a large force exerted over a small distance.

132. A Hydraulic Elevator

Description: You rest an uninflated balloon on the table and hold a small weight on its top. You then inflate that balloon and the weight rises.

Purpose: To show that a solid object can rise up on a trapped volume of hydraulic fluid.

Supplies:

1 rubber balloon
1 small weight

Procedure: Place the uninflated balloon on the table and hold a small weigh on top of it. Now carefully inflate the balloon. The balloon will inflate, carrying the weight upward with it.

Explanation: As you blew high pressure air into the balloon, you did work on that air and the air in turn did work on the weight, lifting it upward against the force of gravity.

133. A Bigger Hydraulic Elevator

Description: A person sits on a large plate that's on top of a plastic garbage bag. When air is pumped into the garbage bag by a vacuum cleaner (running backward), the bag inflates and the person rises into the air.

Purpose: To show that even a small pressure inside a large container can exert enormous forces on the walls of that container.

Supplies:

1 heavy-duty plastic garbage bag (or better yet, several of them, one inside the other)
1 stiff plate that's almost the size of the garbage bag
1 vacuum cleaner that can be run so that it pumps air into its hose
duct tape

Procedure: Tape the plate to the top surface of the plastic bag and then seal the open end of the bag around the outlet of the vacuum cleaner hose. It's best to seal most of the bag's open end to itself with the duct tape (like closing a zipper) and then duct tape the small open corner of the bag to the hose. Place the assembly on the floor or on a large, sturdy table and have a person sit on the plate. Hold that person's hand so that they don't fall over as the bag inflates. Now turn on the vacuum cleaner so that it inflates the bag. The person will rise into the air as air enters the bag and inflates it.

Explanation: Although the air pressure inside the bag is only slightly above atmospheric pressure, it acts on the whole surface area of the plate. The upward force that the plate experiences, due to the high pressure below it than above it, is more than the person's downward weight and the plate accelerates upward.

Alternative Procedure: Inflate a dozen or more rubber balloons and put them on the floor underneath an inverted table. If the area under the inverted table is packed densely enough with balloons, 4 or 5 students will be able to stand on the table without popping any of them. Make sure that someone stands outside the table and holds onto its legs to keep it from tipping over as people climb onto the table.

134. A Hydraulic Jack

Description: Pumping the handle of a hydraulic jack many times causes its main piston to rise only a small distance. However, the piston exerts an enormous force on the object above it. (We have a hydraulic jack that crushes the object above it against a fixed plate—we typically crush a broken electronic device such as an old calculator.)

Purpose: To show that a small force exerted over a long distance on the small piston of a two-piston hydraulic system can exert a large force over a small distance on the large piston of the system.

Supplies:

1 hydraulic jack system, with a hand-operated pump
1 heavy object to put on the jack (or an object to crush, if you have a plate bolted in place above the large piston)

Procedure: Put the jack on the floor or table and place the heavy object on top of its large piston. Explain that moving the handle of the pump up and down pushes a small piston in and out of a narrow hydraulic cylinder. Pushing the handle down pressurizes the hydraulic fluid and squeezes it out of the cylinder, through a one-way valve, and into the large cylinder beneath the large piston. The pressure that you create in the small cylinder by pushing the piston into it also appears in the large cylinder, where it pushes upward on the large piston. But because the large piston has much more surface area than the small piston upon which you push, the upward force that the large piston experiences is much greater than the downward force you exert on the small piston. That's why you can lift a very heavy object with the large piston while exerting only a modest force on the pump handle. Show them that this is so by pumping the handle and lifting the heavy object. Point out that you must move the pump handle a very long distance to raise the heavy object even a small distance. That's because the mechanical advantage in the hydraulic system is allowing you do the work of lifting the heavy object—a large upward force exerted over a small distance—by exerting a small downward force over a very large distance.

Explanation: Pushing the large piston out of the large cylinder requires much more fluid than is provided by pushing the small piston into the small cylinder. Thus you must push the small piston into the small cylinder many times, replenishing its fluid each time from a reservoir, before the large piston moves a reasonable distance out of the large cylinder.

135. A Simple Cable-Lift Elevator

Description: A chair is lifted from above by pulling on a rope that's attached to it.

Purpose: To show that tension in a cord can convey an upward force to an object that's attached to that rope.

Supplies:

1 chair
1 rope sling that attaches to all four legs of the chair and provides a single loop above the chair to which you can attach a rope
1 rope
access to the space above the front of the lecture hall, or else a ladder

Procedure: Attach the rope sling to the chair and attach the rope to the sling. The rope should descend to the chair from the space above the front of the lecture hall. Go up to the top of the rope and lift the chair upward from above at constant velocity. Announce that to make things simple, you will assume that the rope weighs nothing. Point out that you are pulling upward on the rope with a force equal in magnitude to the weight of the chair and that the chair is pulling downward on the rope with a force equal in magnitude to its weight. The rope is thus conveying your force to the chair and the chair's force to you. It has a tension in it equal to the magnitude of the force you and the chair exert on it (not twice that amount).

Explanation: The rope acts as an intermediary between you and the chair. When you pull upward on the rope with a certain force, the rope pulls upward on the chair with that same force (assuming the rope itself doesn't have any weight or mass). The force "passing through" the rope is called the tension in the rope.

136. A Simple Cable-Lift Elevator with a Pulley

Description: A chair is lifted from above by pulling down on a rope that's attached to it and that passes over a pulley near the ceiling.

Purpose: To show that tension in a cord can convey a force to an object, even when that rope passes over a pulley and the directions of the two forces are no longer the same.

Supplies:

- 1 chair
- 1 rope sling that attaches to all four legs of the chair and provides a single loop above the chair to which you can attach a rope
- 1 rope
- 1 pulley attached near the ceiling

Procedure: Attach the rope sling to the chair. Drape the rope over the pulley near the ceiling and attach one end of it to the top of the rope sling. Again, announce that to make things simple, you will assume that the rope weighs nothing. Pull downward on the rope so that the chair rises at constant velocity. Point out that you are pulling downward on the rope with a force equal in magnitude to the weight of the chair and that the chair is pulling downward on the rope with a force equal in magnitude to its weight. The rope is thus conveying your force to the chair and the chair's force to you, even though the pulley is changing the directions of those forces. The rope has a tension in it equal to the magnitude of the force you and the chair exert on it (not twice that amount).

Explanation: The rope acts as an intermediary between you and the chair. When you pull on the rope with a certain force, the rope pulls on the chair with that same force (assuming the rope itself doesn't have any weight or mass). The force "passing through" the rope is called the tension in the rope. But the pulley is changing the directions of the force so that, while the tension remains constant throughout the rope, the direction of the force that you exert on the rope isn't the same as the direction of the force the rope exerts on the chair.

137. A Cable-Lift Elevator with a Multiple Pulley

Description: A chair is lifted from above by pulling down on a rope that's part of a multiple pulley system extending from the ceiling to the chair. Even though a person is sitting in the chair, it takes only a modest force exerted on the rope to lift the chair upward.

Purpose: To show that tension in the cord passing through a multiple pulley can be used several times to exert enormous inward forces on the two ends of a multiple pulley system.

Supplies:

- 1 chair
- 1 rope sling that attaches to all four legs of the chair and provides a single loop above the chair to which you can attach a rope
- 1 multiple pulley system that hangs from the ceiling

Procedure: Attach the top of the multiple pulley to the ceiling. Attach the rope sling to the chair and connect the top of the rope sling to the bottom of the multiple pulley. The end of the multiple pulley's cord should extend downward from the upper portion of the multiple pulley. Have someone sit in the chair. Now pull downward on the rope. The chair and person will rise upward. Point out that you are exerting a relatively small force on the rope and thus creating only a modest tension in the rope. However, because that same cord extends many times between the top and bottom of the multiple pulley, the inward forces exerted by its tension is used several times. If there are 5 rope segments between the two ends of the pulley, then the tension is used 5 times and the force pulling upward on the chair is 5 times the tension in the rope. Note that although you only have to exert a modest force on the cord to lift the chair and person, you must exert that force over a long distance to lift them a short distance.

Explanation: You obtain mechanical advantage with the multiple pulley—a modest force exerted on the rope over a large distance exerts an enormous force on the chair over a small distance.

138. Lifting Yourself with a Cable-Lift Elevator

Description: You sit in the chair of the previous demonstration and lift yourself upward.

Purpose: To show that you can even lift yourself with a multiple pulley.

Supplies:

The setup for the previous demonstration

Procedure: Sit in the chair of the previous demonstration and ask whether you will be able to lift yourself upward. The answer is yes. Point out that you are holding in your hand an additional segment of the multiple pulley—should that make it easier or harder to lift yourself upward? Now pull down on the rope in your hand and you will begin to rise upward.

Explanation: When you sit on the chair and pull downward on the end of the cord of the multiple pulley, there is one additional segment of cord pulling upward on you and the chair. It takes even less tension in the cord to lift you and the chair than it would if someone else were lifting you by pulling on the cord.

139. The Value of a Counterweight

Description: You operate a toy elevator system with an elevator car on one side and a counterweight on the other. As the elevator car rises, the counterweight descends and vice versa.

Purpose: To show how a counterweight can store energy as the elevator car descends and then provide energy to lift the car upward the next time.

Supplies:

1 toy cable-lift elevator—consisting of a "car" and a counterweight, both suspended from the same string that passes over two horizontally separated spools that turn easily on a support
2 pretend passengers (small weights)

Procedure: Start with the elevator car low and the counterweight high. Put the two passengers into the elevator car and begin to raise the elevator car by turning one of the spools. Point out that while the cord is doing work on the elevator car by lifting it upward, the counterweight is doing work on the cord by pulling its other end downward—energy is flowing from the counterweight to the car. Now begin to lower the elevator car. Point out that while the elevator car is doing work on the cord by pulling its end downward, the cord is doing work on the counterweight by pulling it upward.

Explanation: The counterweight provides some of the energy needed to lift the car upward as the car rises and it stores some of the energy released by the car as the car descends.

Section 6.1 Wood Stoves

140. Creating Thermal Energy from Chemical Potential Energy

Description: A burning candle creates thermal energy before it's extinguished.

Purpose: To show that a chemical reaction between wax molecules and oxygen molecules converts stored energy (chemical potential energy) into thermal energy.

Supplies:

1 short candle
1 base for candle
1 large glass jar or beaker that's tall enough to smoother the candle without approaching the candle flame too closely.
matches

Procedure: Mount the candle on the base and light the candle with the match. Discuss how the chemical reactions between the wax molecules and the oxygen molecules in the air are converting their stored energy (chemical potential energy) into thermal energy. Discuss the need for the initial heat (the lighted match) to provide the activation energy that weakens the chemical bonds in the starting materials so that the reactions can proceed. Point out that the thermal energy that this system can provide is limited to the stored chemical potential energy and that when either the candle or the oxygen runs out, the production of thermal energy will cease. Then smoother the candle by placing the inverted jar or beaker over it so that no new oxygen can get to it.

Explanation: With the aid of the heat from the match, the bonds between the hydrogen and carbon atoms in the wax molecules begin to weaken and they become attracted to the oxygen atoms of passing oxygen molecules. New bonds form between the hydrogen atoms and oxygen atoms, and between the carbon atoms and oxygen atoms. Water molecules and carbon dioxide molecules are created. Since the chemical potential energies of these new molecules are lower than those of the starting molecules, some chemical potential energy has been converted into thermal energy.

Follow-up: Discuss how sliding friction provides the activation energy needed to start the chemical reactions in the match that you used to light the candle.

141. Creating Thermal Energy from Electric Energy

Description: Current flowing through a wire causes that wire to glow red hot.

Purpose: To show that friction-like effects inside a wire can convert electric energy (a mixture of kinetic and potential energies in moving electric charges) into thermal energy.

Supplies:

1 large (car) battery or a high-current power supply
1 high-current switch
1 segment of nichrome wire (heating wire)
3 large-gauge wires
1 support base for the nichrome wire

Procedure: Connect one terminal of the battery to the switch, the switch to the nichrome wire (mounted on the base), and the nichrome wire to the other terminal of the battery. Make sure that the switch is open while you're working. Then close the switch and allow current to flow through the circuit. The nichrome wire should become extremely hot. Point out that electricity is flowing through the circuit in an endless loop and that the current of electric charges is obtaining energy from the battery and delivering that energy to the nichrome wire. Through friction-like processes, the electric charges in that current are converting their kinetic and potential energies into thermal energy and this thermal energy is causing the wire to become extremely hot.

Explanation: Collisions between the moving electric charges in the current and the atoms in the nichrome wire transfer energy from the charges to the atoms. The atoms become hotter, vibrating more and more vigorously with their increasing thermal energies.

Simple Alternative: Turn on an incandescent lamp.

142. Creating Thermal Energy from a Phase Transition

Description: You trigger the crystallization of the liquid in a plastic heat pack. The pack becomes warm as its clear liquid converts to a stiff, white solid.

Purpose: To show that still another form of potential energy (also a chemical potential energy) can become thermal energy.

Supplies:

1 heat pack (sodium acetate solution in a plastic envelope, with a metal trigger capsule)

Procedure: Show that the heat pack contains a clear liquid. Explain that this liquid is a supersaturated solution of a chemical that has difficulty crystallizing into a solid—its molecules can't find the proper arrangement for a crystal to begin growing. As a result, the chemical is trapped in its liquid phase despite being at a temperature well below its freezing temperature. Now trigger the crystallization by clinking the trigger capsule. White streams of crystallizing material will emerge from the trigger and spread throughout the heat pack. The heat pack will become hot. Discuss how the molecules release chemical potential energy as they stick to one another to form crystals. This released energy becomes thermal energy and you feel the heat pack become hotter. Explain that the heat pack can be reused by immersing it in boiling water and allowing all the crystals to melt. The boiling water's thermal energy then provides the chemical potential energy needed to separate the molecules and convert the material back into a liquid.

Explanation: The heat released when sodium acetate crystallizes from the supersaturated solution is similar to the heat released when water freezes into ice. In this case, the crystallization occurs well below the sodium acetate's freezing temperature, so that freezing is sudden and the large amount of thermal energy released heats the system up dramatically.

143. How Temperature Affects a Gas

Description: When a sealed sphere containing helium gas is heated or cooled, the pressure of the gas inside that sphere is seen to increase or decrease.

Purpose: To define temperature in terms of the average thermal kinetic energies of the particles in a material.

Supplies:

1 helium-filled sphere with a pressure gauge attached to it
1 gas burner or other heating device (a heat gun or hairdryer)
1 cold bath (liquid nitrogen or ice water)

Procedure: Observe the pressure of the gas inside the sphere while it's at room temperature. Point out that this pressure reflects the thermal motions of the helium atoms—they are hitting the surfaces of the pressure gauge and the pressure that gauge is reading depends on the number of particles hitting each second and on how hard they hit on average. Now heat the sphere up and show that the pressure inside the sphere increases. Because the helium atoms now have more thermal kinetic energy on average than they had at room temperature, they are moving faster, hitting the surfaces in the pressure gauge more often, and hitting those surfaces harder than before. Finally, cool the sphere by immersing it in liquid nitrogen (or ice water). The pressure inside the sphere will drop. Discuss how the average thermal kinetic energy of the atoms has decreased. Discuss how this average thermal kinetic energy can serve as the basis for a temperature scale and that there will be a bottom to this temperature scale—absolute zero—at which point the average thermal kinetic energies of the atoms is zero.

Explanation: Helium is almost an ideal gas—its atoms interact so weakly that they're almost perfectly independent. Virtually all of its thermal energy is in the form of thermal kinetic energy—the motion of its atoms. When you raise or lower its temperature, the average thermal kinetic energies of the atoms increase or decrease in proportion to the temperature change, with the zero of thermal kinetic energy corresponding to the zero of the absolute temperature (assuming that the helium didn't liquefy at about 4.5 K and stop behaving as an ideal gas).

144. Heat Flows from Hot to Cold

Description: A red hot metal rod is immersed in cold water and heat flows from the hot rod to the colder water. A room temperature metal rod is immersed in liquid nitrogen and heat flows from the warm rod to the very cold liquid nitrogen.

Purpose: To illustrate that heat naturally flows from a hotter object to a colder object.

Supplies:

1 metal rod
1 container of water
1 container of liquid nitrogen
1 gas burner
matches
tongs

Procedure: Start the burner and heat the end of the metal rod until it glows red hot. Now immerse it in the cold water. Discuss the fact that heat flowed from the hotter rod to the colder water, not the other way around (what would have happened if it had gone the other way?). Point out that the total amount of thermal energy in the system remained constant (neglecting fine details like the formation of steam). Now immerse the cool metal rod in liquid nitrogen. Again heat flows from the hotter rod to the colder liquid nitrogen.

Explanation: While the flow of heat from a colder object to a hotter object wouldn't violate any of the basic laws of mechanics, it's simply not observed. Such a reverse flow of heat is so unlikely that it never happens. It's as unlikely as having a vase, shattered in a fall to the floor, reconstruct itself during a subsequent fall.

145. Heat Flows from Hot to Cold, Part II

Description: Liquid nitrogen is poured into a cup of water and a cloud of mist appears.

Purpose: To show that heat flows from hotter objects to colder objects.

Supplies:

1 Styrofoam cup, half full of water
liquid nitrogen

Procedure: Pour a modest amount of liquid nitrogen onto the water in the cup and observe the mist flowing out over the edges of the cup. Discuss how heat is flowing from the warmer water to the colder liquid nitrogen and how this is causing the nitrogen to boil violently and atomize the droplets of water. With time, the cold liquid nitrogen will all turn to warmer nitrogen gas and some of the warmer water will turn to colder ice. You can also discuss why the liquid nitrogen floats on the water (its density is much lower than that of water) and why the misty flow of cold nitrogen gas flows downward around the sides of the cup (its density is much higher than that of room temperature air).

Explanation: The boiling nitrogen breaks the water into tiny droplets that float around in the air as mist. Because the mist is chilled by the liquid nitrogen, the water droplets don't evaporate and the mist flows over the edges of the cup.

146. Freezing Objects in Liquid Nitrogen

Description: Various objects are immersed in liquid nitrogen and become hard and fragile.

Purpose: To show that heat flows from hotter objects to colder objects and that the materials properties of common objects can change substantially when they are taken to extreme temperatures.

Supplies:

1 container for liquid nitrogen (a dewar or a Styrofoam container. We use a wonderfully made wide, shallow dewar that was made for us by William Shoup of the University of Virginia glass shop—(804) 924-3967)
1 flower
1 rubber racket ball
1 banana
1 hammer
1 nail with a large head
1 piece of wood
tongs

insulated gloves
safety glasses

Procedure: Pour liquid nitrogen into the container and allow it to stop boiling violently. Then immerse each of the objects into the liquid nitrogen, one at a time, and allow them to freeze. The flower will freeze almost instantly and will become as brittle as glass. If you hold a microphone near it as you strike it on the table, you will hear it shatter as though it were made of paper-thin glass. The racket ball will become extremely hard and will sound like a rigid plastic ball when you bounce it gently on the table. If you throw it against a solid floor, it will shatter. However, be careful of the flying fragments because they're as hard and sharp as pieces from a broken bottle. Finally, freezing the banana will take several minutes. Don't let it freeze too long, or it will shatter spontaneously because of the internal stresses its experiences during the freezing process. Use the frozen banana to pound the nail into wood. While an over-frozen banana will tend to break and the nail may punch holes in the surface of an under-frozen banana, the banana hammer is still impressive.

Explanation: Heat flows out of room temperature objects when they're immersed in liquid nitrogen. While objects that are already solid at room temperature change relatively little when they're cooled to liquid nitrogen temperature (77° K, -195° C, or –319° F), objects that have relatively mobile molecules (liquids, gases, and elastic materials) change dramatically.

147. Making Ice Cream with Liquid Nitrogen

Description: You first mix cream, milk, sugar, and vanilla in a large metal bowl and them begin stirring in liquid nitrogen. In about 5 minutes, you have a bowl of ice cream.

Purpose: To show that heat flows from a hotter object to a colder object (and to make dessert in a hurry).

Supplies:

4 liters of milk and/or cream (I've used 4 liters of half and half to rave reviews)
750 grams (1.5 pounds) of sugar (roughly)
15 ml (1 tbsp.) of vanilla
1 very large, shallow metal mixing bowl (the bigger, the better!)
1 metal mixing spoon
liquid nitrogen (at least 4 liters, perhaps more)

Procedure: Combine the milk, cream, sugar, and vanilla in the mixing bowl and stir thoroughly. Slowly add the liquid nitrogen to the mixture and stir. Don't add to much liquid nitrogen or stir too quickly at first, or the boiling mixture will overflow the bowl. Keep adding liquid nitrogen, about 0.5 liters at a time, and then stir until it has mostly boiled away. By the time you have added about 4 liters of liquid nitrogen, the mixture should have thickened into ice cream.

Explanation: Heat flows from the warmer ice cream mixture to the much colder liquid nitrogen. Most of the gaseous nitrogen escapes, but some is trapped in the ice cream and improves its taste.

148. Breaking a Penny

Description: A recent United States Penny (1983 or later) is cooled in liquid nitrogen, placed on a hard surface, and struck with a hammer. It shatters into fragments.

Purpose: To show that cooling some metals makes them brittle.

Supplies:

1 recent penny (1983 or later, because they are mostly zinc with a thin copper coating. Very recent pennies seem to have the thinnest copper coatings and probably work best.)
tongs
1 hammer
1 anvil or another hard, sturdy surface
safety glasses

Procedure: First place the penny on the hard surface and hit it with the hammer. It may dent, but it will not break. Then chill it to liquid nitrogen temperature and repeat the experiment. It will shatter into pieces. This demonstration works best if you support one edge of the penny with the tongs while you hit the penny with the hammer. That way, the hammer will bend the penny rather than simply compressing it. The cold penny will break rather than bend and will crumble into small fragments.

Explanation: Even some solids become more brittle when they are cooled to very low temperatures.

149. Thermal Conductivities of Metals

Description: A thick metal disk has three metal spokes extending from it at equally spaced angles. One spoke is aluminum, one is copper, and the third is stainless steel. Metal marbles hang by wax from these spokes at equal distances from the central disk. When the disk is heated by a gas burner, the spokes begin to warm up and the marbles begin to drop. They leave the copper spoke first, then the aluminum spoke, and lastly the stainless steel spoke.

Purpose: To show that different metals have different thermal conductivities.

Supplies:

1 thick metal disk (copper, aluminum, or brass)
3 metal spokes that fit tightly into the metal disk (one copper, one aluminum, and one stainless steel). They should all have equal dimensions.
1 ring stand for the disk and spoke assembly
12 metal marbles
hard wax (sealing wax)
1 gas burner
matches

Procedure: Assemble the spokes on the metal disk so that they all are in good thermal contact with the disk. Screw-in attachment is ideal, if you can thread the metal components. Now mark each metal spoke at 4 evenly space intervals and use the wax (melting it with a match or burner) to attach a metal marble at each mark on the three spokes. Hot glue (glue gun glue) may work instead of the wax—I haven't tried it. Now suspend the disk and spoke assembly on the ring stand. When ready, place the burner under the central disk and ignite it. As the disk warms up, heat will begin to flow out the three metal spokes and will eventually melt the wax. Since copper is the best conductor of heat, the marbles will begin to fall from the copper spoke first. Aluminum will be next, followed by stainless steel. Point out that copper is also the best electric conductor, followed by aluminum, followed by stainless steel.

Explanation: The relationship between thermal conductivity and electric conductivity isn't a coincidence. The mobile electrons in these metals dominate their thermal conductivities.

150. Holding Red Hot Thin-Walled Stainless Steel Tubing

Description: You hold one end of a piece of thin-walled stainless steel tubing in your hand and heat the other end red hot.

Purpose: To show that some metal objects have such poor thermal conductivities that two regions of very different temperatures can exist very near one another.

Supplies:

1 piece of thin-walled stainless steel tubing (about 30 cm of 1 cm tubing, with as thin a wall as you can find)
1 gas burner
matches

Procedure: Ignite the burner and hold one end of the thin-walled tube in your hand. Hold the other end of the tube in the flame and allow it to begin glowing red hot. Be prepared to drop the tube if for some reason it becomes uncomfortably hot.

Explanation: Stainless steel is a poor conductor of both electricity and heat. When reduced to a thin cylindrical surface (a thin-walled tube), stainless steel loses heat so quickly to the air that even regions only a few centimeters from a burner remain relatively cool.

Simple Alternative: You can also hold one end of a piece of aluminum foil and heat the other end of the foil until it melts or burns. This works because the foil is so thin that air is able to carry away its heat before it reaches your fingers.

151. Visualizing Convection in Water

Description: Light is projected through a clear glass cell containing water and an electrically heated metal wire. When electricity heats the wire, swirls of rising water can be seen leaving the filament.

Purpose: To show how convection carries heat upward from a hot object.

Supplies:

1 glass or plastic box, or a miniature aquarium
1 nichrome wire or filament
2 heavy-gauge wires
1 powerful battery or power supply
1 slide projector or other bright light source
1 large converging lens with holder (about 5 cm in diameter and roughly 20 cm focal length)
2 large flat mirrors and supports (optional)
water

Procedure: Form a small coil from the nichrome wire. Attach the heavy wires to the nichrome wire and place the nichrome wire at the bottom of the glass or plastic box. Be sure that the nichrome itself doesn't touch the sides of the box (use the heavy-gauge wires to anchor the nichrome wire in place). Fill the box almost full of water. Direct the light from the slide projector through the water-filled box and place the converging lens on the far side of the box. Move that lens back and forth until it projects a clear image of the nichrome wire on the wall or a screen. This image will be inverted, so you should point this out to the observers. (If you add two mirrors to this set up, one at 45° to bend the horizontal light so that it travels straight upward and the other at 45° to bend the upward light so that it travels horizontally but in the reverse direction from its starting direction, you can cast an upright image onto the wall.) Now connect the wires to the battery and begin heating the nichrome filament. Swirls of hot water will appear in the image projected on the wall and will move toward the top of the box (they'll move downward in an inverted image).

Explanation: When the filament heats the water, that water becomes less dense than the surrounding water and it floats upward, lifted by the buoyant force.

152. Boiling Water in a Hand-held Test Tube

Description: You hold the bottom of a water-filled test tube in your hand and heat the top of that test tube with a gas burner. The water at the top of the test tube begins to boil.

Purpose: To show that convection only works when the heat source is at the bottom of a fluid.

Supplies:

1 large Pyrex or Kimax test tube
1 gas burner
water

Procedure: Almost fill the test tube with water (don't overfill it, because boiling water will then pour down its outside surfaces and reach your hand). Ignite the gas burner. Hold the bottom of the test tube in your hand and tip the top of the test tube into the flame. After a few seconds, the water at the top of the test tube will begin to boil but the water near your hand will remain cool. (Keep an eye on the swirling water below the boiling area—the stirring effect of the bubbles is mixing the hot and cold regions together. Don't let the hot water drift downward to your hand.)

Explanation: Heating the water near the top of the test tube causes it to expand and become less dense. It floats easily atop the cooler, more dense water at the bottom of the test tube. Convection never starts and your hand remains cool.

153. Boiling Water in a Paper Cup

Description: A water-filled paper cup is carefully suspended above the flame of a gas burner. While the free edges of the cup soon burn away, most of the cup remains intact and the water in it eventually begins to boil.

Purpose: To show that water can be so effective at removing thermal energy from a thin paper surface that that surface won't burn even when exposed to an open flame.

Supplies:

1 wax-coated paper cup (a Dixie cup works well)
1 ring-shaped metal support for the cup (this ring must catch the cup uniformly around its middle, within the water-filled portion of the cup)
1 gas burner
matches

Procedure: Partially fill the paper cup with water and insert it into the metal support. The cup must be filled at least to the level at which it's supported, otherwise the cup will burn near the support and will fall. Place the burner underneath the cup and ignite it. While the exposed edges of the cup will soon burn, the portions of the cup that are touching the water will do little more than scorch. The water will gradually warm up and will eventually boil.

Explanation: Although the burner transfers considerable heat to the paper surfaces of the cup, the paper surfaces quickly transfer that heat to the water. Since the temperatures of the paper surfaces never greatly exceed the boiling temperature of water, the paper doesn't burn and the water's temperature rises to its boiling point.

154. Cooking with Light - Thermal Radiation

Description: A bright light bulb in the focus of a large parabolic reflector projects a dazzling beam of light across the room. A second reflector collects this light and concentrates it on various objects in its focus.

Purpose: To show that thermal radiation and light are the same things and that thermal radiation can carry heat from a hotter object to a colder object.

Supplies:

2 large parabolic metal reflectors, with supports
1 small, clear, high wattage light bulb (we use a projector bulb, but a 500 W halogen lamp

bulb should also work—it's a little long, but very bright.)
1 power source for the light bulb
1 match
2 marshmallows
black spray paint
1 support for the match
1 stick for the marshmallows

Procedure: Carefully align the light bulb in the focus of the first reflector. When you have it properly aligned, the reflector should project an intense beam of light across the room. Align the second reflector so that it catches this beam of light and concentrates the light at its focus. Be careful not to injure your eyes or to burn yourself. Dimming the lamp makes alignment easier. Now turn off the light bulb, place the match in the support, and position the match head at the focus of the second reflector. When everything is well aligned, turn up on the lamp. The match will promptly ignite. Remove the match and its support and begin toasting the marshmallow in the focus of the second reflector. To speed the cooking, spray paint the second marshmallow black and place it in the focus of the second reflector. This black marshmallow will cook extremely quickly and may even ignite.

Explanation: The filament of the light bulb is the hottest object in the room and it transfers heat via radiation to everything around it. The reflectors simply improve the coupling between the filament and whatever is in the focus of the second reflector. Spray painting the marshmallow black increases its emissivity, making it better at both absorbing and emitting thermal radiation.

155. Using a Thermopile to "See" Thermal Radiation

Description: A thermopile is pointed at a number of objects to see which are emitting the most thermal radiation.

Purpose: To show that even room temperature objects emit thermal radiation.

Supplies:

1 thermopile, a device that detects the infrared radiation emitted by relatively low temperature objects

1 moderately heated cube with different surfaces (black, white, shiny, and dull metallic gray)

1 container of liquid nitrogen

Procedure: Point the thermopile at various surfaces to show that they emit different amounts of thermal radiation. The heated black surface will emit quite a bit while the colder, less black room will emit substantially less. Compare the emission by the black surface to that emitted by the shiny and gray surfaces (which are at the same temperature). The latter surfaces should emit less thermal radiation. Examine the thermal radiation from the white surface. In our apparatus, the white surface emits considerable thermal radiation, an indication that it's not "white" in the infrared. Examine the thermal radiation from your hand. Finally, examine the thermal radiation from the container of liquid nitrogen (don't look at the liquid nitrogen through any room temperature glass walls—you must point the thermopile directly at the liquid from above). There will be very, very little thermal radiation emerging from the liquid nitrogen.

Explanation: The thermal radiation emitted by a surface depends on that surface's temperature and on its emissivity (its ability to emit and absorb light; in short, its blackness).

Section 6.2 Clothing and Insulation

156. Poor Conductors of Heat - Glass

Description: You hold a glass rod in your hand and heat its other end until that end melts.

Purpose: To show that glass is a very poor conductor of heat.

Supplies:

1 glass rod (about 20 cm is fine)
1 gas burner
1 piece of paper (to burn)
matches
water (to put out the burning paper, if necessary)

Procedure: Light the burner. Hold one end of the glass rod in your hand and place the other end of the rod in the burner flame. After a few seconds, the rod will begin to melt. Note that the end you are holding is still cool. Note also that you can barely see the red glow emitted by the hot glass—it's emissivity is very low in the visible (it's transparent and doesn't couple well to visible light). Now remove the glass rod from the flame and touch it to the paper (be sure that nothing else flammable is nearby). The paper will burst into flames. Carefully extinguish the paper.

Explanation: Glass is a poor conductor of heat primarily because it has no mobile electrons—it's an electric insulator. Heat flows so slowly through glass that you can heat one end of the rod red hot while the other end of the rod remains cool.

157. Which Feels Hotter, Glass or Metal?

Description: Your students touch two chilled plates with equal temperatures. One is glass and the other is metal. The metal plate feels much colder than the glass plate.

Purpose: To show that thermal conductivity plays a role in our perception of temperature.

Supplies:

1 glass plate (or a plastic plate)
1 metal plate (copper would be best, but aluminum will do, too)
ice

Procedure: Chill both plates in the ice so that they have equal temperatures. (Or you can even use room temperature plates, assuming that the room isn't too warm.) Remove the plates from the ice, dry them completely, and have the students touch them. The metal plate will feel much colder than the glass plate.

Explanation: You perceive an object as cold because it extracts heat from your skin. The surface of the glass plate quickly warms up as heat flow into it from your skin, so the rate at which heat flows out of you soon decreases. As a result, the glass doesn't feel very cold. The metal plate conducts heat well, so that you will be unable to heat its surface significantly. Heat will continue to flow rapidly out of your skin to the plate, so the plate will feel very cold.

Follow-up: Why is it more hazardous to touch your tongue to a metal surface in freezing cold weather than it is to touch it to a glass surface?

158. Glass Wool - Insulating with Air

Description: You place a coin on a thick layer of glass wool that you're holding in your hand and heat that coin red hot with a blowtorch. Your hand remains cool.

Purpose: To show that air trapped in a fibrous material is an excellent thermal insulator.

Supplies:

1 thick pad of glass wool (I use the glass fiber wrapping material that's used with large hot or cold water pipes)
1 coin (a solid copper penny works well; but don't use a recent penny—after about 1982—because it will be made of zinc and will melt)
1 hand-held propane torch
matches
water (in case you have to cool anything quickly)

Procedure: Light the propane torch. Hold the pad of glass wool in one hand and place the coin on top of it. Make sure that the pad completely covers your hand and be prepared to get your hand out of the way instantly if you begin to feel heat. Now carefully heat the coin with the torch. If you feel heat on your hand, something is wrong and you should stop the experiment immediately. The coin should soon begin glowing red hot but you should feel essentially no heat from the torch. (The glass fibers themselves will begin to melt somewhat. That's normal and won't cause trouble unless your pad isn't thick enough. Once the pad has thinned noticeably, it's time to stop the experiment and discard the pad. However, let the pad and the coin cool completely before touching them or discarding them.)

Explanation: Because the glass fibers trap the air and prevent it from undergoing convection, the only way that heat can flow from the coin to your hand is via conduction through the air and glass. Since neither of these materials is a good conductor of heat, that heat flow is very slow. Even though the coin is red hot, your hand remains cool.

159. Countercurrent Exchange in Your Arm

Description: You immerse your hand in a bucket of ice. Even though your hand becomes quite cold, your body remains warm.

Purpose: To show how heat exchange processes in your arm allow your hand to become much colder than your body without wasting very much thermal energy.

Supplies:

1 bucket of ice
2 skin thermometers (thin plastic strips with liquid crystals inside and numbers on their surfaces that indicate the current temperature of your skin)

Procedure: Place one of the skin thermometers on your hand and the other on your upper arm. Note the temperatures at these two locations. Then immerse your hand in the ice. Despite the continuing flow of blood to and from your hand, only your hand becomes cold. The temperature of your hand drops substantially while the temperature of your upper arm remains unchanged.

Explanation: As blood flows toward your hand, it gives up heat to the blood returning from your hand in a process called countercurrent exchange. The temperature of the blood decreases on its way to your hand and increases on its way back.

160. Blocking Thermal Radiation

Description: A thermopile measures the heat emitted by a warm surface. You put various materials over that warm surface and the amount of thermal radiation detected by the thermopile decreases.

Purpose: To show how various barrier layers reduce radiative heat transfer.

Supplies:

1 warm, black surface
1 thermopile
1 plate of glass
1 sheet of aluminum foil
1 sheet of cloth

Procedure: Point the thermopile at the warm surface and note how much thermal radiation that surface is emitting. Now insert the glass, aluminum foil, and cloth in between the surface and thermopile, one at a time. In each case, the amount of thermal radiation will decrease.

Explanation: Glass is a good absorber and emitter of room-temperature thermal radiation (infrared light). Since the glass is cooler than the warm surface, the glass absorbs more of the warm surface's thermal radiation than the glass emits itself. The thermopile sees the glass's weaker thermal emission rather than the warm surface's stronger thermal emission. Aluminum foil is a good reflector of thermal radiation. It blocks the thermal radiation from the warm surface and allows the thermopile to see a reflection of its own weak thermal radiation. The cloth absorbs hot surface's thermal radiation and emits thermal radiation of its own. Since the cloth exchanges heat readily with the air around it and is at room temperature, it emits less thermal radiation than the warm surface.

161. A Thermos Bottle or Dewar

Description: A Thermos bottle or dewar holds a very hot or very cold liquid and keeps it hot or cold for a long time.

Purpose: To show that it's possible to stop virtually all heat transfer in some cases.

Supplies:

1 Thermos bottle or dewar flask
liquid nitrogen or another hot or cold liquid

Procedure: Pour the liquid nitrogen into the Thermos bottle or dewar flask. After a few seconds of violent boiling, the liquid will settle and boil relatively gently. The liquid will take a very long time to boil away completely.

Explanation: The Thermos bottle or dewar has a double wall structure, with a vacuum in between. The double wall makes it difficult for conduction to transport heat to or from the contents of the bottle. The walls are made of a material with a poor thermal conductivity (either glass or stainless steel). The space between the two walls contains a vacuum, so that convection can't carry heat between the walls. And in many Thermos bottles or dewar flasks, the inner surfaces of the double walls are mirrored to prevent radiation from carrying heat between the walls. With almost no way for heat to flow to or from the liquid in the container, it remains hot or cold for a very long time.

Section 6.3 Incandescent Light Bulbs

162. Opening an Incandescent Light Bulb

Description: You place an incandescent light bulb in a paper bag and tap it with a hammer until the glass envelope breaks. The filament and its supporting structure are then visible.

Purpose: To show the active structures inside the incandescent bulb, particularly the filament.

Supplies:

1 inexpensive incandescent light bulb
1 hammer
1 small, sturdy paper or cloth bag

1 magnifying glass or low-magnification microscope

Procedure: Insert the light bulb in the bag and close the bag to prevent glass from escaping. Place the wrapped bulb on a hard surface and tap it carefully with the hammer until the glass envelope breaks (squeezing it in a vise also works well). Carefully extract only the inner portion of the bulb and discard the broken envelope. Point out the filament and the two wires that carry current to and from it. Use a magnifying glass or microscope to study the double spiral structure of the filament—it's a very thin wire that has been wound into a spiral and then wound into a spiral again so that the long filament wire will fit in a small space.

Explanation: The light emerging from an incandescent light bulb originates in its filament. The glass bulb serves only to protect the filament and to diffuse the light from the filament.

163. An Incandescent Light Bulb at Various Temperatures

Description: An incandescent light bulb is connected to a variable voltage transformer. As the current passing through the bulb's filament increases, so does its temperature. The bulb's brightness increases and the color of its light shifts from reddish, to orangish, to yellowish as it heats up.

Purpose: To show that both the brightness and spectrum of thermal radiation depend on the temperature of the emitting surface.

Supplies:

1 incandescent light bulb
1 lamp or bulb holder
1 variable voltage transformer (a Variac autotransformer is ideal)

Procedure: Insert the incandescent bulb in the lamp or bulb holder and plug the lamp into the variable voltage transformer. Slowly turn up the voltage of the transformer until the bulb glows a dim red. You may want to turn out the room lights. As you turn up the voltage still further, the temperature of the bulb's filament will increase and its brightness will also increase. Point out that the color of the light emitted by the bulb also changes—it becomes less red and more yellow. That's because an object's spectrum of thermal radiation shifts toward shorter wavelengths as that object becomes hotter.

Explanation: The bulb's filament is essentially a black body with a temperature that's determined by the amount of electric power it receives. As you turn up the voltage of the transformer, the filament receives more and more power and becomes hotter and hotter. (The filament's temperature is determined by its need to get rid of energy as heat just as quickly as that energy arrives as electric power. As more power arrives at the filament, its temperature must rise higher in order for more heat to leave each second.) With its increasing temperature, the filament emits both more light and shorter wavelength light.

Follow-up: If you put a transmission diffraction grating in front of a color CCD camera and point the camera at the proper angle with respect to the glowing light bulb, you will see the spectrum of light emitted by the bulb as a rainbow smear of color on the color monitor. Placing a black surface strategically in front of the camera helps clarify the spectrum, and using a tall, thin, clear incandescent bulb helps even more. As you turn up the temperature of the filament, the smear of color will shift toward short wavelengths to include more and more green and blue light. Use an auto-iris camera and/or crossed polarizers, so that you don't saturate the camera as the brightness of the bulb increases.

164. Different Wattage Bulbs - More of the Same Light

Description: Several bulbs of different wattages are illuminated at once. While they have different brightnesses, their colors are the same.

Purpose: To show that the filaments of different wattage bulbs all operate at essentially the same temperature.

Supplies:

3 normal bulbs (made by the same manufacturer and not extended life) of different wattages (such as 25 W, 60 W, and 100 W)
3 bulb holders

Procedure: Insert the three bulbs in the bulb holders and turn them all on. Note that while the 25 W bulb is much dimmer than the 100 W bulb, it has essentially the same color (spectrum) of light.

Explanation: The low wattage bulb's filament operates at the same temperature as that of the high wattage bulb. However, the low wattage bulb's filament is smaller and thus less bright than that of the high wattage bulb.

165. Long Life Bulbs - Less Light for the Money

Description: You compare the light produced by a normal incandescent bulb to the light produced by a long-life bulb of an equivalent wattage. The long life bulb emits redder, dimmer light.

Purpose: To show that the filament of the long life bulb operates at a lower temperature than that of a normal bulb.

Supplies:

1 normal incandescent bulb (60 W)
1 long life incandescent bulb (approximately 60 W)
2 bulb holders

Procedure: Insert the two bulbs in the bulb holders and turn them on. Note that the long life bulb is dimmer and redder than the normal incandescent bulb, even though both are using essentially the same amount of electric power. Point out that while the long life bulb may be more convenient because it doesn't require changing as often, it produces less light for each kilowatt hour of electricity.

Explanation: The filament of the long life bulb last so long because it operates at a lower temperature than the filament of a normal incandescent bulb. Its long life isn't free—you pay for it with decreased light efficiency over the whole operating life of the bulb.

166. Heat Lamps

Description: You turn on a heat lamp and observe that it barely produces any visible light at all. Its dim, red glow is just the tip of the iceberg—most of its thermal radiation is invisible infrared light.

Purpose: To show that a low temperature filament produces very little visible light but lots of invisible infrared light.

Supplies:

1 heat lamp

Procedure: Turn on the heat lamp and examine its light. All that you can see is a dim red glow. However, if you put your hand near it, you can feel the warmth transferred to you via invisible infrared light. Because its filament operates at a relatively low temperature, most of the heat lamp's thermal radiation is this infrared light.

Explanation: Below about 1500°C, a hot filament emits relatively little visible light and what little it does emit is red light. Most of the filament's thermal radiation is at much longer wavelengths and is invisible.

167. An Unprotected Filament Burns Up

Description: You turn on a light bulb that has had its outer glass envelope removed. The filament burns with a cloud of white smoke.

Purpose: To show that hot tungsten burns and must be protected from oxygen.

Supplies:

1 incandescent light bulb without its glass envelope (Remove the glass envelope by wrapping the bulb in a paper or cloth bag and tapping it with a hammer until the glass shatters.)
1 lamp holder

Procedure: Unplug the lamp holder. Carefully insert the exposed light bulb in the lamp holder (don't cut your fingers or break the filament). Now plug in the lamp holder and turn on the bulb. The filament will burn.

Explanation: Tungsten, like most metals, can oxidize and it burns readily at high temperatures. In a normal incandescent bulb, the tungsten is protected from oxygen by the glass envelope.

168. The Diffusing Effect of the Glass Envelope

Description: You turn on two different light bulbs of equal wattage: one has a normal, clouded envelope and the other has a clear envelope. The clear bulb is much less pleasant to look at.

Purpose: To show that the clouded surface of a normal bulb diffuses the light so that it appears to originate from a larger, dimmer surface.

Supplies:

1 normal incandescent bulb (60 W)
1 clear incandescent bulb (60 W)
2 bulb holders

Procedure: Insert both bulbs in lamp holders and turn them on. The normal bulb will emit light from its entire surface, so that the surface appears relatively dim. The clear bulb emits light only from its filament, which appears dazzlingly bright. The colors of the two bulbs are identical—the white coating only redirects the light from the filament.

Explanation: The white particles on the inside surface of the normal incandescent bulb scatter and redirect light from the filament. The result is light that emerges from a larger surface and thus appears less dazzling and casts more diffuse shadows.

169. A Three-Way Bulb

Description: A three-way bulb emits three different light levels as you turn its switch.

Purpose: To show that the light emitted by a three way bulb doesn't change in color—it changes only in brightness.

Supplies:

- 1 three-way bulb
- 1 lamp for the three-way bulb
- 1 paper or cloth bag
- 1 hammer

Procedure: Cycle the bulb several times through its three different light levels. Point out that while its brightness is changing, the color of the light it emits isn't changing. This means that the temperature of the filament(s) inside isn't changing with the light level. The only way that this can occur is if the filament(s)'s surface area is changing. That's exactly what's happening. The bulb contains 2 separate filaments. At the lowest light level, only the smaller filament is operating. At the medium light level, only the larger filament is operating. And at the highest light level, both the filaments are operating.

Finally, break open the bulb—insert it in the bag and tap it with the hammer until the glass shatters. Carefully remove the exposed bulb from the bag and discard the glass fragments. Examine the two different-sized filaments.

Explanation: To maintain a constant filament temperature, light spectrum, and energy efficiency while varying its brightness, the bulb must change the size of its filament. It does this discretely by using one or both of its two different filaments.

170. A Halogen Bulb

Description: The active portion of a halogen bulb is a small, clear envelope with a tungsten filament inside. When it's turned on, the filament emits a brilliant yellow-white light and the small envelope gets rather hot.

Purpose: To show that the structure of a halogen bulb isn't quite the same as that of a normal incandescent bulb.

Supplies:

- 1 screw-in halogen bulb (a replacement for a normal incandescent bulb—this type of halogen lamp has a heavy protective envelope)
- 1 small halogen lamp (any halogen lamp that doesn't have a large protective envelope)
- 1 normal incandescent lamp of roughly the same wattage as the screw-in halogen bulb
- 2 bulb holders for the screw-in bulbs

Procedure: Show that the active component of a halogen lamp is quite small. It has to be small because it must operate at high temperatures. Insert both of the screw-in bulbs into the lamp holders and turn them on. Show that the halogen lamp is somewhat brighter and emits a whiter (less yellow) light than the normal incandescent bulb.

Explanation: The halogen lamp recycles the tungsten atoms that sublime from the tungsten filament during operation. For this halogen-mediated recycling to work, the entire bulb (including the clear envelope around the filament) must operate well above room temperature. That's why the envelope is small and close to the filament. Because the filament is continuously rebuilt, it can and does operate at higher temperatures than the filament of a normal bulb without exhibiting a short operating life. The halogen bulb thus emits a larger fraction of its thermal radiation as visible light, making it brighter. Its thermal radiation includes a larger fraction of green and blue wavelengths, making that radiation less yellow and more white than the light of a normal bulb.

Section 6.4 Thermometers and Thermostats

171. An Illustration of Thermal Expansion - Cans and Rubber Bands

Description: Several beverage cans are connected with rubber bands to form a lattice. When they're "heated" to higher temperatures and vibrate relative to one another, their average spacings increase—the lattice expands.

Purpose: To show why heating most substances causes them to occupy more volume.

Supplies:

2 or more beverage cans
rubber bands

Procedure: Place the cans upright on a table and arrange them to form a lattice. Now attach adjacent cans to one another with rubber bands—loop each rubber band around two adjacent cans. When you hold up this lattice and don't push on it, the lattice is analogous to a solid at absolute zero. But if you begin to stretch and release the rubber bands, so that the cans begin to vibrate against one another, the lattice is analogous to a solid at a finite temperature. The more vigorous the vibrations, the hotter the solid. If you now observe the average spacings between the cans (the atoms), you'll see that they become larger as the system's temperature increases.

Explanation: At absolute zero, the atoms in a classical solid are all in equilibrium and don't move. This equilibrium is stable, so that if you displace one of the atoms, it will experience a restoring force. However, this restoring force isn't symmetric—the repulsive forces between atoms that are too close are stiffer than the attractive forces between atoms that are too distant. As a result, atoms that are vibrating when the temperature is above absolute zero spend more time too far apart than they spend too close together. As a result, the lattice expands. The same situation holds for the can/rubber band analogy: the repulsive forces between squeezed cans are stiffer than the attractive forces of stretched rubber bands. Thus as the cans vibrate back and forth more vigorously, their lattice expands, too.

172. Expansion of Metals - a Ball and a Ring

Description: A metal ball is too large to fit through a metal ring when they are both at the same temperature. But heating the ring and/or cooling the ball makes it possible for the ball to pass easily through the ring.

Purpose: To show that metals expand when heated.

Supplies:

1 ball and ring set (from a scientific supply company)
1 gas burner
1 container of liquid nitrogen
matches

Procedure: First show that the ball can't fit through the ring—it's too large for the ring. Now chill the ball by dipping it in liquid nitrogen. The ball will contract and it will then be able to fit through the ring. Allow the ball to warm to room temperature and repeat the experiment. However, this time light the burner and heat the ring until it's almost red hot. While it might seem as though heating the ring should make it expand and shrink the hole inside it, the entire ring will expand outward and the hole will become larger. The ball will now fit through the ring.

Explanation: Raising the temperature of most metals moves their atoms farther apart on average and causes them to increase in size in all directions. Hollow spots, such as the hole in the ring, expand in size as the overall metal expands. While having the innermost layer of atoms in the ring expand inward would move those atoms farther from the atoms in the next to innermost layer, it would also move the atoms of the innermost layer closer to one another. In thermal expansion, every atom moves farther from its neighbors, and that can only occur when all the atoms expand outward from the center of the object. This rule applies even to the innermost layer of atoms in the ring—they move outward from the center of the ring.

Follow-up: Drill a hole in an aluminum plate. The diameter of that hole should be just too small for an aluminum rod to enter it. Now chill the aluminum rod in liquid nitrogen and insert the contracted rod in the hole. Allow the rod to warm up. It will be impossible to remove the rod from the hole.

173. Expansion of an Metal Tube with Temperature

Description: When steam flows through an aluminum tube, the tube's temperature increases and so does its length.

Purpose: To show that metals expand when heated.

Supplies:

1 aluminum tube (roughly 5 mm in diameter and 30 cm long)
1 hose
1 steam boiler
1 stand for the steam boiler
1 gas burner
matches
1 flat weight
1 paper pointer with a pin through it
tape

Procedure: Use the hose to attach the aluminum tube to the boiler. Lay the aluminum tube along the edge of the table or a heat-resistant surface and tape the hose end of the tube firmly to the table. Insert the pin of the paper pointer under the open end of the aluminum tube and lay the weight over the tube to press it against the pin. As the open end of the tube moves toward or away from the hose end, the pin will rotate and the pointer will change its direction of pointing. Place the steam boiler on the stand, light the burner, and allow the boiler to make steam. As the steam flows through the aluminum tube, the tube's length will increase and the pointer will turn.

Explanation: The steam will heat the aluminum tube and cause it to expand a small fraction of its length. The pointer makes that small expansion more visible.

Alternative Procedure: Make the simple plastic ruler thermometer of described in the opening of Chapter 6.

174. Glass/Liquid Thermometer

Description: When a common glass/liquid thermometer is heated or cooled, the level of liquid inside it rises or falls, even though both the glass and the liquid are experiencing the same changes in temperature.

Purpose: To show that liquids normally expand or contract more with temperature changes than solids do.

Supplies:

1 glass/liquid thermometer
1 container of hot water
1 container of ice water

Procedure: Observe the reading of the thermometer at room temperature. Immerse the thermometer in hot water and watch as the level of liquid inside it rises. Point out that both the glass and the liquid are expanding with temperature, but that the liquid is expanding more rapidly than the glass. Now immerse the thermometer in ice water and water as the level of liquid inside it falls. Again, the liquid is contracting more rapidly than the glass.

Explanation: When the temperature of a solid changes, its atoms vibrate more vigorously and their average spacings increase. However, they don't normally rearrange much. When the temperature of a liquid changes, its atoms not only vibrate more vigorously, so that their average spacings increases, but they also tend to rearrange and adopt less tightly packed formations. That's why liquids expand more rapidly with temperature than solids do. In the case of the glass/liquid thermometer, the rapidly expanding liquid is force to flow up the thin tube inside the glass because the liquid expands more rapidly than the hollow volume inside the glass does.

175. A Rubber Band Thermometer

Description: A weight hangs from the end of a rubber band. When you heat the rubber band, its length decreases and the weight rises.

Purpose: To show that not all materials simply expand with temperature.

Supplies:

1 rubber band
1 weight
1 support for rubber band
1 heat gun or hairdryer

Procedure: Attach the rubber band to the support and hang the weight from the rubber band. The rubber band should be stretched almost to its elastic limit. Note how far the rubber band has stretched. Now heat the rubber band without touching it. The rubber band will shrink and pull the weight upward.

Explanation: The rubber band contracts upon heating because the long organic molecules inside it develop more and more kinks as their temperatures rise. In a cold, unstretched rubber band, these molecules are wound up into random coils. Stretching the rubber band unwinds those coils. However, the random coils are the more thermodynamically favorable arrangement so the molecules recoil and shorten when you either relieve the tension on the rubber band or heat the rubber band up.

176. A Bimetallic Strip Thermometer

Description: A thin metal strip, made of a sandwich of two metals, bends whenever its temperature changes.

Purpose: To show that different metals expand differently with temperature and that this can be used to make objects that bend with temperature.

Supplies:

1 bimetallic strip (typically iron and brass)
1 gas burner
matches
1 container of ice water

Procedure: Examine the bimetallic strip, pointing out that it's made of two different metals that have been bonded together. Note that at room temperature the strip is flat. Now light the burner and heat the strip gently. It will curl in one direction as the outer metal (brass) surface expands more rapidly than the inner metal surface (iron). Now immerse the strip in ice water and watch as it curls the other way. The surface of the strip that expanded more rapidly when heated (brass) also shrinks more rapidly when cooled and becomes the inner surface of the curling strip.

Explanation: The characteristics of the forces between atoms varies from metal to metal, so that different metals have different coefficients of volume expansion. The strip is made of two different metals with different coefficients of volume expansion. As a result, it only remains flat at one temperature.

177. An Electric Light Blinker

Description: A bimetallic strip is used as an electric switch, opening a circuit when it becomes hot. When the circuit is used to power a heater near the bimetallic strip, the strip repeated opens and closes the circuit. A light bulb attached to the circuit also blinks on and off.

Purpose: To illustrate how both a light blinker and a thermostat work.

Supplies:

1 bimetallic strip
1 switch mount for the bimetallic strip (see below)
1 powerful battery
1 nichrome wire heater
1 small light bulb
wires

Procedure: Mount the bimetallic strip so that it barely touches a metal contact while the strip is at room temperature and bends away from that contact when it's somewhat hotter than room temperature. Connect one terminal of the battery to the bimetallic strip. Connect the metal contact to one terminal of the nichrome wire heater and also to one terminal of the light bulb. Place the nichrome wire heater very close to the bimetallic strip (or touching it, if the nichrome is insulated). Now connect the other terminals of the nichrome wire heater and the light bulb to the other terminal of the battery. Current will begin to flow through the bimetallic strip and metal contact. It will continue through both the heater and the light bulb before returning to the battery. The light bulb will light and the heater will heat. When the bimetallic strip's temperature exceeds some value, it will bend away from the metal contact and current will stop flowing. The light will go out and the heater will stop heating. After a few seconds, the strip will have cooled enough to straighten out and will again touch the metal contact. The light will turn back on and so will the heater. The system will switch on and off indefinitely.

Explanation: This blinker arrangement oscillates indefinitely because whenever the heater is on it soon turns itself off and whenever the heater is off it soon turns itself on.

178. Liquid Crystal Thermometers

Description: Numbers on a flat plastic strip change colors as the strip's temperature changes. A larger sheet of plastic changes colors as you rub your hand across it.

Purpose: To show how temperature can affect the ordering of liquid crystals.

Supplies:

1 liquid crystal room or aquarium thermometer (a flat plastic strip thermometer that measures temperatures near room temperature)
1 sheet of liquid crystal film that changes colors in the temperature range only slightly above room temperature

Procedure: Show that the liquid crystal thermometer is reading room temperature—that only one or two of its numbers are brightly colored. Then warm the thermometer with your hand and show that the different numbers appear and disappear as the strip's temperature rises. Each number appears when the liquid crystal it contains achieves the proper ordering characteristics. Now examine the liquid crystal film. At room temperature, it should be mostly colorless. But when you begin to heat it with your hands, it will become brightly colored. As its temperature increases, the liquid's order becomes such that it reflects visible light.

Explanation: These temperature sensitive films contain chiral nematic liquid crystals that naturally form spiral structures within the film. The pitch of these spirals is temperature dependent. When the temperature of a particular liquid crystal mixture is such that its spiral pitch is equal to the wavelength of visible light, that liquid crystal will reflect some of the visible light. The liquid crystals in the various numbers of the thermometer are slightly different and achieve the right pitch at different temperatures. In the large film, only the portions of the film that are with the right temperature range reflect visible light.

179. Color-Changing Toys

Description: Toys ranging (from shirts to pens) made from special plastics change colors when heated by body heat, friction, or contact with hot water.

Purpose: To show another type of crude thermometer.

Supplies:

1 color changing toy (BIC makes a set of color changing pens call "wavelengths")

Procedure: First examine the toy or pen while it's at room temperature. Then warm the toy or pen by holding it or rubbing its surface (sliding friction). The toy or pen's color will become much lighter.

Explanation: The plastic contains tiny bubbles. Each of these bubbles contains a mixture of chemicals, one of which melts at a temperature slightly above room temperature. At room temperature, that chemical is solid and the remaining liquid chemicals are brightly colored. But when the plastic is heated and the solid chemical melts, it interferes chemically with the coloring molecules of the liquid. The liquid loses its color. Upon cooling, the melted chemical solidifies again and the liquid's color returns. The plastic often contains a second, temperature-insensitive dye that becomes visible when the other color vanishes at elevated temperatures.

180. Thermocouples as Temperature Sensors

Description: You measure the voltage developed between the two wires of a thermocouple when that thermocouple is immersed in liquid nitrogen or heated over a burner.

Purpose: To show that mobile electrons not only make metals good conductors of heat, they also gives metals interesting electric properties when the metals are exposed to temperature gradients.

Supplies:

1 thermocouple (two different wires of, for example, iron and constantin, that have been twisted or welded together at one end)
1 sensitive voltmeter (or thermocouple readout)
1 gas burner
matches
1 container of liquid nitrogen

Procedure: Form the thermocouple by removing about 1 cm of insulation from each end of the two different wires and twisting the pair of wires together at one of their ends. Attach the voltmeter to the free ends of the two wires. With everything at room temperature, the voltmeter will read zero volts. But when you heat or cool the twisted end of the thermocouple, the voltmeter will read a small non-zero voltage (in the tens of millivolts range).

Explanation: When you heat or cool the twisted end of the thermocouple, there is a temperature gradient along each wire. Because the mobile electrons in each wire are moving fastest at the hotter end, they tend to migrate to the colder end and make the colder end of each wire negatively charged (the Seebeck Effect). However, the extent of this negative charging depends on the wire. By comparing the charging of two different wires, you can determine the temperature difference across the wires.

181. Thermistors as Temperature Sensors

Description: The electric resistance of a thermistor decreases as its temperature increases.

Purpose: To show that semiconductors become better conductors as their temperatures rise.

Supplies:

1 thermistor
1 ohm meter
hot water
ice water

Procedure: Connect the two wires of the thermistor to the ohm meter and determine its resistance at room temperature. Now immerse the thermistor in hot water (or simply pinch it in your fingers) and observe its decrease in resistance. Finally, immerse the thermistor in cold water and observe its increase in resistance.

Explanation: The thermistor is a semiconductor that would normally not conduct current if it weren't for thermal energy. At absolute zero, the semiconductor would have all of its valence levels filled and all of its conduction levels empty and it would be unable to transport electric charge. Thermal energy transfers electrons from filled valence levels to unfilled conduction levels and makes it possible for the semiconductor to transport charge—to carry current. The more thermal energy (i.e. the higher the temperature), the more easily the semiconductor carries charge.

182. Copper wire as a Temperature Sensor

Description: The electric resistance of a coil of copper wire decreases as its temperature decreases.

Purpose: To show that metals become better conductors as their temperatures fall.

Supplies:

1 coil of thin copper wire
1 light bulb (one that requires a fair amount of current)
1 battery
1 container of liquid nitrogen
wires

Procedure: Form a complete circuit by connecting one terminal of the battery to one end of the coil of copper wire, the other end of the coil of copper wire to one end of the bulb, and the other end of the bulb to the other terminal of the battery. The bulb should glow dimly because the current should be losing most of its energy in the copper wire. Now immerse the coil of copper wire into liquid nitrogen. As its temperature drops, the copper will become a better electric conductor and the light bulb will become much brighter.

Explanation: As current flows through room temperature copper wire, the individual charges collide with the vibrating copper atoms and transfer some of their energies to the copper atoms. When the copper is chilled to low temperature, the copper atoms vibrate less and their increased order makes them less likely to be hit by moving charge. Copper's electric resistance drops as its temperature drops and it becomes a better conductor.

Section 7.1 Air Conditioners

183. A Bean Illustration of Heat Flow from Hot to Cold

Description: A glass dish is initially divided into two sides. One side contains mostly black beans (representing fast moving atoms) while the other side contains mostly white beans (representing slow moving atoms). When the division is removed and the beans are stirred randomly, the result is an even mixture of beans in each side, not an accumulation of pure black beans on one side and pure white beans on the other.

Purpose: To show how statistical issues affect physical problems.

Supplies:

1 bag of black beans
1 bag of white beans
1 shallow glass dish (a rectangular baking pan)
1 cardboard or wooden divider for the pan

Procedure: Divide the pan in half and partially fill the two halves of the pan with beans. On the left, put mostly black beans and on the right, mostly white beans. Announce that the black beans represent fast moving and thus energetic atoms and that the white beans represent slow moving and thus less-energetic atoms. Because of how the beans are distributed, the left side of the pan is hot (mostly fast atoms) while the right side of the pan is cold (mostly slow atoms).

Now remove the divider and stir the beans randomly. After a few seconds, reinsert the divider and examine the beans. Note that each side now contains a roughly equal mixtures of the two beans. Each side is now at an intermediate temperature, neither hot nor cold. Point out that there is no fundamental law that makes it impossible for all the white beans to end up on the right (extra cold) and all the black beans to end up on the left (extra hot). That outcome is not forbidden, it's just incredibly unlikely.

The same result holds true for temperature—if a hot object and a cold object touch, there's no mechanical law that forbids heat from flowing from the cold object to the hot object so that the hot object becomes hotter and the cold object becomes colder. That outcome is not forbidden by the laws of motion, it's just incredibly unlikely.

Explanation: The laws of thermodynamics incorporate statistical issues that are not contained in the basic laws of motion. They predict the dynamics of large assemblies of particles that are exhibiting thermal behaviors. This illustration with beans shows how statistical issues similarly contribute to more visible situations.

184. A Simple Heat Pump Using Air

Description: As you pump air into a sealed jug, its temperature rises and heat flows out of it into the room. When you let the air in the jug expand, its temperature drops and heat flows into it from the room.

Purpose: To show how compression and expansion of a gas can be used to move heat around.

Supplies:

1 strong narrow mouth jug (plastic or glass)
1 one-hole rubber stopper for the jug with a pipe in the hole
1 small electronic temperature sensor
1 hose
1 hand air pump (a bicycle pump, for example)

Procedure: Insert the temperature sensor into the jug, so that its sensor is hanging freely in the air inside the jug. Now insert the stopper into the jug. Use the hose to connect the pipe in the stopper to the air pump. Note the temperature of the air inside the jug.

Now begin to pump air into the jug. As you do, the temperature inside the jug will rise. You'll have to go fast enough that the heat won't have time to flow out into the room, or you won't see much of a temperature rise.

While the air inside the jug is still pressurized, wait for it cool down to room temperature. Then suddenly release the pressure, either by popping the stopper out of the jug or removing the hose from the pipe. As the air expands and flows out of the jug, the temperature of the remaining air will fall well below room temperature.

Explanation: When you compress air to pack it into the jug, you're doing work on that air and its energy is increasing. This increased energy takes the form of a rise in the air's thermal energy, and is thus accompanied by a rise in temperature. When you allow the air to expand out of the jug, it must lift the surrounding air out of its way and thus does work on the surrounding air. Its energy is decreasing. This decreased energy takes the form of a drop in the air's thermal energy and is thus accompanied by a drop in temperature.

Follow-up: Discuss how you would use this process to move heat from one room to another. At what times should you move the apparatus between the rooms?

185. A Simple Heat Pump Using a Condensable Liquid

Description: You fill a clear glass tube with gas and insert a piston into the tube. When you push the piston deep into the tube, the gas inside it turns into a liquid. When you pull the piston out of the tube, the liquid turns back into a gas.

Purpose: To show that compressing some gases can actually cause them to liquefy at room temperature and that allowing some liquids to decompress can actually cause them to become gaseous at room temperature.

Supplies:

- 1 fire syringe (available from a scientific supply company—normally used to show that compressing air suddenly can cause it to become hot enough to ignite cotton)
- 1 gas duster (an aerosol canister that's used to blow dust off optics—it contains a hydrofluorocarbon that's liquid at high pressure but gaseous at low pressure, even at room temperature)

Procedure: Remove the piston from the fire syringe and spray the gas duster into the cylinder until all the air has been displaced and replaced by the hydrofluorocarbon (HFC) gas. Quickly insert the piston so as to trap the HFC gas. Now push the piston deep into the cylinder. When the pressure in the gas becomes high enough, it will liquefy. You should obtain a small fraction of a milliliter of liquid at the very bottom of the cylinder when the piston is almost at the bottom. When you then let the piston move back away from the bottom of the cylinder, the liquid will boil away into a gas. While in principle you should be able to feel the cylinder become hot during the compression process and become cold during the decompression process, the effect is so small that I've been unable to feel it.

Explanation: At room temperature, the HFC compound forms a liquid when its pressure is high and a gas when its pressure is low. Compressing the gas first causes it to become a hot gas. After most of its excess heat has flowed into the cylinder walls, this cooling gas becomes a liquid. As that condensation occurs, still more heat flows out of the material and into the cylinder walls. Now decompressing the liquid first causes it to become a cold gas. After heat has flowed into it from the cylinder walls, this warming liquid becomes a gas. As that evaporation occurs, still more heat flows into the material from the cylinder walls.

186. Examining a Refrigerator

Description: You examine the three major components of a small refrigerator—the compressor, the evaporator, and the condenser.

Purpose: To show how a real heat pump works.

Supplies:

- 1 small (dormitory size) refrigerator

Procedure: Follow the path of the working fluid from the compressor (located at the bottom back of the refrigerator), through the condenser (the coils on the back of the refrigerator), through the evaporator (the case of the freezing compartment), and back to the compressor.

Explanation: The working fluid in the refrigerator enters the compressor as a room temperature, low-pressure gas and leaves as a hot, high-pressure gas. It then enters the condenser and leaves as a room temperature, high-pressure liquid. It then enters the evaporator and leaves as a cool, low-pressure gas. Finally it returns to the compressor.

187. A Peltier Junction - An Electronic Heat Pump

Description: An electric current is run through a thermoelectric cooler, causing one of its surfaces to become hot and the other surface to become cold.

Purpose: To display a thermoelectric effect in which electric power is used to pump heat from a colder surface to a hotter surface.

Supplies:

1 thermoelectric cooler, based on Peltier junctions (available from a scientific supply company)
1 power supply or hand-powered generator

Procedure: Attach the two terminals of the thermoelectric device to the power source and send current through it. One surface of the device will become quite hot and the other quite cold. If you attach the hot surface to a good room temperature heat sink and place a drop of water on the cold surface, the drop of water will soon freeze to form ice. Show that reversing the direction of current flow through the device reverses the direction in which heat is pumped between its surfaces.

Explanation: The thermoelectric device is using the Peltier effect, the reverse of the Seebeck effect, to pump heat from a colder surface to a hotter surface. The device contains a number of individual Peltier junctions, formed by touching two dissimilar semiconductors. Just as a thermocouple can power an electric current when it has a temperature difference across its wires, a thermoelectric device can produce a temperature difference across its junctions when it's powered by an electric current.

Section 7.2 Automobiles

188. A Simple Heat Engine - A Steam Engine

Description: The boiler of a toy steam engine is heated by a gas flame. When steam from the boiler is delivered to its cylinder, the steam engine's piston begins to move back and forth and a flywheel spins rapidly.

Purpose: To show that heat flowing from a hot region to a cold region can be used to do "useful" work.

Supplies:

1 toy steam engine (available from a scientific supply company)
water
natural gas (or alcohol, if appropriate)
matches

Procedure: Fill the boiler with water and connect the steam engine to the gas supply. Light the engine's burner and allow the water to begin to boil. When pressurized steam begins to flow to the cylinder, the piston will begin to move in and out and the steam engine's flywheel will begin to turn.

Explanation: Heat from gas flame enters the colder water and heats it to its boiling temperature. The hot, high-pressure steam then flows to the lower pressure in the cylinder and pushes the piston out of the cylinder. The piston's movement opens a valve that vents the steam from the cylinder and allows the piston to return into the cylinder. Once the piston reaches the bottom of the cylinder, the valve closes and steam once again pushes the piston out. This motion of the piston repeats over and over, while the piston's reciprocating motion causes the flywheel to turn. The flywheel stores energy and helps the piston move smoothly through its cycle. Overall, heat is flowing from the boiler to the outside air and a small fraction of that heat is diverted by the steam engine and converted into mechanical work.

189. A Simple Heat Engine - a Dipping Duck

Description: A glass duck toy is placed so that it can dip its bill into a glass of water. It repeatedly leans forward and appears to drink from the glass of water. This tipping behavior is powered by a heat engine in the duck.

Purpose: To demonstrate an interesting form of heat engine.

Supplies:

1 dipping duck heat engine toy (from a scientific supply company)
1 very full glass of water for the duck to "drink"

Procedure: Place the dipping duck next to the glass of water so that it can lean forward until it's horizontal and just dips its bill into the water. Tip the duck forward so that its bill gets wet and then allow it to return to upright. In a few seconds, evaporative cooling will lower the temperature of its head and fluid will begin to rise up inside of the duck's body. The duck will tip over and take a drink of water, while the fluid returns to the bottom of its body. The duck will return to its upright position and the process will begin again.

Explanation: Evaporative cooling keeps the duck's wet head colder than its dry tail. Because of its cold head, gas inside the duck's body evaporates in the tail area and condenses in the head area. This process creates a pressure imbalance between the duck's head and tail that pushes the liquid upward from the tail to the head. Each time this transfer of liquid occurs, the duck's center of gravity rises until the duck becomes unstable and tips forward. When the duck reaches a horizontal orientation and wets its bill in the water, the liquid is able to flow back toward its tail. Overall the duck is a heat engine, using the flow of heat from its warmer tail to its colder head to make the duck dip repeatedly.

190. Knocking in an Automobile Engine

Description: A tiny piece of cotton or paper towel is dropped to the bottom of a clear glass cylinder. A narrow piston is inserted into that cylinder and shoved suddenly to the bottom, compressing the air inside the cylinder. The air becomes so hot during the compression that it ignites the cotton or paper, which burns with a bright flash of light.

Purpose: To show just how hot air can become when it's compressed tightly and to show how knocking occurs in an automobile engine.

Supplies:

- 1 fire syringe (from a scientific supply company)
- 1 tiny piece of cotton or paper towel

Procedure: Make sure that the inside of the glass fire syringe is clean and dry, and that the air it contains is fresh. Make sure that the piston travels smoothly through the cylinder and lubricate the O-rings very lightly with salad oil if it doesn't. Drop or push a tiny piece of cotton, just a dozen fibers or so, to the bottom of the cylinder and insert the piston. Install the plastic guard around the glass tube and place the whole assembly on a firm rubber pad that is itself on a solid table. When you're ready, push the piston suddenly and vigorously to the bottom of the cylinder. The cotton will burst into flames.

Explanation: You do work on the air as you push the piston into the cylinder. The air's energy increases and this energy increase takes the form of thermal energy—the air becomes hot. Since you compress the air very suddenly, heat has little time to flow out of the air to the walls of the tube and the air becomes so hot that it ignites the cotton. Since the cotton is surrounded by hot, compressed air, it burns with a bright flash of light.

191. Burning a Fuel and Air Mixture - an Exploding Milk Container

Description: A gallon plastic milk jug, containing air and a small amount of alcohol, is exposed to a high voltage spark. With a bang and a bright flash of light, the container leaps up into the air.

Purpose: To illustrate how much energy is contained in even a small amount of liquid organic fuel.

Supplies:

- 1 gallon polyethylene milk container, with a screw top (clean and completely dry)
- 2 medium-sized nails
- 1 hammer
- 1 board, about 20 cm on a side and about 1 cm thick
- 1 clamp
- wires
- a spark coil or tesla coil
- safety glasses
- methyl alcohol (methanol)
- 1 small beaker, marked at 0.5 ml volume intervals

Procedure: Pound the nails through the middle of the board, about 1 cm apart, so that their points emerge from the board. Bend these sharp points slightly toward one another and attach wires to them from the other side of the board. Clamp the board to the edge of a table, with the nail points sticking upward. Connect one of these wires to an earth ground and put the other wire where you can reach it easily with the spark generator. The wire should be long enough that you will be 2 m or more away from the milk container when it explodes.

Now measure 1.5 ml of alcohol in the beaker and pour this into the milk container. Put the top on the container and swirl the alcohol around the inside of the container to help it evaporate. Give it about twenty seconds to evaporate completely. Invert the milk container and push the cap down over the two upward-pointing nails so that the nails pierce the cap.

Step back to a safe distance, put on the safety glasses, and touch the spark generator to the exposed wire. A spark will occur inside the milk container, igniting the alcohol and air mixture. The container will explode with a flash and a loud report, and it will fly up into the air. In most cases, the milk container will tear open and will not be reusable.

Explanation: The spark provides the initial activation energy needed to start the chemical reaction between the alcohol and air. Once ignited, the burning mixture does lots of work on its environment and on your ears.

Section 8.1 Water, Steam, and Ice

192. Melting Ice

Description: A thermometer inserted in a container filled with a mixture of water and ice reads 0° C, even when the container is heated by a flame or cooled by dry ice.

Purpose: To show that the phase transition between water and ice occurs at 0° C, and that adding or removing heat from a mixture of the two causes one phase to transform into the other and doesn't change the temperature of the mixture.

Supplies:

1 Pyrex or Kimax beaker
water and ice mixture
1 thermometer
1 support for the beaker
1 support for the thermometer
1 gas burner
matches
1 cube of dry ice

Procedure: Place the beaker on the support and fill it with a mixture of ice and water. Insert the thermometer in the beaker and support the thermometer so that it doesn't touch the sides of the beaker. In a few seconds, the thermometer will read 0° C. To show that adding or removing heat from the mixture of water and ice won't change its temperature, first add heat to the mixture by heating it gently with the gas burner (don't heat too aggressively, or you'll break the beaker). The thermometer will still read 0° C. Finally, put away the burner and put the beaker on the cube of dry ice. Make sure that the thermometer doesn't touch the sides of the beaker. The thermometer will still read 0° C.

Explanation: While water and ice are in equilibrium with one another, the temperature must be 0° C. If you add heat to this mixture, some of the ice will transform into water but the mixture's temperature will remain at 0° C. If you remove heat from this mixture, some of the water will transform into ice but the mixture's temperature will remain at 0° C.

193. Boiling Water with Heat

Description: A beaker of water is heated with a burner. Although water will be seen to evaporate once the water is hot, it will only begin to boil when the water's temperature approaches 100° C. Once the water is boiling, additional heat will not cause its temperature to rise.

Purpose: To show that while evaporation can proceed at any temperature, boiling appears when evaporation becomes rapid enough to occur within the body of the liquid. Also to show that during boiling, adding heat to the water causes it to transform into steam rather than to become hotter.

Supplies:

1 Pyrex or Kimax beaker
water
1 support for the beaker
1 gas burner
matches
1 thermometer
1 support for the thermometer

Procedure: Place the beaker on the support and fill it half way full of water. Insert the thermometer into it and support the thermometer so that it doesn't touch the sides of the beaker. Light the burner and put it under the beaker. Heat the beaker gently so that it doesn't break. As the water becomes warmer, mist will appear above the water. A short while later, gas bubbles will appear on the walls of the beaker. And finally, bubbles of steam will appear within the water and the water will begin to boil. At that point, the temperature of the water will be approximately 100° C and this temperature will remain constant, despite the continued input of heat by the burner.

Explanation: As the water warms up, evaporation from its surface will become faster and faster. A mist will appear above the water when the evaporation becomes fast enough to send hot, water-saturated air upward into the cooler air above the beaker—as this hot, water-saturated air cools, water droplets form in it and create the mist that you see. The gas bubbles that appear on the walls of the beaker are dissolved gases that comes out of solution as the water nears its boiling temperature—most gases are less soluble in hot water than in cold water. Finally, boiling occurs when evaporation is so rapid that it begins to occur within the body of the liquid. For these evaporation bubbles to form and grow, they must be able to withstand the crushing effects of atmospheric pressure. By the time the water reaches 100° C, the bubbles of steam inside the water are so dense with water molecules that they have a pressure equal to atmospheric pressure and can't be crushed by atmospheric pressure.

194. Boiling Water in a Vacuum

Description: A glass of room temperature water is put in a glass bell jar and the air is removed from that bell jar by a vacuum pump. The water begins to boil. Moments later, air is admitted to the bell jar and it's removed. The water is still cool.

Purpose: To show that water's boiling temperature depends on the ambient pressure.

Supplies:

1 glass
water
1 bell jar and vacuum pump system

Procedure: Fill the glass half way full of water and insert your finger in it to show that it's cool. Put the glass in the bell jar and turn on the vacuum pump. When enough air has left the bell jar, the water will begin to boil. Stop the vacuum pump and allow air to reenter the bell jar. Open the jar and insert your finger into the water to show that its still cool.

Explanation: While evaporation is always occurring at the surface of cold water, it can't normally occur in the body of cold water because any evaporation bubble that appears inside the water will have too low a density and pressure to withstand the crushing effects of atmospheric pressure. But when a vacuum system has removed most of the air and air pressure from around a glass of water, evaporation bubbles that appear inside the water will be able to grow and expand. The water will boil even at low temperatures.

Follow-up: Try to soft boil an egg in a glass of water that's boiling in a bell jar. The egg won't cook at all. That's because boiling a three minute egg really means exposing that egg to water at 100° C for three minutes. In the vacuum chamber, you're exposing an egg to water at room temperature for three minutes and that has no effect on the egg at all. Why does it take longer to boil an egg at high altitude than it does at sea-level?

Another Follow-up: Try putting ice water in the vacuum. It will also boil if you're patient enough.

195. Condensing Steam - Crushing a Beverage Can

Description: You heat a small amount of water in an open beverage can until the can fills with steam. You then quickly invert the can and plunge it into a pan of cold water. The can is immediately crushed by atmospheric pressure.

Purpose: To show that removing heat from steam causes it to condense into water and that water occupies a much smaller volume than steam.

Supplies:

1 empty aluminum beverage can
1 ring stand
1 gas burner
1 cooking pan
tongs
matches
water

Procedure: Fill the cooking pan with about 3 cm of cold water. Pour about 2 ml of water into the beverage can and place it on the ring stand. Light the burner and heat the bottom of the can until the water boils. After the can has completely filled with steam and the steam has completely displaced any air the can contained (about 20 seconds of boiling), use the tongs to pick the can up, invert it, and plunge it into the pan of cold water. The can will collapse with a crunching sound.

Explanation: Boiling water in the can fills it with steam rather than air. When the steam is immersed in cold water, it gives up heat to the cold water and undergoes a phase change back into water. Water occupies much less volume than steam and the can is left virtually empty. With nothing inside it to support its walls, the can is crushed by the surrounding air pressure.

196. Dissolving Salt, Sugar, and Carbon Dioxide in Water

Description: You mix sugar, then salt, then carbon dioxide into water. All three dissolve easily.

Purpose: To discuss the mechanisms whereby added materials dissolve in water.

Supplies:

3 glasses
water
salt
sugar
1 soda siphon
1 carbon dioxide cylinder
1 spoon

Procedure: First add a spoonful of salt to a glass of water and stir. In a few seconds, the salt will have disappeared. Point out that the salt is still there, it has just decomposed into individual sodium positive ions and chlorine negative ions, each of which is now wrapped in an entourage of water molecules.

Now add a spoonful of sugar to the glass of water and stir. Again, it will dissolve. Point out that the sugar molecules are separated from one another and surrounded by shells of water molecules.

Finally, fill the soda siphon with water, put the top on, and charge the siphon with carbon dioxide according to its instructions. Shake the siphon to disperse the carbon dioxide and wait a few seconds. Then serve the carbonated water into a glass. It will bubble merrily. Note that the carbon dioxide molecules have attached themselves to water molecules to form a weak acid known as carbonic acid.

Explanation: Salt dissolves well in water because water molecules are strongly attracted to sodium and chlorine ions. They wrap those ions in solvation shells of water molecules. The negative ends of the water molecules (their oxygen atoms) turn toward a positive sodium ion and the positive ends of the water molecules (their hydrogen atoms) turn toward a negative chlorine ion. Sugar dissolves well in water because water molecules bond relatively well to sugar molecules. Water molecules form hydrogen bonds with the oxygen-hydrogen groups on a sugar molecule and construct a solvation shell around the sugar molecule. Finally, carbon dioxide dissolves well in water because water molecules combine with carbon dioxide molecules to form a new molecule—carbonic acid. The binding between these two molecules is modest but it's enough to make it easy for carbon dioxide to dissolve in water.

197. Depressing the Melting Point of Ice with Salt or Sugar

Description: A beaker of melting ice initially has a temperature of 0° C. When salt or sugar is added to the ice, the temperature drops well below 0° C.

Purpose: To show that adding a water-soluble solid to ice depresses its melting temperature.

Supplies:

1 beaker
ice
salt or sugar
1 thermometer
1 support for the thermometer
1 spoon

Procedure: Fill the beaker with ice and carefully insert the thermometer in it. Support the thermometer so that it doesn't touch the walls of the beaker. After a few seconds, the thermometer will read 0° C. Now remove the thermometer and add a large spoonful of salt or sugar to the ice. Stir the mixture and reinsert the thermometer. After a few seconds the thermometer will read below 0° C.

Explanation: Adding a water soluble solid to ice destabilizes the solid phase at 0° C. The ice begins to melt to form salty or sugary water at 0° C, but this melting requires heat. The ice that does melt extracts heat from the ice that doesn't melt and the remaining ice becomes colder and colder. Soon the entire mixture, including the salty or sugary water, is at a temperature well below 0° C. The addition of the salt or sugar has caused more of the ice to become water and, because melting the ice has used some of the mixture's thermal energy, the mixture is now colder than it was before.

198. Raising the Boiling Point of Water with Salt or Sugar

Description: A beaker of boiling water initially has a temperature of 100° C. When salt or sugar is added to the water, the temperature rises well above 100° C.

Purpose: To show that adding a water-soluble solid to water raises its boiling temperature.

Supplies:

1 beaker
water
salt or sugar
1 thermometer
1 support for the thermometer
1 spoon
1 support for the beaker
1 gas burner
matches

Procedure: Place the beaker on the support and fill it with water. Carefully insert the thermometer in it and support the thermometer so that it doesn't touch the walls of the beaker. Light the burner and gently heat the beaker. Be careful not to heat the beaker too quickly or it may break. Soon the water will boil and the thermometer will read about 100° C. Now add a large spoonful of salt or sugar to the boiling water. Stir the mixture. When the mixture again begins to boil, the thermometer will read well above 100° C.

Explanation: Adding a water soluble solid to water interferes with its ability to evaporate. With many of the water molecules involved in stabilizing the dissolved solid, there are fewer water molecules evaporating at any given temperature. The water temperature must exceed 100° C before evaporation is fast enough for evaporation bubbles to become stable within the body of the water so that boiling can occur.

199. Regelation of Ice

Description: A heavily weighted wire is draped over a melting ice cube. The wire slowly descends into the ice cube, leaving a healed scare of solid ice above it.

Purpose: To show that pressure depresses ice's melting temperature.

Supplies:

- 1 large ice cube (frozen in a rectangular muffin tin)
- 1 board to support the ice cube
- 1 clamp
- 1 piece of piano wire
- 1 heavy weight

Procedure: Clamp the support board to a sturdy table so that it extends out over the floor. Place the ice cube on the support. Tie loops at the two ends of the piano wire, drape the wire over the ice cube, and hang the heavy weight from the two loops so that the wire is pulled tightly against the ice cube. When the ice cube warms to 0° C and begins to melt, the wire will begin to cut into the ice cube and will soon disappear below its surface. The ice will reform above it, so that the wire will soon be trapped in solid ice.

Explanation: This whole process takes place while the ice cube is at almost exactly 0° C. The elevated pressure below the piano wire depresses the ice's melting temperature so that water's liquid phase is more stable below the wire than is water's solid phase. The ice there melts and the wire descends into the liquid water. Relieved of the pressure, the water returns to its solid phase. Ice thus melts below the wire and reforms above the wire. In fact, there is a continual heat transfer from the freezing water above the wire to the melting ice below the wire. In this manner, the wire drifts right through the solid ice cube.

Section 9.1 Clocks

200. Pendulums as Time-Keepers

Description: You swing several pendulums back and forth. Each one has a steady period that doesn't depend on how far it swings. The taller the pendulum, the longer its period.

Purpose: To show that a pendulum has the characteristics of a harmonic oscillator—a restoring force that's proportional to displacement (almost) and consequently a period that doesn't depend on the amplitude of motion (almost).

Supplies:

- 2 or more pendulums (one should be about 0.25 m tall, from pivot to center of mass/gravity, and another should be about 1.00 m tall).
- supports for the pendulums

Procedure: With the 0.25 m pendulum motionless, discuss the fact that it's in a stable equilibrium. Discuss that the restoring force it experiences is proportional to how far it's displaced from its equilibrium position. (Avoid discussing it's slight anharmonicity here—you'll confuse the students.) Note that this proportionality between displacement and restoring force makes the pendulum a harmonic oscillator.

Now displace the pendulum from equilibrium and release it. Time the swings to determine its period. The period should be almost exactly 1 s. Show that swinging the pendulum harder or softer doesn't affect its period (but don't swing it too hard or you'll discover the slight anharmonicity). Now do the same with the 1.00 m pendulum. Discuss how the short pendulum could serve as the time-keeper for a clock with a second hand that advances by 1 s for each full cycle of the pendulum and the long pendulum could serve as the time-keeper for a clock with a second hand that advances by 2 s for each full cycle of the pendulum.

Explanation: The period of a pendulum is equal to 2π times the square root of its length divided by the acceleration due to gravity. A 0.25 m pendulum thus has a period of about 1 s while a 1.00 m pendulum has a period of about 2 s. The increase in period with length is due to a softening of the restoring force—the longer the pendulums arm, the less rapidly the restoring force increases as you displace the pendulum bob from its equilibrium position. Increasing the acceleration due to gravity would stiffen the restoring force and speed the pendulum's motion and period.

201. A Mass on a Spring as a Time-Keeper

Description: A mass hanging on a spring bounces up and down with a steady period, regardless of the amplitude of that bounce. The larger that mass, the longer the period of the bounce.

Purpose: To show that a mass on a spring has the characteristics of a harmonic oscillator—a restoring force that's proportional to displacement and consequently a period that doesn't depend on the amplitude of motion.

Supplies:

1 large coil spring (medium stiffness)
2 different masses
1 support for the spring

Procedure: Hang the spring from the support and attach the smaller mass to it. Allow the spring to stretch until the mass and spring are in equilibrium. Point out that the mass is in a stable equilibrium, that the spring is exerting just enough upward force on the mass to support its weight and that the mass is experiencing zero net force. Show that displacing the mass up or down causes it to experience a restoring force that's proportional to the displacement. Now displace the mass from equilibrium and release it. Time the bounces to determine their period. Show that this period doesn't depend on how large the amplitude of motion is. Repeat this process with the larger mass hanging from the spring. Discuss why the period of oscillation is now longer than with the smaller mass.

Explanation: In this system, gravity merely shifts the mass's equilibrium position because the mass's weight doesn't change with its position. Only the spring exerts a force that changes with position and only the spring contributes to the oscillatory motion. In this case, the period decreases with the increasing stiffness of the spring (stiffer restoring forces cause more rapid accelerations) and increases with the increasing mass of the oscillating mass (larger masses cause slower accelerations).

202. A Mass on a Hacksaw Blade as a Time-Keeper

Description: A ball of putty attached to a hacksaw blade oscillates back and forth rhythmically. Adding more putty slows the oscillation while shortening the blade speeds the oscillation up.

Purpose: To show that mass-on-spring harmonic oscillators can take many forms.

Supplies:

1 hacksaw blade (a stiff metal-saw blade)
1 ball of putty
1 clamp

Procedure: Clamp the hacksaw blade on the edge of a sturdy table so that it extends far out over the edge of the table. Attach the ball of putty to the free end of the blade. Allow the ball and blade to settle and point out that the ball is now in equilibrium. Show that displacing the ball from equilibrium, either up or down, causes it to experience a restoring force that's proportional to its displacement. Now displace the ball from equilibrium and let go. It will oscillate up and down with a period that doesn't depend on its amplitude of motion. It's another harmonic oscillator. Discuss ways of changing its period (changing the mass of the ball or changing the length of blade that extends over the table). Try these approaches to see what happens.

Explanation: The spring-like blade exerts a restoring force on the putty and the putty's mass resists acceleration. Since the blade's restoring force is proportional to its bend, the system is a harmonic oscillator. Decreasing the mass of the putty allows it to accelerate more rapidly and shortens the oscillator's period. Shortening the portion of the blade that extends out from the table stiffens it and also shortens the oscillator's period.

203. A Ball Rolling in a Bowl or Trough as a Time-Keeper

Description: A ball or marble rolls back and forth in a shallow bowl with a period that doesn't depend on the amplitude of its motion.

Purpose: To show yet another form of harmonic oscillator. This one resembles a pendulum, but without the string.

Supplies:

- 1 ball or marble
- 1 large, round-bottom bowl or trough

Procedure: Place the ball at the bottom of the bowl or trough and show that it's in a stable equilibrium. Show also that the restoring force the ball experiences is proportional its displacement from equilibrium. Now displace the ball from equilibrium and release it. It will roll back and forth with a period that's independent of its amplitude of motion.

Explanation: Neglecting the rolling process, the ball is following the same path that a pendulum bob would and is thus simply a modified pendulum oscillator. The shallower the bowl, the longer the effective pendulum's string and the longer the oscillator's period.

204. A Ruler Vibrating on the Edge of a Table

Description: You hang a meter stick over the edge of a table and pluck it downward. It vibrates with a period that doesn't depend on its amplitude of motion. As you shift it onto the table and shorten the portion that extends out over the edge, the period of oscillation becomes shorter and shorter.

Purpose: To illustrate yet another harmonic oscillator.

Supplies:

- 1 meter stick (or another thin, stiff stick)

Procedure: Extend the meter stick out over the edge of a sturdy table and hold the portion that rests on the table firmly against the table. Show that the free end of the meter stick is in a stable equilibrium. Now push the free end away from its equilibrium position and release it. The meter stick will vibrate up and down with a steady period that doesn't depend on its amplitude of motion. Now shift more of the meter stick onto the table and repeat the experiment. Its period will be shorter.

Explanation: The meter stick is a harmonic oscillator with a period that depends on its stiffness and mass. Shortening its free end reduces the oscillating mass and stiffens the restoring force. Since both of these changes make accelerations more rapid, the meter stick's period of oscillation shortens dramatically as you decrease the length of the free end.

205. A Torsional Pendulum as a Time-Keeper

Description: A massive disk hanging from a stiff wire twists back and forth with a period that doesn't depend on the amplitude of its twisting motion.

Purpose: To show that some harmonic oscillators involve restoring torques and angular accelerations rather than restoring forces and accelerations.

Supplies:

- 1 heavy disk
- 1 stiff metal wire, thin metal rod, or relatively thin wooden dowel
- 1 support for the wire, rod, or dowel

Procedure: Attach the wire, rod, or dowel to the center of the heavy disk. Make sure that the disk is balanced and remains horizontal when it's hanging from the wire, rod, or dowel. Attach the wire, rod, or dowel to the support and allow the disk to reach its equilibrium orientation. Show that the disk is in a stable equilibrium orientation—that it's experiencing zero torque but that it experiences a restoring torque whenever it's displaced from its equilibrium orientation. Point out also that the restoring torque it experiences is proportional to its angular displacement.

Now displace the disk from its equilibrium orientation and release it. It will twist back and forth with a period that depends only on the disk's moment of inertia and the stiffness of the wire, rod, or dowel. If you're careful, you can change the moment of inertia with added masses (keep them balanced!) and you can adjust the stiffness of the restoring torque by changing the length of the wire, rod, or dowel.

Explanation: This torsional harmonic oscillator has a restoring torque rather than a restoring force and a moment of inertia rather than a mass. Its period motion involves angular acceleration and angular velocity rather than acceleration and velocity. Nonetheless, its period doesn't depend on its amplitude of motion because the restoring torque is proportional to angular displacement.

206. Examine a Pendulum Clock

Description: You open a pendulum clock to show how the swinging pendulum controls the turning of the clock's hands.

Purpose: To show how the clock uses its pendulum to time the steps of its second hand.

Supplies:

1 real pendulum clock (not an electronic clock with a decorative pendulum)

Procedure: Time the period of the clock's pendulum and examine its length. It should be 0.248 m long for a 1 s period or 0.996 m long for a 2 s period (from pivot to center of mass/gravity). If you can view the clock's mechanism, watch the swinging pendulum release the toothed wheel that governs the turning of the clock hands. The anchor that tips with the pendulum adds energy to the pendulum and controls the turning rate of the clock hands. Look to see if the pendulum has a temperature compensation system and a length adjustment. What provides the energy that keeps the pendulum swinging?

Explanation: A pendulum clock has a simple mechanism—the pendulum receives small pushes as it swings and it allows the clock's second hand to advance one step with each swing.

207. Examine a Balance Ring Clock

Description: You open a balance clock to show how the rocking balance ring controls the turning of the clock's hands.

Purpose: To show how the balance ring clock uses the balance ring to time the steps of its second hand.

Supplies:

1 balance ring clock or watch

Procedure: Observe the balance ring rocking back and forth. Identify the spring that provides the restoring torque for this torsional motion. Find the lever and anchor that deliver the tiny pushes that keep the balance ring rocking and that control the advance of the clock's second hand.

Explanation: In a balance ring clock, the balance ring is a harmonic oscillator that experiences the restoring torque of a small coil spring. As the balance ring rocks back and forth, it allows the second hand to advance a small amount for each cycle.

208. A Tuning Fork as a Time-Keeper

Description: The tines of a tuning fork oscillate in and out with a period that doesn't depend on their amplitudes of motion.

Purpose: To show that a tuning fork is another harmonic oscillator—one that has been used in clocks.

Supplies:

2 tuning forks of different sizes and pitches
1 tuning fork mallet

Procedure: Point out that the tines of a tuning fork and the metal bridge between them forms a harmonic oscillator—displacing the tines causes them to experience restoring forces. Strike one of the tines with the mallet to displace it and cause the tuning fork to vibrate. Note that its pitch (associated with its period) is independent of its amplitude of motion.

Explanation: The tuning fork acts like two masses on the ends of a single spring. The masses (tines) oscillate in opposite directions with a period that increases with their masses and decreases with the stiffness of the spring between them.

209. A Water Balloon as a Model for a Quartz Crystal Oscillator

Description: You strike a hanging water balloon with your hand and its surfaces vibrate in and out symmetrically with a steady period that doesn't depend on their amplitudes of motion.

Purpose: To illustrate the mode of vibration that's used in most quartz crystal oscillators.

Supplies:

1 large water-filled balloon (a large-size latex rubber balloon, filled as full as is practical with water)

Procedure: Hold the water balloon by its nipple in one hand and hit it moderately firmly with the other hand. (Don't break it, of course.) The balloons surfaces will oscillate in and out, with surfaces on opposite sides of the balloon moving simultaneously in opposite directions. Viewed from above, the balloon will first become narrower from left to right and wider from top to bottom and then wider from left to right and narrower from top to bottom. This motion repeats.

Explanation: The balloon acts much like two masses on a central spring. These two masses, effectively the left and right sides of the balloon, move alternately toward one another and away from one another. Their masses and the stiffness of the effective spring depend mostly on the size of the water balloon—the bigger the balloon, the slower its period of oscillation. In a real quartz oscillator, the stiffness is much greater and the period of oscillation is much shorter.

210. A Singing Aluminum Rod

Description: You rub a hard aluminum rod along its length and it begins to emit a clear, high-pitched tone.

Purpose: To illustrate the mode of oscillation used in a quartz oscillator.

Supplies:

1 rod, made of hard aluminum alloy, with a diameter of about 1 cm and a length of about 1 or 2 m
rosin or grip-enhancing spray

Procedure: Apply rosin or grip-enhancing spray to the fingers of one hand. Hold the aluminum rod at its midpoint and gently pull your rosined fingers along one end of the rod. Your skin should slide across the metal with a slip-stick motion, as though you were bowing a violin. When you achieve the correct sliding motion, the rod will begin to vibrate, getting louder and louder as your fingers slide more vigorously along the rod.

Explanation: Your fingers are gradually adding energy to a vibrational mode of the aluminum rod. In this mode, the two ends of the rod are moving in opposite directions and experience restoring forces from the spring-like middle portion of the rod. The period of oscillation depends on the stiffness of the aluminum—its Young's modulus—and on the length (and therefore mass) of the rod.

211. A Quartz Crystal Oscillator

Description: An electronic oscillator without a quartz crystal in it produces a current that fluctuates at a moderately steady rate. When a quartz crystal is added to the oscillator, the fluctuations become extremely steady at a particular value—the natural resonant frequency of the quartz crystal itself.

Purpose: To show that the mechanical vibrations of a quartz crystal can be used to control the electric oscillations of an electronic device.

Supplies:

1 quartz crystal
1 conventional electronic oscillator with a natural frequency of oscillation that's very close to that of the quartz crystal. (Many types of oscillators will do and I don't have a particular one to recommend. When I find a simple arrangement that I really like, I'll post information about it on the web site associated with demonstrations.)
1 frequency meter

Procedure: Use the frequency meter to monitor the frequency of the conventional oscillator. It will drift in frequency with time and temperature and won't hold any specific value for very long. Now insert the quartz crystal into the oscillator in a place where the crystal's natural resonance can affect its frequency of oscillation. If you place it in the proper part of the oscillator, the crystal will begin to oscillate and will pull the frequency of the conventional oscillator into synchrony with its own frequency. The frequency of the crystal oscillator won't drift with time and will remain at a particular value indefinitely.

Explanation: A quartz crystal is a piezoelectric device. When exposed to fluctuating electric fields, it begins to undergo mechanical vibrations. These vibrations are strongest when it's vibrating on its natural resonance. As the crystal vibrates, its piezoelectric nature causes charge to shift on and off its surfaces. In the oscillator, the fluctuating charges in the wires attached to the quartz crystal cause the quartz crystal to vibrate. Once the crystal is vibrating on its natural resonance, it begins to cause large charge fluctuations on its own surface and these charge fluctuations begin to affect the oscillator's frequency. Pretty soon, the crystal's vibrations are determining the oscillator's frequency—the oscillator has become phase-locked to the crystal's vibrations.

212. Atomic Transitions for Atomic Clocks

Description: A gas discharge is shown to emit very specific wavelengths or frequencies of light.

Purpose: To show that atoms absorb and emit characteristic wavelengths or frequencies of light that can be used as time-keepers for exquisitely accurate clocks—atomic clocks.

Supplies:

1 low-pressure gas discharge lamp (a narrow hydrogen tube is a good choice)
1 transmission diffraction grating (or prism)
1 CCD camera and monitor (optional)

Procedure: Observe the gas discharge lamp through the diffraction grating, or allow the CCD camera to observe the discharge through the diffraction grating and project its image on the monitor. Don't aim the grating-covered camera directly at the discharge; aim it to one side, where it will record dispersed lines of different colors. These are the atomic emission lines with very specific wavelengths and frequencies that are determined only by the characteristics of the atoms involved. Since atoms of the same atomic weights and numbers are indistinguishable, the atoms in this discharge lamp emit the same spectral lines as those in any other similar lamp. If these lines are used as the time-keepers for an atomic clock, the clock won't need to be calibrated, at least in principle.

Explanation: The light being emitted by the discharge lamp has characteristics that are determined by its atoms. Apart from perturbation effects due to electric fields, magnetic fields, and collisions with other atoms, the wavelengths and frequencies of the spectral lines emitted by these atoms will be identical to those in similar discharge lamps anywhere else. These lines can thus be used as precise time-keepers for atomic clocks. (Note that true atomic clocks must use lines that have very narrow intrinsic linewidths—lines that correspond to relatively weak transitions between atomic levels. Those that are easily observed in the visible light from a gas discharge lamp occur too easily and have rather broad intrinsic linewidths.)

Section 9.2 Violins and Pipe Organs

213. Pluck the String of a Stringed Instrument

Description: You pluck the string of a stringed instrument and it emits a single tone. Changing the length and tension of the string changes the frequency (and pitch) of the tone but the amplitude of the vibration (and the volume of the sound) doesn't affect its pitch.

Purpose: To demonstrate the vibration of a string and to show that it's another type of harmonic oscillator.

Supplies:

1 stringed instrument

Procedure: Pluck the string of the instrument and listen to its tone. Note that the tone starts loud and gradually diminishes, but without changing pitch. Point out that this is evidence that the string is another type of harmonic oscillator. Like many other harmonic oscillators, you can give it a large amount of energy to start with and it will gradually lose this energy as it oscillates or vibrates. Now change either the tension or the length of the string and observe the change in frequency (pitch). Discuss why such a change should occur.

Explanation: The string is vibrating primarily in its fundamental vibrational mode and emitting a single pitch (we'll deal with harmonics later). While the amplitude of the vibration doesn't affect its frequency, the tension and length of the string do. Increasing the tension stiffens the restoring forces and increases the frequency. Shortening the string both stiffens the restoring forces and decreases the mass, again increasing the frequency.

214. The Fundamental Mode of a String

Description: A long rope that's fixed at one end and that's turned by a variable-speed electric motor at the other end is made to vibrate in its fundamental vibrational mode.

Purpose: To display the fundamental vibrational mode of a string.

Supplies:

1 rope (at least 3 m long and about 1 cm or more thick)
1 elevated support for the fixed end of the rope
1 variable-speed (low speed) electric motor
1 short side arm for the motor so that it can swing one end of the rope around in a small circle
1 swivel clip to attach the rope to the motor's side arm
2 clamps
1 strobe system (optional)

Procedure: Attach the side arm to the motor's shaft so that as the motor shaft turns, the side arm swings around in a circle. Attach one end of the swivel clip to the end of the side arm and attach the other end of the swivel clip to one end of the rope. Attach the other end of the rope to the elevated support. Clamp both the motor and the elevated support to a sturdy table. Overall, the rope should be pulled slightly taut between the elevated support on one end of the table and the electric motor and its side arm on the other end of the table.

Now start the motor turning slowly. The rope will begin to jiggle about at first but when its rotational speed is timed to coincide with fundamental vibrational frequency of the rope, the rope will begin to swing in a wide arc. This motion is the same as that of a normal jump rope. Show that you have to turn the motor at just the right speed or the rope won't vibrate properly. If you increase the tension in the string or shorten its length, you will have to turn the motor more rapidly to excite this fundamental vibrational mode. (If you have a strobe system, time the strobe to fire once per turn of the motor and adjust the phase to freeze the rope while it's an upward or downward curving arc.)

Explanation: The frequency of the rope's fundamental vibrational mode is determined by its mass density, its tension, and its length. The motor's motion can excite this fundamental vibrational mode if it's rotating at just the right speed. This is another case of resonant energy transfer between the turning motor and the swinging rope. Only when they both have the same frequencies of motion is there significant energy transfer from the motor to the rope.

215. Bowing the String of a Stringed Instrument - Resonant Energy Transfer

Description: You bow the string of a stringed instrument and it gradually begins to emit a tone.

Purpose: To demonstrate that bowing is a form of resonant energy transfer that gradually increases the vibrational energy of a string.

Supplies:

1 stringed instrument (ideally a violin)
1 violin bow

Procedure: Slowly draw the bow across the string. Describe the stick-slip process that's occurring as you pull. Whenever the string is moving with the bow, static friction occurs and the bow is able to do substantial work on the string. But whenever the string is sliding against the bow, sliding friction occurs (a much weak force) and the bow does only a tiny amount of negative work on the string. In effect, the bow is exerting carefully timed pushes on the string that always increase the string's vibrational energy. Overall, the vibrational energy in the string gradually increases and it begins to produce significant sound.

Explanation: Bowing is a form of resonant energy transfer because the bow's pushes are always synchronized to the vibration of the string.

216. Resonant Energy Transfer in a Pendulum

Description: You give a pendulum a series of carefully timed pushes and cause it first to swing more and more vigorously and then less and less vigorously. Randomly timed pushes do nothing to it on the average.

Purpose: To illustrate resonant energy transfer.

Supplies:

1 tall pendulum (as tall as possible—we use a bowling ball suspended from the ceiling)
1 support for the pendulum

Procedure: Allow the pendulum to settle at its equilibrium position (if it stores energy well, you may have to help it settle). First show that you can give it energy all at once by displacing it from equilibrium and releasing it. In that case, it's energy changes abruptly and it then oscillates at full amplitude. You might point out that as it oscillates, its total energy remains essentially constant, but that this energy transforms back and forth between gravitational and potential energies.

Settle the pendulum at its equilibrium position and this time give it a series of small pushes, timed to coincide with the moments when it's heading away from you. Note that during these moments, you do work on the pendulum by pushing it away from you as it moves away from you. Its amplitude of motion will increase with each properly timed push. You are transferring energy to the pendulum via resonant energy transfer.

Now shift the timing of your pushes so that you push the pendulum when it's heading toward you. Its amplitude of motion will decrease with each properly time push. You are extracting energy from it via resonant energy transfer.

Finally, push the pendulum at randomly timed moments and show that its average amplitude of motion is unaffected. To transfer significant energy to it or from it, you must be in synchrony with it.

Explanation: By timing your pushes to coincide with the cyclic motion of the pendulum, you are allowing energy to flow via resonant energy transfer between two coupled systems with identical frequencies of motion (you are deliberately moving at the pendulum's natural frequency).

217. Resonant Energy Transfer Between Tuning Forks - Via Contact

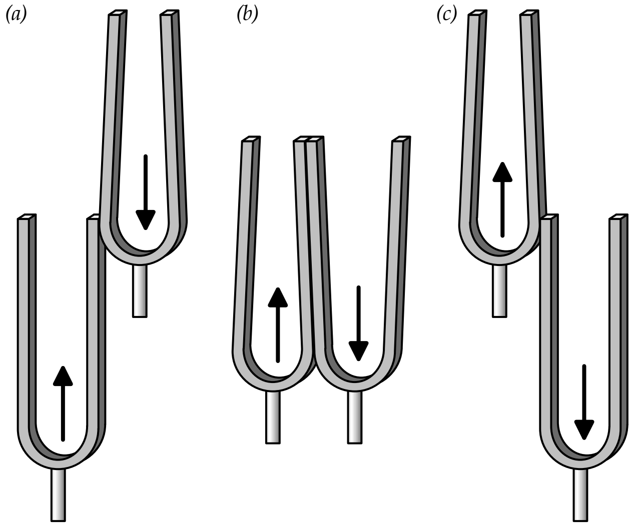
Description: You start one of two identical tuning forks vibrating. By carefully sliding them against one another, you transfer the vibration from the first tuning fork to the second tuning fork.

Purpose: To demonstrate resonant energy transfer.

Supplies:

2 identical tuning forks
1 tuning fork mallet (option)

Procedure: Strike one of the tuning forks with the mallet or against a firm object (I used the heel of my shoe). Now hold the two tuning forks parallel to one another and touch them together so that the tip of a tine on the non-vibrating tuning fork is touching the base of a tine on the vibrating tuning fork (see figure below, part *a*). Now gradually slide the tines along one another so that the tuning forks are soon side by side (part *b*) and then so that their relationships are reverses: the tip of the tine of the initially vibrating tuning fork should now touch the base of the tine of the initially non-vibrating tuning fork (part *c*). At this point, the initially vibrating tuning fork will not be vibrating and the initially non-vibrating tuning fork will be vibrating—they will have completely exchanged their vibrational energies.



Explanation: The vibrating tuning fork will do work on the non-vibrating tuning fork over and over and will gradually transfer its energy to the non-vibrating tuning fork. By sliding the two tuning fork across one another, you allow them to efficiently transfer their energy. The coupling between them gradually increases as they move toward being side by side and then gradually decreases as they again move toward being widely separated.

218. Resonant Energy Transfer Between Two Tuning Forks - Via Their Sound

Description: You start one of two identical tuning forks vibrating. By exposing the second tuning fork to the sound of the first tuning fork, you transfer some of the vibrational energy to the second tuning fork.

Purpose: To demonstrate resonant energy transfer.

Supplies:

- 2 identical tuning forks, mounted on resonant enclosures that assist the tuning fork in producing or absorbing sound (Our tuning forks sit atop rectangular wooden boxes that are open on one side)
- 1 tuning fork mallet

Procedure: Strike one tuning fork with the mallet and listen to the sound emerging from the resonant enclosure. Now place the two tuning forks side by side, so that their resonant enclosures face one another, and strike one of the tuning forks. After a few seconds, stop the first tuning fork from vibrating and listen to the sound from the second tuning fork. It will have acquired some of the vibrational energy from the first tuning fork.

Explanation: Sound emerging from the first tuning fork and its resonant enclosure has transferred energy to the second tuning fork and its resonant enclosure. The transfer occurred through air in the form of sound waves. The rhythmic pushes exerted on the second tuning fork and its resonant enclosure did work on the second tuning fork and gradually increased its energy. In principle, the two tuning forks will pass the vibrational energy back and forth completely, with a time of transfer that depends on the coupling between them.

Follow-up: Add a small ball of putty to one tine of one of the tuning forks. The mass of the ball will shift the resonant frequency of that tuning fork and the resonant energy transfer will no longer occur.

219. Resonant Energy Transfer in a Stringed Instrument - Via Sound

Description: A simple stringed instrument has two strings with identical pitches. When one of the strings is plucked, the second string will also begin to vibrate.

Purpose: To demonstrate resonant energy transfer in a stringed instrument.

Supplies:

- 1 stringed instrument with two of its strings tuned to the same frequency
- 1 small piece of paper

Procedure: Fold the small piece of paper in half and drape it over one of the two strings. Now pluck the second string. The first string will soon begin to vibrate, as indicated by the jittering of the piece of paper. If you change the pitch of the second string, by shorting it or changing its tension, this resonant energy transfer will no longer occur.

Explanation: Because the two strings are coupled by the musical instrument and by the air, when one string vibrates it exerts tiny rhythmic forces on the other string. Because these tiny forces are timed to coincide with the vibrations of the second string, they transfer energy between the two strings quite effectively.

220. Helping a Tuning Fork Produce Sound

Description: By itself, a tuning fork produces very little sound. But when you hold a cardboard frame around one tine of the fork, its volume increases substantially.

Purpose: To show that narrow vibrating objects (e.g. violin strings) aren't very good at producing sound.

Supplies:

- 1 tuning fork
- 1 piece of cardboard, with a slot cut in it just a little wider than the side width of the tuning fork's tines
- 1 tuning fork mallet (optional)

Procedure: Strike the tuning fork with the mallet or against a firm object (again, I use the heel of my shoe). Point out how weak its sound is. Now repeat this procedure, but hold the vibrating tuning fork up behind the cardboard sheet so that one of its tines vibrates in and out of the slot in the cardboard sheet. The volume of sound emitted by the tuning fork will increase dramatically.

Explanation: The wavelength of the sound that the tuning fork emits is much larger than the width of the tuning fork's tines. As a result, air has plenty of time to move around the tines during each cycle of vibration. Thus instead of pushing the air toward and away from your ear as it vibrates, each tine tends to push the air back and forth around its surfaces. Blocking the path around the sides of the tine prevents the air from flowing around it and helps the tine push the air toward and away from your ear. You hear much more sound as a result.

Follow-up: Listen to a very small, unenclosed speaker playing music. Then place the speaker against a hole in a broad sheet of cardboard. Again, the volume of the speaker will increase dramatically when the air can no longer flow around its sides from front to back and must instead form compressions and rarefactions that travel as sound to your ears.

221. Resonant Energy Transfer in a Mass and Spring

Description: A weight hangs from a coil spring that's attached to a rope. When the rope is given rhythmic jerks at just the right frequency, the weight begins to bounce more and more vigorously.

Purpose: To demonstrate resonant energy transfer.

Supplies:

- 1 coil spring (long and soft, if available)
- 1 weight

Procedure: Hang the weight from the bottom of the coil spring and hold the top of the spring in your hand. Gently pull the top of the spring upward in a rhythmic fashion. Show that if you choose a beat at random, the weight won't move very much. However, when you pull upward in synchrony with the weight's bouncing, you can get it to bounce more and more vigorously. Be careful the weight doesn't bounce off the spring and fall.

Explanation: When the upward movements of your hand are timed properly, they always do work on the spring and mass, and add energy to that harmonic oscillator.

Follow-up: Rather than using your hand, you can suspend the coil and spring from a device that supplies the rhythmic upward movements. We use a cord that runs over a pulley and is then attached to a variable-speed electric motor. As the motor turns, the cord is gently jerked and the spring and mass are similarly jerked upward. Selecting the right frequency causes the weight to begin bouncing wildly.

222. Resonant Energy Transfer Between a Drill and Some Hacksaw Blades

Description: Three hacksaw blades are clamped to a board so that they project outward from the board by different amounts. A variable-speed electric drill with a bent nail in its chuck is also attached to the board. When the drill is turning at just the right speed, one of the hacksaw blades begins to vibrate strongly.

Purpose: To demonstrate resonant energy transfer.

Supplies:

- 3 hacksaw blades
- 1 board (about 30 cm on a side)
- 1 small board (to hold the hacksaw blades against the other board)
- 1 variable-speed electric drill

1 large nail, bent at a right angle
2 clamps

Procedure: Place the 3 hacksaw blades on the board, so that they extend outward from its edge by different amounts. Place the small board on top of the blades, along the edge of the larger board and clamp the two boards together so that the blades can't slide or move. Put the bent nail in the chuck of the drill and clamp the drill to the board. Make sure that the free end of the bent nail won't hit either you or the board as the drill chuck rotates.

Start the drill rotating. As you slowly increase the drill's rotational speed, the hacksaw blades will begin to move slightly. When you reach the resonant frequency of the longest hacksaw blade, it will begin to vibrate strongly. Keep increasing the rotational speed until the middle length blade and finally the shortest blade exhibit their resonances.

Explanation: The rotating nail is transferring energy to the hacksaw blades via resonant energy transfer. Only when it's turning at just the right rate will it be able to push on one of the hacksaw blades in synchrony with that blade's vibrational motion.

223. Resonant Energy Transfer in a Crystal Wineglass - Via Bowing with Your Finger

Description: You draw your wet finger along the rim of a crystal wineglass and it emits a tone.

Purpose: Another illustration of resonant energy transfer to an object with a fundamental vibrational mode.

Supplies:

1 crystal wineglass
water

Procedure: Wet one finger and draw it slowly and gently along the rim of the wineglass. You are trying to achieve a stick-slip bowing effect, in which your finger sticks while the rim is moving with your finger's motion and your finger slides easily while the rim is moving against your finger's motion. With a little practice, you can get the wineglass to vibrate strongly and emit a loud, clear tone.

Explanation: You are bowing the wineglass in much the same way a violinist bows a violin string. With each cycle of vibration in the wineglass, you add a little energy to its motion. You do a little work on it each time its rim moves in the direction that your finger is moving and you do much less negative work on it each time its rim moves in the opposite direction from that of your finger. Overall, you transfer energy to the vibrating wineglass and it vibrates vigorously.

224. Resonant Energy Transfer in a Crystal Wineglass - Via Sound (Breaking the Wineglass)

Description: A wineglass is exposed to intense sound from a speaker driver. When the pitch of the tone emitted by the driver is just right and the volume is loud enough, the wineglass shatters.

Purpose: To illustrate resonant energy transfer (and to have lots of fun.)

Supplies:

1 crystal wineglass
1 midrange driver, approximately 100 W (the magnet and coil assembly portion of a large horn speaker—available from audio electronics companies)
1 audio amplifier, 100 W or more
1 audio sine wave signal generator
1 small microphone (and power source, if required)
1 oscilloscope
mounting hardware
1 strobe system (optional)

Procedure: Tap the bowl of the crystal wineglass gently and listen to its fundamental tone. This pitch is the one that will eventually break the glass. Stand the wineglass on a table and mount the midrange driver about 1 cm away from bowl so that the sound waves emerging from the driver will hit the side of the glass just below its rim.

Mount the microphone in the same position relative to the wineglass, but a quarter of the way around the glass. If you look down on the arrangement, the midrange driver should be at 3 O'clock relative to the wineglass and the microphone should be at either 12 O'clock or 6 O'clock. Connect the microphone to the oscilloscope—this will be the system that detects when you are using the correct frequency to drive the speaker. Now connect the audio signal generator to the audio amplifier and the audio amplifier to the midrange driver.

You're ready to begin. Turn everything on and adjust the signal generator's frequency and the amplifier's volume so that the midrange driver begins to emit a gentle tone with the same frequency that you heard when you tapped the wineglass. The wineglass will begin to oscillate weakly and the microphone will detect this oscillation in the wineglass and display a fluctuating voltage on the oscilloscope. Carefully adjust the frequency of the audio signal generator to find the wineglass's precise resonance. When you reach it, the wineglass's vibration will increase dramatically and the microphone and oscilloscope will detect this enhanced vibration.

When the frequency of the audio signal generator is perfect, you're ready to go. If you have a strobe system, time it to flash almost—but not quite—in synch with the audio signal. You will see the rim of the crystal wineglass undergo a remarkable quadrupole oscillation in which two opposite sides—say east and west—will move toward one another as the other two opposite sides—say north and south—move away from one another.

To break the glass, turn up the volume. The tone will probably have to become unpleasantly loud before the wineglass finally breaks. It's amazing how far wineglasses can move before they shatter. How they shatter depends on the wineglass and on your luck. Sometimes they break beautifully into little pieces and sometimes they just crack undramatically.

Explanation: The rhythmic pushes from the sound waves emerging from the midrange driver gradually add energy to the vibrating wineglass. When its vibration exceeds the wineglass's elastic limits, it shatters. Without the oscilloscope, you would have enormous difficulty hitting the resonance accurately enough to break the wineglass. It's extremely unlikely that a singer could hit the required note accurately enough, long enough, and loud enough to break the glass without electronic assistance of some form.

225. The Harmonic Modes of a String

Description: A long rope that's fixed at one end and that's turned by a variable-speed electric motor at the other end is made to vibrate in its harmonic vibrational modes.

Purpose: To display the harmonic vibrational mode of a string.

Supplies:

- 1 rope (at least 3 m long and about 1 cm or more thick)
- 1 elevated support for the fixed end of the rope
- 1 variable-speed (low speed) electric motor
- 1 short side arm for the motor so that it can swing one end of the rope around in a circle
- 1 swivel clip to attach the rope to the motor's side arm
- 2 clamps
- 1 strobe system (optional)

Procedure: Repeat the procedure needed to demonstrate the rope's fundamental vibrational mode. However, this time continue to increase the rotational speed of the motor until the rope begins to turn as two half-ropes. This second harmonic mode will appear when the motor is turning twice as fast as it was for the fundamental vibrational mode. If you have a strobe system, time the strobe to fire once per turn of the motor and adjust the phase to freeze the rope while it's an S-shaped arc, curving first upward and then downward.

If you increase the motor's rotation rate still further, you'll observe the third harmonic mode (three third-strings), the fourth harmonic mode (four quarter-strings), and so on.

Explanation: The rope's harmonic modes occur when the rope vibrates as several shorter ropes. These harmonic modes occur at multiples of its fundamental vibrational frequency. Although the rope can undergo several different modes of vibration at once, this technique for transferring energy to the rope—resonant energy transfer—only excites one of the modes at a time.

226. Air Vibrating in a Bottle

Description: You blow gently across the lip of a bottle and it emits a tone. Adding water to the bottle raises the pitch of that tone. The amplitude of vibration (and the volume of the sound) don't affect its pitch.

Purpose: To show that a column of air can vibrate as a harmonic oscillator.

Supplies:

- 1 beverage bottle with a narrow neck
- water

Procedure: Place your lips against the mouth of the bottom and blow gently across the mouth of the bottle. Air from your mouth should be directed so that it can flow either over the far edge of the bottle mouth or against that far edge. When you aim the air correctly, it will cause the air inside the bottle to begin vibrating and the bottle will emit a tone. Adding water to the bottle will shorten the air column inside it and raise the frequency and pitch of the tone. Point out that the amplitude of the vibration (and the volume of the tone) don't affect the frequency (and pitch) of the tone—you have another harmonic oscillator.

Explanation: Air from your mouth is adding energy to the vibrating air in the bottle. The pressure in the bottom of the bottle is fluctuating up and down, and the velocity of the air in the neck of the bottle is fluctuating in and out. Air from your mouth joins air vibrating in and out of the neck of the bottle, doing work on that vibrating air at just the right times to cause resonant energy transfer. By adding water to the bottle, you shorten the air column, stiffening its restoring forces and decreasing its mass. As a result, its frequency of oscillation (and its pitch) increases.

227. Harmonic Vibrations in a Plastic Tube

Description: You hold an open plastic tube by one end and swing it in a circle. It emits a tone that changes in discrete steps as its speed changes, like the tones of a bugle.

Purpose: To show that the air vibrating in a container can exhibit harmonic vibrational modes.

Supplies:

1 flexible plastic tube with two open ends (about 2 or 3 cm in diameter and about 1.5 m long)

Procedure: Hold one end of the tube and swing it rapidly in a circle. Keep the end that you're holding relatively still. A tone will soon emerge from the tube. If you swing the tube relatively slowly, the tone will be low. But as you swing the tube faster and faster, you'll hear a series of higher pitched tones.

Explanation: The lowest tone that you hear at low speeds is the fundamental vibrational mode of the tube—the air at the tube ends flows inward and outward together and the air at the middle of the tube experiences up and down pressure fluctuations but no velocity fluctuations. The higher tones correspond to harmonic vibrational modes, in which there are two or more regions within the tube that are experiencing up and down pressure fluctuations but no velocity fluctuations.

228. Air Vibrating in an Organ Pipe

Description: As air blows through the whistle of an organ pipe, the pipe emits sound.

Purpose: To demonstrate how an organ pipe makes sound.

Supplies:

1 organ pipe (or a penny whistle or a recorder, which are effectively small, shrill organ pipes)
1 air blower (or your mouth)

Procedure: Connect the organ pipe to the air blower and start it emitting sound. Point out that air is vibrating in and out of both ends of the pipe—the open top and the open hole in the whistle at the base of the pipe. The air being blown across the whistle is adding energy to the air vibrating in the pipe. Note also that changing the volume of the pipe doesn't change its pitch—it's a harmonic oscillator.

Explanation: In the organ pipe's fundamental vibrational mode, air is flowing into or out of both ends of the pipe at the same time and the air pressure near the middle of the pipe is fluctuating up and down around atmospheric pressure.

229. Air Vibrating in a Carpet Tube

Description: A giant cardboard tube is lowered over a large gas burner. A loud, low tone soon emerges from the tube.

Purpose: A fun demonstration of resonant energy transfer.

Supplies:

1 or more carpet tubes (large, sturdy cardboard tubes placed at the centers of wall-to-wall carpet when it's delivered to a carpet store. Other wide pipes will also work.)
1 large gas burner (e.g., a Fisher burner)
matches
water (to extinguish a burning carpet tube, if necessary)

Procedure: Light the burner and place it on the floor. Slowly lower one end of the open carpet tube over the burner. It will emit a low, loud tone. This tone may actually extinguish the burner, so be careful. Also be careful not to start a fire. The longer the tube, the lower its pitch.

Explanation: Hot, rising air from the flame tends to add energy to the air vibrating up and down near the lower end of the tube. Through resonant energy transfer, the flame gradually increases the strength of this vibration.

Follow-up: We have a shorter metal tube (about 1 m long and about 4 cm in diameter) that contains a piece of stainless steel gauze near one end. When that gauze is heated red hot by a burner and the tube is then held vertically, with the hot gauze at the bottom, it emits a tone. Tipping the tube horizontally stops the tone but the tone reappears when the tube is returned to its vertical orientation.

230. Vibrational Modes of a Surface - Chladni Plates

Description: You sprinkle sand on a metal plate that's supported at its center and then bow its edge with an cheap violin bow. The plate emits a tone and the sand forms interesting patterns on the plates surfaces.

Purpose: To show that surfaces can also act as harmonic oscillators, with pitches that don't depend on their amplitudes of motion, and to show that the pitches of their harmonic vibrations don't occur at simple integer multiples of their fundamental pitches.

Supplies:

1 Chladni plate (a hard metal plate that's supported at its center by a rigid post and clamp)
1 cheap violin bow
sand

Procedure: Mount the Chladni plate on a sturdy table so that it's surface is horizontal. Sprinkle sand lightly on its surface. Now bow the edge of the plate gently. Try to keep the bow in the same spot on the plate edge as you bow. The plate will begin to vibrate and the sand will begin to move. When you excite a strong vibrational mode of the surface (and hear a clear tone), the sand will move into the vibrational nodes of the mode—the portions of the plate that don't move while the plate is experiencing that vibrational mode.

Experiment with bowing at different places around the plate and you'll find the fundamental vibration and various harmonics. Note that the harmonic frequencies of this vibrating two-dimensional surface aren't simply integer multiples of the fundamental vibrational frequency. Only in some one-dimensional oscillators such as strings and organ pipes are the harmonic frequencies all integer multiples of the fundamental vibrational frequency.

Explanation: Surfaces have complicated vibrational patterns and don't vibrate as "half-surfaces or third-surfaces" the way strings do. As a result, their harmonic vibrations have pitches that aren't integer multiples of their fundamental pitches and they have interesting patterns of vibrational nodes and antinodes for any given harmonic vibration. The sand tends to accumulate in the nodes, so that you can see these patterns. Just how you bow the plate (and where you might be touching it as well) determines which vibrational mode is excited by the bow and which pattern the sand adopts.

Section 10.1 The Sea and Surfing

231. Water Sloshing in a Tank

Description: You move your fingers gently back and forth in a rectangular tank of water. When you move your hands rhythmically at just the right frequency, the water begins to slosh vigorously.

Purpose: To show that resonant energy transfer can excite a natural resonance in the water.

Supplies:

1 rectangular water tank (a glass or plastic aquarium)
water

Procedure: Fill the tank half full of water and allow the water to settle. Insert your hand into the water and jiggle it back and forth randomly. Point out that the water acquires relatively little energy from this random motion. Now move your hand back and forth rhythmically so that you excited the fundamental sloshing mode for the water in the tank. Pretty soon the water will be sloshing vigorous back and forth and may even slosh out of the tank.

Explanation: The water has a natural resonance in which it travels back and forth from one end of the tank to the other. You are exciting that resonance by pushing it forward as it sloshes forward and backward as it sloshes backward. In the tank, this resonance has a relatively high frequency of perhaps once per second. But in a huge channel, it may have a period of 12 hours and 26 minutes so that it can be excited by the tide.

232. Transverse Waves on a Long Slinky

Description: A long Slinky stretches from your hand to a fixed point far away. Quick shifts of your hand cause ripples—transverse waves—to travel along the Slinky.

Purpose: To illustrate transverse waves that are similar to water surface waves.

Supplies:

1 long Slinky (or a loose spring or even a rope)
1 fixed support

Procedure: Attach one end of the Slinky to the fixed support. Hold the other end of the Slinky in your hand and stretch it just enough to lift the middle well off the floor. Now jerk the end that you have in your hand upward and then back to its starting place. An upward heading ripple will head out across the Slinky. When it reaches the fixed end, it will reflected back toward you. The speed with which the wave travels increases with the tension in the spring and decreases with the spring's mass density. That's why a loose but massive Slinky makes it possible to have slow moving transverse waves.

Explanation: The Slinky behaves like a very massive, low-tension string. While it could easily be made to exhibit standing waves, such as its fundamental vibrational mode, it can also be made to exhibit transverse traveling waves.

233. Longitudinal Waves Between Magnets

Description: A set of repelling magnetic rollers rests in a track. When one of the rollers is suddenly displaced, it initiates a longitudinal wave that passes through the whole collection of rollers.

Purpose: To illustrate longitudinal waves.

Supplies:

1 set of magnetic rollers on a track (available from a scientific supply company)

Procedure: Turn the rollers so that they repel one another and allow them to settle so that they're even space on the track. Now push the last roller toward its neighbor and watch the longitudinal wave travel from roller to roller all the way along the track.

Explanation: At rest, all of the rollers are in equilibrium. Displacing one upsets the equilibrium of the next, which in turn upsets the equilibrium of the next and so on. The speed with which the wave travels through the collection of rollers depends on their masses and on the stiffness of the forces between them.

234. Helical Waves on a Wire

Description: A wire that's supporting a long collection of torsion beams rests on a support. When one of the torsion beams is twisted, it initiates a torsional wave that pass down the wire and twists each of the torsion beams in turn.

Purpose: To illustrate torsional waves.

Supplies:

1 wire with torsion beam attached (available from a scientific supply company)

Procedure: Set up the wire and allow the torsion beams to settle to a horizontal orientation. Now displace the beam at one end of the wire and then return it to its original orientation. A torsional wave will travel along the wire from torsion beam to torsion beam.

Explanation: At rest, all of the torsion beams are in equilibrium (they're experiencing zero torque). Displacing one beam upsets the equilibrium of the next and so on. The speed with which the wave travels through the torsion beams depends on their moments of inertia and on the torsional stiffness of the wire that connects them.

Section 11.1 Electronic Air Cleaners

235. Removing Dust from the Air

Description: You clap chalky erasers together and note how slowly gravity removes the chalk particles from the air.

Purpose: To show that gravity is slow and ineffective at removing tiny particles from the air.

Supplies:

- 2 chalky erasers or another source of visible, nontoxic dust
- 1 piece of chalk (or a bulk form of whatever dust you choose)

Procedure: Clap the erasers together and show that it hangs in the air for a long time. Drop the piece of chalk to show that it falls rapidly—buoyancy isn't supporting the chalk dust, air resistance (viscous drag) is. Discuss the concept of terminal velocity; of the falling particles experiencing upward forces that balance their weights when they reach very small downward velocities relative to the air. Point out that to be drawn through the air at larger terminal velocities, the particles need to be exposed to stronger forces than gravity—for example, to Coulomb forces!

Explanation: Small particles have such large surface-to-volume ratios that their interactions with air dominate their dynamics. To pull them through the air at more than a snail's pace, they need to be exposed to forces stronger than those of gravity.

236. Electric Charge and Coulomb Forces

Description: Two pith balls hang from threads. One of them is given negative charge by a negatively charged Teflon rod and the two objects repel one another. The other pith ball is given positive charge by a positively charged acrylic rod and the two objects also repel one another. Finally, the two pith balls are carefully brought toward one another. They suddenly draw together and touch, showing that they attract one another.

Purpose: To demonstrate the strong repulsive and attractive forces between electric charges and to show that there are two types of electric charges: positive and negative.

Supplies:

- 2 silvered pith balls hanging from threads and supports (we sometimes use carbon-coated latex rubber balloons, which work very nicely but age badly and must be made fresh for each use. The carbon-coating is done with Aerodag colloidal carbon spray and makes the balloons electrically conducting.)
- 1 Teflon rod
- 1 Acrylic rod
- 1 piece of silk

Procedure: Set the two pith balls so that they hang about 40 cm apart. Rub the Teflon rod with the silk, a process that will transfer negative charge to the Teflon and leave the silk positively charged. Touch the Teflon rod to one of the pith balls. The pith ball will immediately repel the Teflon rod. Demonstrate this repulsion.

Now rub the acrylic rod with the silk, a process that will transfer negative charge to the silk and leave the acrylic positively charged. Touch the acrylic rod to the other pith ball. The pith ball will immediately repel the acrylic rod, although you may have to recharge the acrylic rod with the silk and repeat the charge transfer once or twice (acrylic doesn't work as well as Teflon). Demonstrate this repulsion, too.

Finally, shift the supports for the pith balls slowly toward one another so that the balls move closer and closer. When they are near enough, they will pull together and "kiss." Once they have touched, they will drop limply because they have little net charge left. Point out that this attraction between the pith balls is evidence that the two pith balls were oppositely charged and that there are two different charges present in our universe. Identify them as positive and negative and discuss how sliding friction tends to move them between objects (which is how you charged the rods with the silk.) Note that like charges repel but opposite charges attract.

Explanation: Sliding friction rubbed negatively charged electrons off the silk and onto the Teflon. It also rubbed negatively charged electrons off the acrylic rod and onto the silk, leaving the acrylic rod with a net positive charge.

237. Detecting Charge with an Electroscope

Description: You transfer charge from a Teflon rod to the foils of an electroscope and they repel outward to indicate the presence of charge.

Purpose: To show how a simple apparatus can detect the presence of electric charge.

Supplies:

1 electroscope
1 Teflon rod
1 silk cloth

Procedure: Rub the Teflon rod with the silk to give the rod a net negative charge. Touch the Teflon rod to the top of the electroscope so that negative charge flows onto the foils. They will repel one another and swing outward. Point out that the electroscope uses this repulsion between like charges to indicate the presence of charge on the foils.

Explanation: When you touch the Teflon rod to the electroscope, negative charges flow onto the foils. Since like charges repel one another, the two foils are swung outward by the repulsions between their charges.

238. Electric Conductors and Electric Insulators

Description: A metal rod connected to the foils of an electroscope conduct charge to the foils when you touch the rod with a charged Teflon rod. A plastic rod connected to the foils doesn't conduct charge to the foils when you touch it with the charged Teflon rod.

Purpose: To show that some materials can transport electric charge and are electric conductors, while other materials can't transport electric charge and are electric insulators.

Supplies:

1 electroscope
1 metal rod that can attach to the electroscope
1 plastic rod that can attach to the electroscope
1 Teflon rod
1 piece of silk

Procedure: Start with the electroscope uncharged and with the metal rod attached to its foils. Charge the Teflon rod by rubbing it with the silk. Now touch the Teflon rod to the metal rod so that the foils swing outward. Point out that the metal rod has transported the charge to the foils and is thus an electric conductor.

Now remove the metal rod and replace it with the plastic rod. Again start with the electroscope uncharged. Touch the charged Teflon rod to the plastic rod and show that the foils don't swing outward. Point out that the plastic rod hasn't transported the charge to the foils and is thus an electric insulator.

Explanation: The metal rod has mobile electrons (conduction level electrons or perhaps empty levels in its valence bands) that allow it to transport electric charges from one end to the other. The plastic rod has no such mobile electrons (its valence levels are completely filled and it has no conduction level electrons) and can't transport electric charges from one end to the other.

239. Faraday's Ice Bucket

Description: You transfer electric charge to an isolated metal cup and then use an electrometer to look for that charge. You find that it's on the outside of the cup, not on the inside.

Purpose: To show that charge distributes itself relatively uniform around the outsides of conducting objects.

Supplies:

1 metal cup on an insulating stand (a cylindrical metal can with a bottom but no top)
1 metal ball on an insulating stick (for charge transfers)
1 electroscope
1 Teflon rod
1 piece of silk

Procedure: Rub the Teflon rod with the silk to give the rod a negative charge. Transfer this charge to the metal cup (Faraday's ice bucket) by rubbing the rod lightly against the cup. Now locate the charge on the cup. First look for the charge inside the cup by carefully inserting the transfer ball into the cup (don't touch the lip of the cup) and by touching the inside surface of the cup. Remove the ball from the cup and touch it to the electroscope. There will be no deflection of the foils, indicating no charge on the ball and no charge on the inside surface of the cup.

Now touch the ball to the outside surface of the cup. Again touch the ball to the electroscope. The foils will bend outward, indicating charge on the ball and charge on the outside surface of the cup.

Explanation: Like charge becomes more widely separated by spreading itself on the outside surfaces of a conducting object. No charge is found on the inside surfaces of a conducting object.

240. A Van Der Graaf Generator

Description: A van der Graaf generator operates like an automated version of Faraday's ice bucket. A belt delivers charge into a conducting ball and this charge runs quickly to the outside surfaces of the ball.

Purpose: To show how a large quantity of like charge is accumulated on the surface of a van der Graaf generator.

Supplies:

1 van der Graaf static generator

Procedure: First examine the components of the van der Graaf generator. It has a conducting metal sphere on top that will store like charge on its surface. It has an insulating rubber belt that will deliver charge to the inside of the conducting metal sphere. It has a charging system at the base of the belt that deposits charge on the belt. And finally it has a motor that turns the belt and pushes the charged belt toward the like-charged metal sphere.

Now turn on the van der Graaf generator and allow it to begin producing sparks. Point out that the motor is doing work on the charges in order to push them onto the sphere (the charges already on the sphere are repelling the newly arriving charges).

Explanation: Whenever the belt carries a charge into the sphere and allows that charge to transfer to the sphere, the charge quickly moves onto the outer surface of the sphere. Once on the outer surface of the sphere, the charge can only leave through a spark or on a passing air molecule. As more and more charges accumulate on the sphere, their potential energies increase and thus the voltage of the charges increase (voltage is energy per charge). (However, our van der Graaf generator accumulates negative charge, so it reaches a very large *negative* voltage.)

241. Launching a Styrofoam Cup

Description: A Styrofoam Cup placed upside down on a van der Graaf generator lifts itself into the air.

Purpose: To show the tendency for electric charges to transfer from the surface of the van der Graaf generator onto nearby objects and to show that like charges repel.

Supplies:

1 van der Graaf static generator
1 Styrofoam cup
1 grounding ball, stick, and wire

Procedure: Turn on the van der Graaf generator and ground the sphere of the van der Graaf generator (we use a metal ball on a long insulating stick, with a wire that connects the ball to earth ground) to make it safe (or less painful) to touch. Put an inverted Styrofoam cup on top of the ball and remove the grounding ball. As charge accumulates on the van der Graaf generator's sphere, some of it will transfer to the nearby cup. Soon the sphere and cup will repel one another strongly enough for the cup to lift up into the air.

Explanation: An electric charge on the surface of the van der Graaf generator can lower its total energy by moving to the Styrofoam cup. It does so with the help of passing air molecules, which serve as ferries for the charges. Once the cup and the sphere are each sufficiently charged, the upward Coulomb force on the cup exceeds its weight and the cup accelerates upward.

242. Making the Strands of a Pom-Pom Stand Up

Description: A plastic Pom-Pom is attached to the sphere of a van der Graaf Generator. As charge accumulates on its strands, they spread outward until the Pom-Pom resembles a dandelion tuft.

Purpose: To demonstrate the repulsion between like charges.

Supplies:

1 van der Graaf static generator
1 Pom-Pom (a ball of thin plastic stripes attached to a stick)
1 suction cup
1 grounding ball, stick, and wire

Procedure: Turn on the van der Graaf generator and ground its sphere to make it safe to touch. Attach the stick of the Pom-Pom to the top of the van der Graaf generator with the suction cup. Remove the grounding ball and allow charge to accumulate on the sphere and on the Pom-Pom. The plastic strands of the Pom-Pom will soon spread outward into a large uniform ball of straight plastic strips.

Explanation: Air molecules ferry electric charges from the van der Graaf generator to the plastic surfaces of the Pom-Pom. Once there are enough charges on those strands, they repel one another strongly and stand up to form a round ball.

243. Making Peoples' Hair Stand Up

Description: A person stands on a plastic stool and touches the sphere of a van der Graaf generator. As charge accumulates on the sphere and their body, their hair begins to stand up.

Purpose: To demonstrate the repulsion between like charges (and to have fun).

Supplies:

1 van der Graaf static generator
1 plastic stool (a one-step stool, about 30 cm tall)
1 grounding ball, stick, and wire

Procedure: Place the van der Graaf generator at the edge of a table and put the plastic stool a short distance away on the floor. The volunteer who will stand on the stool (for electric insulation from the ground) should be able to reach out and touch the sphere of the van der Graaf generator comfortably, but without coming too close to anything else, particularly the base of the van der Graaf generator. Before the volunteer arrives, turn on the van der Graaf generator and touch the grounding ball to the van der Graaf generator's sphere to eliminate any charge from its surface. Have the volunteer stand on the stool (it's not a matter of how tall they are—they need the electric insulation that the stool provides) and touch the sphere of the van der Graaf generator. They should feel absolutely no shock while they're doing this because you are still grounding the sphere.

When the volunteer is ready and not near anything besides the sphere and the stool, move the grounding ball away from the van der Graaf generator's sphere. Never move the grounding ball back to the van der Graaf generator's sphere while the person is still touching the sphere because the volunteer will feel a shock. As charge accumulates on the sphere and the volunteer, that person's hair will begin to stand up. Some people's hair works better than others and there is simply no predicting whose hair will work best. It's completely trial and error! The only exception to that rule is with children—young children with fine, straight, white-blond or jet black hair always work well.

Explanation: The charge that migrates onto the volunteer's body through their conducting skin also works its way onto their hairs. When each hair is sufficiently charged, the Coulomb repulsions between the hairs lift them upward against their own weights.

244. Sharp Points and Charge - Lightning Rods

Description: When you approach the sphere of a van der Graaf generator with a smooth grounded object, sparks occur. But when you approach the sphere with a sharp grounded object, the sphere loses its charge quietly without any sparks.

Purpose: To show that sharp points are particularly good at emitting electric charges into the air.

Supplies:

1 van der Graaf static generator
1 grounding ball, stick, and wire
1 pin, needle, or sharpened metal rod

Procedure: Turn on the van der Graaf generator and allow charge to accumulate on the surface of its sphere. Approach that sphere with the grounded ball and show that sparks leap from the sphere to the ball. Now attached the pin to the surface of the grounding ball and repeat the same experiment. No sparks will occur. Moreover, you can hear the motor of the van der Graaf turning more easily—the pin is helping charge to move between the sphere and the ball so that very little charge accumulates on the sphere of the van der Graaf generator! (I do this experiment with my bare hands. I approach the charged sphere with my knuckles and it sends sparks at them—unpleasant, but not particularly painful. I then approach the charged sphere with a sharp pin in my hand and it doesn't send any sparks at all.)

Explanation: As you approach the sphere with the sharp pin, charges that are opposite to those on the sphere begin to leap off the pin's point and onto passing air molecules—a corona discharge. These charges quickly move toward the sphere and land on it, neutralizing the sphere's charge. Although the motor and belt try to recharge the sphere, the charge transfer from the pin is so effective that the sphere loses most of its net charge and can't produce any sparks.

245. An Electrostatic Bell

Description: A metal ball, hanging from a string between two oppositely charged plates, begins to move back and forth between those plates. It's ferrying charge and creating lots of noise.

Purpose: To show that opposite charges attract one another and that like charges repel.

Supplies:

- 1 Wimshurst static generator
- 2 vertical metal plates, about 10 cm square, supported on insulators
- 1 ball
- string
- 1 support for ball
- 2 wires

Procedure: Use the string to hang the ball from the support and place it between the two plates. The two plates should be just far enough apart to give the ball a little room to move. The ball should just barely touch one of the two plates. Touch the two contacts of the Wimshurst static generator together to eliminate any charges they may have and connect the two contacts to the two plates. Now separate the two contacts and begin cranking the Wimshurst generator. When enough charge has accumulated on the two plates, the ball will be repelled by the plate that it's touching and will accelerate toward the other plate. As soon as it touches the other plate, it will reverse its charge and accelerate in the opposite direction. It will shuttle back and forth between the plates as long as you continue to turn the crank of the Wimshurst generator.

Explanation: The metal ball is repelled by the like charge of the plate that is has just touched and attracted to the opposite charge of the other plate. It accelerates back and forth between the two.

246. Putting Out a Candle with Static Electricity

Description: A candle that's placed between two oppositely charged plates is ripped apart by the Coulomb forces it experiences and extinguishes itself.

Purpose: To show that a candle flame contains some electrically charged particles and Coulomb forces acting on those charged particles can make it impossible for the flame to operate.

Supplies:

- 1 Wimshurst static generator
- 2 vertical metal plates, about 10 cm square, supported on insulators
- 1 candle
- matches

Procedure: Space the two metal plates about 4 cm apart and put the candle between the two plates. Touch the two contacts of the Wimshurst static generator together to eliminate any charges they may have and connect the two contacts to the two plates. Light the candle. Now separate the two contacts and begin cranking the Wimshurst generator. When enough charge has accumulated on the two plates, the candle flame will become severely distorted and will probably extinguish itself.

Explanation: The charged particles in the flame are pulled toward opposite charges and the flame becomes a very horizontal, rather than vertical, structure. In its new shape, the flame has trouble sustaining itself and tends to put itself out.

247. A Simple Electrostatic Precipitator

Description: Smoke drifts upward through a metal can containing a thin metal wire. When opposite electric charges are placed on the can and the wire, the smoke suddenly disappears.

Purpose: To demonstrate the principles of electrostatic precipitation.

Supplies:

- 1 large coffee can, open at both ends
- 1 extremely thin metal wire
- 1 insulated support for the metal wire
- 1 insulated support for the coffee can
- 1 weight for the metal wire
- 1 Wimshurst static generator (or another high voltage power supply)
- 2 wires
- 1 smoke source (for example, unscented incense sticks)
- matches

Procedure: Support the coffee can about 50 cm above the table and lower the metal wire through its center. Support the top of the wire and hang the weight from the bottom of the wire to pull the wire straight. Touch the two contacts of the Wimshurst static generator together to make sure that they have no charges on them and connect one contact to the coffee can and the other contact to the wire. Be careful not to break the wire. (It does matter somewhat which charge you put on the wire and which charge you put on the can, but you'll have to experiment to see which works best.)

Now light the smoke source and allow its smoke to drift upward through the coffee can. To demonstrate the electrostatic precipitator, separate the two contacts of the Wimshurst machine and turn its crank. As charge begins to accumulate on the can and wire, the smoke will abruptly disappear as it travels through the can.

Explanation: A corona discharge occurs around the electrically charged wire and this discharge transfers charge onto passing air molecules and smoke particles. These ionized particles are then repelled by the wire and are attracted to the inside surfaces of the coffee can. The missing smoke is actually coating the inside of the coffee can as a thin film of particles.

248. Deflecting a Stream of Water with a Charged Comb

Description: A thin stream of water is deflected by a nearby comb.

Purpose: To show that a charged object can electrically polarize another object and the two will attract.

Supplies:

1 hose
1 support for the hose
1 rubber or plastic comb (or a Teflon rod)
flowing water

Procedure: Connect the hose to a water faucet and support its end over the drain. Adjust the water flow so that a thin but continuous stream of water flows from the hose. Now charge a comb either by drawing it through your hair several times or by rubbing it with a piece of silk. Hold the comb near the upper part of the water stream and watch as the water stream bends toward the comb.

Explanation: The comb's electric charge attracts opposite charges onto the water stream and repels like charges out of the water stream. Since the stream is now polarized, with charges that are opposite to those on the comb closer then charges that are like those on the comb, the stream is attracted to the comb and bends toward the comb.

249. Sticking a Balloon to the Wall with Charge

Description: You rub a balloon through your hair and then stick it to the wall. Its electric charge holds it in place.

Purpose: To show that a charged particle is naturally attracted to any uncharged surface because it will polarize that surface and obtain an attractive force.

Supplies:

1 balloon (a long, thin one oriented vertically works well because it can't roll down the wall)
1 wall

Procedure: Charge the balloon by rubbing it through your hair (or rubbing it with a silk cloth). Hold it against the wall and observe that it sticks.

Explanation: The electrically charged balloon pulls opposite charges in wall toward it and repels like charges in the wall away from it. This polarization of the wall makes it possible for the balloon to stick to the wall through Coulomb forces.

Section 11.2 Xerographic Copiers

250. Photoconductors - A CdS Cell

Description: A cadmium-sulfide photoconductive cell measures the amount of light reaching its surface.

Purpose: To show how light can convert a photoconductor from an insulator to a conductor.

Supplies:

1 CdS (Cadmium-Sulfide) photoconductive cell, or an equivalent photoconductive cell
1 ohm meter (or a display that shows the electric resistance of the CdS cell
1 flashlight (or another light source)
wires

Procedure: Connect the CdS cell to the ohm meter. Show that the darkened CdS cell is basically an insulator. Now expose the CdS cell to light and show that it becomes electrically conducting.

Explanation: Light promotes electrons from the filled valence levels in the CdS cell to the empty conduction levels in the CdS cell. This shifting of charges allows the CdS to transport electric charge. The ohm meter applies a modest electric field across the CdS cell and, when light is present, electric charge begins to flow through the CdS cell.

251. Forming a Charge Image

Description: Charge is deposited on an insulating surface with an array of sharp, electrically charged points. The charge in some areas of the surface is erased with your finger. Finally, felt dust is sprinkled on the surface and it sticks to those areas that are still charged.

Purpose: To illustrate the xerographic process, although without the photoconductive aspect.

Supplies:

- 1 metal sheet (about 30 cm on a side)
- 1 clear plastic sheet (self-adhesive laminate plastic works well)
- 1 support for the metal sheet
- 1 van der Graaf static generator
- 1 strip of metal screening, cut to reveal a row of sharp metal points
- 1 wooden stick handle for the metal screening
- 2 wires
- 1 shaker container of felt dust (or another fine, non-conductive powder)

Procedure: Attach or glue the clear plastic sheet to the surface of the metal sheet. Make sure that the entire surface of the metal sheet is covered by plastic. Mount the sandwich on the support and ground the metal sheet with one wire. Attach the metal screening to the stick and connect it to sphere of the van der Graaf generator with the other wire. Turn on the van der Graaf generator and brush the metal screening across the plastic coated surface. This action will cover the plastic with charges. Turn off the van der Graaf generator. With you finger, rub an identifiable mark on the plastic surface. While you won't see anything, you will have removed charge from part of the plastic surface. Now sprinkle the felt dust on the plastic surface and blow away any excess. You should see the mark you made as a light region in an otherwise relatively dark background on the plastic sheet.

Explanation: The charged metal screening deposited electric charge on the plastic surface. When you touched parts of the plastic surface, you provided a way for the charge to escape from the surface and erased those parts of the surface. In a real xerographic copier this erasure is done by light, which turns the photoconductor (here the plastic layer) into a conductor so that the charge can escape into the metal sheet. When you then sprinkle dust onto the sheet, the dust is attracted to any charged portions of the sheet. (In a real xerographic copier, the toner particles are charged by their carrier system. Here, the felt dust isn't explicitly charged and is held in place largely by polarization effects.)

Follow-up: I plan to build a metal sheet with a real photoconductor surface—one that will be sensitive to blue light but insensitive to red light. I will be able to work with it in class under red illumination and expose it to a pattern of blue light to form a charge image. When I have a version that works, I will post information about it on the demonstration web site.

Section 11.3 Magnetically Levitated Trains

252. The Forces Between Magnets

Description: A bar magnet on a horizontal pivot always turns so that its north pole faces the south pole of a magnet you're holding in your hand, or vice versa.

Purpose: To show that magnets have two different poles and that like poles repel while opposite poles attract.

Supplies:

- 2 bar magnets
- 1 horizontal swivel mount for one of the bar magnets

Procedure: Suspend one of the bar magnets on the horizontal mount. Hold the second magnet in your hand and show that its poles repel like poles of the horizontally supported magnet and that its poles attract opposite poles of that magnet.

Explanation: As with electric charges, magnetic poles come in two types: north and south. But unlike electric charges, its impossible to find an isolated north pole or an isolated south pole. Each bar magnet has a north and a south pole. Like poles on two bar magnets experience repulsive forces and opposite poles on two bar magnets experience attractive forces.

253. Visualizing a Magnetic Field

Description: A small bar magnet is inserted into a magnetic field visualizer and the magnetic flux lines become visible.

Purpose: To show how the magnetic field extends from a magnet's north pole outward and around to the magnet's south pole.

Supplies:

- 1 magnetic field visualizer (a clear plastic rectangle, filled with iron powder and oil, with a hollow region into which you can put a small bar magnet)
- 1 bar magnet

Procedure: Shake the visualizer to disperse the iron powder evenly. Insert the bar magnet into the visualizer and watch as the iron powder accumulates along the magnetic flux lines. Point out that these lines indicate the direction of the force that an isolated north pole would experience if it were at one of those locations. (The fact that isolated north poles aren't available doesn't alter the meaning of the magnetic field lines.)

Explanation: The iron powder particles are magnetized by the magnetic field and line up along the flux lines because they respond to the magnetic forces associated with those flux lines.

254. Magnetic Levitation - First Attempt

Description: You place one magnet over another so that the upper magnet is supported by repulsive forces from the lower magnet. However, you must put a stick through the two magnets to keep the upper magnet from falling off the lower magnet's magnetic cushion.

Purpose: To show that, while you can suspend one disk or ring magnet over another by magnetic repulsion, the equilibrium created by that levitation technique is unstable.

Supplies:

2 ring-shaped magnets
1 wooden dowel

Procedure: Show that when the two ring-shaped magnets are stacked so that they have like poles facing one another, they repel strongly enough to support the upper magnet. Show also that you can't balance the upper magnet above the lower magnet. Show that only when you put the dowel through the holes in the two rings can you can get a stable arrangement.

Explanation: They same repulsive force that supports the weight of the upper magnet also tends to push it to the side so that it falls off the magnetic cushion provided by the lower magnet. It's in an unstable equilibrium.

255. Magnetic Levitation - Second Attempt

Description: You place one bar magnet above another so that their like poles are on top of one another. While the magnetic repulsion supports the upper magnet, it tends to fall of the magnetic cushion. Only when you box in the upper magnet so that it can't move horizontally will it float over the lower magnet.

Purpose: To show that, while you can suspend one bar magnet over another by magnetic repulsion, that the equilibrium created by this levitation scheme is unstable.

Supplies:

2 strong bar magnets
1 frame that prevents horizontal motion of the bar magnets

Procedure: Show that when the two bar magnets are aligned with their like poles on top of one another, that the upper magnet can be suspended by the repulsive forces. Now show that you can't balance the upper bar magnet over the lower bar magnet—the equilibrium there is unstable. Add the frame and show that only with its help to prevent horizontal motion can you suspend one bar magnet over another.

Explanation: The same repulsive forces that support the upper bar magnet also tend to push it to the side so that it falls off its magnetic cushion.

256. Magnetic Levitation - An Almost Free Bearing

Description: A magnetic toy spins above a magnetic base. While it appears that the magnetic toy is levitating, it's actually touching the base a one point. Without that contact, it would be unstable.

Purpose: To show that magnetic suspension with permanent magnets is inherently unstable.

Supplies:

1 magnetic bearing toy (available from scientific supply companies)

Procedure: Suspend the magnet bearing toy in its base and give it a spin. Show that while the bearing remains suspended by repulsive forces above its magnetic base, it's equilibrium is unstable in one horizontal direction. It touches the base at one point in order to avoid falling off the base in the unstable direction.

Explanation: The repulsion between the floating bearing toy and its base leaves the bearing's equilibrium stable in the up-down and back-front directions. However, that equilibrium is unstable in the left-right direction and the toy needs the contact point to avoid falling off its magnetic cushion.

257. Electronic Feedback - Newton's Folly

Description: A magnetized metal marble hangs in midair beneath an electromagnet. When you block the electric eye that senses the marble's height, it either falls or sticks to the electromagnet.

Purpose: To demonstrate that feedback can be used to make an unstable system stable.

Supplies:

1 Newton's Folly (available from Edmunds Scientific)

Procedure: Plug in Newton's Folly and carefully raise the magnetized marble toward the electromagnet from below (as per the instructions). Be careful not to block the electric eye. When the ball is in the correct position, it should become stably suspended—you can let go and lower your hands. Show that the marble is truly suspended by putting a business card between it and the electromagnet above it. But show also that it the device needs to monitor the marble's height continuously in order to avoid dropping it or attracting it all the way to the electromagnet. You can show this by blocking the electric eye (the small holes on either side of the frame). Depending on how you block the electric eye system, the marble will either fall downward or leap upward toward the electromagnet.

Explanation: The basic system uses attraction between two opposite poles to suspend the marble. This arrangement is stable in the horizontal directions but unstable in the vertical direction. Only through the use of feedback can this system be made stable.

258. AC Magnetic Levitation - Jumping Rings

Description: A small aluminum ring is placed around a group of iron rods that pass through a coil of wire connected to the AC power line. When AC current flows through the wires, the ring is repelled by the coil of wire and leaps upward.

Purpose: To show that an electromagnet that's powered by alternating current repels nearby metal.

Supplies:

1 AC electromagnet with an iron-rod pole piece that extends vertically above the wire coil
1 solid aluminum ring that fits around the iron pole pieces
1 cut aluminum ring (cut so that it isn't a complete ring and can't conduct electricity in a full circle)

Procedure: Place the aluminum ring around the pole piece and lower it onto the coil of wire. Now allow AC current to pass through the coil of wire. An AC current will begin flowing through the ring and the ring will become magnetic. The ring will experience a strong repulsion from the coil of wire and will leap up into the air.

Repeat this process with the cut aluminum ring. Because that ring can't conduct electricity, it won't become magnetic and won't be repelled by the wire coil.

Explanation: When AC current flows through the coil of wire, the electromagnet's poles reverse rapidly. The changing magnetic field induces an AC electric current in the aluminum ring and, in accordance with Lenz's law, the upward pointing pole of the coil is always the same as the downward pointing pole of the aluminum ring. The two objects repel.

259. Eddy Current Pendulum

Description: A metal pendulum swings freely through the pole pieces of an inactive electromagnet. But when the electromagnet is on, the pendulum slows to a stop as it tries to swing through the pole pieces of the electromagnet.

Purpose: To show that a conducting object that enters a magnetic field experiences a repulsive force that slows it down.

Supplies:

1 strong DC electromagnet
1 copper or aluminum pendulum with support (don’t use iron, steel, or any other ferromagnetic metal in the pendulum)

Procedure: With the DC electromagnet off, arrange the pendulum so that it swings smoothly between the electromagnet's pole pieces. Show that the inactive electromagnet has no effect on the pendulum. Now turn on the electromagnet and repeat the demonstration. The pendulum will slow dramatically as it enters the pole pieces and will probably come to a stop between them.

Explanation: As the pendulum approaches the pole pieces, the changing magnetic field it experiences induces currents in its surface. It becomes magnetic and, in accordance with Lenz's law, it repels the poles of the electromagnet. This repulsion slows its motion. The currents that gave rise to the magnetization in the pendulum quickly lose energy in the metal and the pendulum comes to rest between the pole pieces.

Follow-up: Repeat the experiment with another pendulum that can't conduct electricity (either a plastic pendulum or a metal pendulum with cuts through it that prevent currents from flowing). This modified pendulum will swing through the electromagnet even when that electromagnet is on.

260. A Magnet Falling Through A Copper Pipe

Description: A small magnet falls incredibly slowly through a copper pipe.

Purpose: To demonstrate the repulsive magnetic fields that appear when a magnet moves across a conductive surface.

Supplies:

1 small neodymium-iron-boron magnet
1 metal cylinder the same size as the magnet
1 narrow copper pipe
1 support for the copper pipe

Procedure: Support the copper pipe so that it's vertical. Drop the metal cylinder through the copper pipe and note how quickly it falls. Now drop the magnet through the pipe and watch how slowly it descends.

Explanation: As it falls, the magnet induces currents in the copper pipe and these currents exert repulsive magnetic forces on the magnet. These repulsive forces slow the magnet’s descent.

261. A Magnet Sliding Through a Half-Copper, Half-Plexiglas Track

Description: A small disk magnet rolls through a narrow track that's made of Plexiglas at one end and copper at the other. The magnet rolls quickly through the Plexiglas portion of the track but slows dramatically when it enters the copper portion of the track.

Purpose: To demonstrate the repulsive forces that occur when a magnet moves past a conducting surface.

Supplies:

1 small disk neodymium-iron-boron magnet
1 track for the magnet, cut from a square copper bar at one end and from a square Plexiglas bar at the other end. The two bars are joined and framed in Plexiglas to keep them together and to keep the magnet in the track.

Procedure: Tilt the track so that the magnetic disk rolls along the track. Show that the disk rolls quickly through the Plexiglas portion of the track but slows when it rolls through the copper portion of the track.

Explanation: The moving magnet induces currents in the conducting copper and experiences repulsive magnetic forces from the currents it induces. The magnet rolls freely through the Plexiglas because currents can't flow in the Plexiglas.

262. Electrodynamic Magnetic Levitation of Magnet on a Spinning Metal Disk

Description: A large disk magnet floats above a spinning aluminum disk.

Purpose: To demonstrate electrodynamic levitation.

Supplies:

1 large neodymium-iron-boron disk magnet (the larger and thinner, the better)
1 sturdy aluminum disk about 40 cm in diameter, with a spindle attached
1 variable-speed motor for spinning the aluminum disk
1 sturdy mount for the motor

Procedure: Mount the aluminum disk on the motor and attach the motor to a sturdy table so that the aluminum disk spins in a horizontal plane. Be sure that everything is well balanced and strong enough to tolerate high rotational speeds. The disk's surface should be able to reach speeds of 200 km/h without any damage! If you are concerned about the disk coming apart at these high speeds, build a safety fence around the spinning disk. Support the magnet on a flexible strap that will keep it horizontal but will allow it to rise or fall vertically.

Turn on the motor and bring the aluminum rotor to a relatively high surface speed of at least 100 km/h. Use the strap to lower the magnet carefully toward the outer surface of this disk. The strap should be oriented tangent to the disk's edge, with the disk turning in the direction that leads from your hand toward the magnet. The magnet will be pulled in the direction of the disk's rotation by magnetic drag forces and you should hold the strap tightly so that it isn't pulled out of your hand. Before the magnet touches the aluminum disk, it will experience a strong magnetic repulsion and it will begin to hover a few centimeters above the spinning aluminum disk. The faster the aluminum disk turns, the higher the magnet will hover and the less magnetic drag force it will experience. Be carefully not to spin the disk so fast that it flies apart. Safety first!

Explanation: The magnet induces currents in the aluminum disk and the disk becomes magnetic. It repels the magnet, suspending the magnet in the air and giving rise to the magnetic drag force that tends to pull the magnet along with the disk. The magnetic drag force diminishes with higher speeds because the currents in the aluminum have less time to waste energy.

263. Superconductors and Magnetic Levitation

Description: A small permanent magnet hovers above the surface of a high temperature superconductor.

Purpose: To demonstrate the perpetual current flow and magnetization of a superconductor when approached by a magnet.

Supplies:

1 high-T_c superconductor disk
1 small neodymium-iron-boron magnet
1 Styrofoam cup
1 thin foam rubber or sponge pad
liquid nitrogen

Procedure: Cut the Styrofoam cup to form a shallow tub and place the superconductor disk on the foam rubber pad in the middle of this tub. Fill this tub with liquid nitrogen and allow the disk to cool until the liquid nitrogen is barely boiling. Now lower the permanent magnet onto the disk and watch as it floats above the disk.

Explanation: The approaching magnet induces currents in the superconductor disk and the two repel one another. This repulsion suspends the magnet in midair. Because the currents in the superconductor don't decay away or lose energy, the suspension continues indefinitely.

Follow-up: Even if you leave the magnet on the superconducting disk while it's cooling down, the magnet will lift up off the surface of the superconductor as soon as the superconductor becomes cool enough to superconduct. This behavior, in which magnetic fields are excluded from a superconductor, is called the Meissner effect and is something not seen in normal electrodynamic levitation. It's unique to certain types of superconductors.

Section 12.1 Flashlights

Some of the demonstrations from Section 6.3 would also be valuable as an introduction (or reintroduction) to light bulbs.

264. A Simple Circuit with a Battery and Light Bulb

Description: You connect a battery and a light bulb with wires and create a circuit. The light bulb begins to emit light.

Purpose: To show how a circuit works.

Supplies:

3 fresh 1.5 V batteries (flashlight batteries)
3 battery holders
1 1.5 V light bulb
1 3.0 V light bulb
1 4.5 V light bulb
1 light bulb holder
1 current visualizer (available from a scientific supply company—an electronic device with a row of LEDs that create a moving light pattern to illustrate the direction and amount of current flow)
1 switch
6 wires

Procedure: Start with one battery and the 1.5 V light bulb. Connect one wire between the battery's positive terminal and one terminal of the light bulb. Discuss that while this single connection is enough to allow positive charge to flow briefly from the battery to the light bulb, that this flow quickly stops. Now connect a second wire from the battery's negative terminal to the other terminal of the light bulb. The light bulb begins to glow. Discuss why the second wire is so important.

Now insert the current visualizer into the circuit between the battery's positive terminal and the light bulb. The visualizer will show that current (the flow of positive charge) always flows through the circuit in one direction, from the battery's positive terminal to the light bulb and back to the battery's negative terminal. Point out that the same electric charge is being used over and over—that it's flowing in a loop, picking up energy from the battery (at a rate of 1.5 J for each coulomb that passes through the battery; hence the label "1.5 V"), releasing that energy in the light bulb, and returning to the battery to make another trip.

Now reverse the battery connections. The flow of current through the rest of the circuit will reverse. This demonstration shows that the battery is responsible for determining the direction of current flow in the circuit.

The battery creates the initial charge imbalance that pushes charge through the circuit.

Once it's clear how the circuit works, add the switch to the circuit. Show how opening the switch stops the flow of current through the circuit and turns off the light. Discuss the fact that you can insert the switch at any point in the circuit because any break in the circuit stops the current flow.

Now replace the 1.5 V light bulb with the 3.0 V light bulb. It will glow dimly. Discuss the fact that this bulb needs a current of more energetic charges to glow properly. Add a second battery in series with the first battery (connect the negative terminal of one battery to the positive terminal of the other to produce a battery chain with a total voltage of 3.0 V) and note that the light bulb glows much more brightly. Discuss the fact that the current now passes through both batteries and thus receives more energy per charge (3.0 J per coulomb, in accordance with the total battery voltage of 3.0 V).

Replace the 3.0 V light bulb with a 4.5 V light bulb and then add a third battery to the chain of batteries. Once again, the bulb will glow brightly. However, now reverse one of the batteries in the chain. The 4.5 V light bulb will become very dim. Replace it temporarily with the 1.5 V light bulb to show that the chain of batteries is now giving the current flowing through it only 1.5 J per coulomb (1.5 V). The reversed battery is actually taking away energy from the charges passing through it! As a result, the reversed battery is "recharging," although probably not very well because it's not designed to be recharged.

Replace the 1.5 V light bulb with the 4.5 V light bulb and return the battery to its proper situation in the chain. Again, the light bulb will glow brightly.

Explanation: Electric charge mustn't accumulate at any point in this arrangement of components. If it did, it would repel any additional charge and the current would stop flowing. By arranging the components in a circuit, the charge can flow continuously through it without accumulating anywhere. The charge simply shuttles energy from the battery to the light bulb's filament. Reversing one battery in the chain causes that battery to extract energy from the current passing through it, rather than adding energy to that current.

265. A Short Circuit

Description: A circuit consisting of 3 batteries and a light bulb is working properly and the light bulb is emitting light. When a wire is connected directly from one terminal of the light bulb to the other, the light bulb dims and the wire begins to glow red hot—a short circuit.

Purpose: To show that current can take alternative paths through a circuit, some of which can be dangerous.

Supplies:

- 3 fresh 1.5 V batteries
- 3 battery holders
- 1 4.5 V light bulb
- 1 light bulb holder (with extra terminals for the nichrome wire below)
- 4 not-too-heavy gauge wires
- 1 piece of nichrome wire with terminals at its ends that connect easily and safely to the terminals of the light bulb holder
- 1 piece of paper
- water to extinguish the burning paper if necessary

Procedure: Connect the 3 batteries in series and then connect the chain of batteries to the light bulb. The light bulb should glow brightly. Discuss the operation of the circuit. Now insert the nichrome wire across the terminals of the light bulb, so that current can flow through the nichrome wire rather than through the light bulb (the two should be wired in parallel to one another). The light bulb will dim and the nichrome wire will begin to glow red hot (adjust the length and thickness of the nichrome wire so that it glows nicely). For illustrative purposes, you can light a small piece of paper on fire with the hot wire. Discuss how the short circuit that the nichrome wire provides diverts current from the light bulb and why the nichrome wire becomes so hot.

Explanation: The nichrome wire presents a low resistance path for the current to take through the circuit. Since various resistances within the rest of the circuit limit the amount of current that can flow, the amount of current available for the light bulb decreases significantly and it dims. The nichrome wire converts much of the current's electrostatic potential energy and kinetic energy into thermal energy and it becomes very hot.

Section 12.2 Electric Power Distribution

266. Ohm's law

Description: A simple arrangement of a variable DC power supply, a resistor, a voltmeter, and an ammeter demonstrate that the current passing through the resistor is proportional to the voltage drop across it—Ohm's law.

Purpose: To show the relationship between current and voltage in an object that obeys Ohm's law.

Supplies:

1 variable-voltage DC power supply (for example, 0–10 V)
1 resistor (for example, 1000 ohms)
1 voltmeter (for example 0–10 V full scale)
1 ammeter (for example 0–10 mA full scale)
wires

Procedure: Form a circuit by connecting the positive terminal of the power supply to the positive terminal of the ammeter, the negative terminal of the ammeter to one end of the resistor, and the other end of the resistor to the negative terminal of the power supply. Also connect the positive terminal of the voltmeter to the ammeter-side of the resistor and the negative terminal of the voltmeter to the power supply side of the resistor.

Now show that as you slowly turn up the voltage of the power supply, the voltage drop across the resistor (as measured by the voltmeter) increases and the current through the resistor (as measured by the ammeter) increases in equal proportion. Point out that this perfect proportionality between the voltage drop across the resistor and the current that passes through the resistor is true of almost any conducting object, including electric wires—the more voltage drop that they experience, the more current that flows through them, or the more current that flows through them, the more voltage drop that they experience! Ohm's law. Point out that a wire that's carrying lots of current and that's thus experiencing a large voltage drop is also consuming lots of power. The power that it's consuming is the product of its current times its voltage drop.

Explanation: An ohmic device draws a current that's proportional to the voltage drop across it (or equivalently, it experiences a voltage drop that's proportional to the current passing through it). Since most conductors behave in an ohmic fashion, this relationship between current and voltage is almost universal. Because the power consumed by a device (energy per second) is the product of the current passing through it (charges per second) times the voltage drop across it (energy consumed per charge), the power consumed by an ohmic device is proportional to the square of its voltage drop or, equivalently, to the square of the current passing through it. The other factor that figures into this power consumption is the resistance of the ohmic device. For a set current flow, the power consumption of an ohmic device decreases as its resistance decreases.

267. Distributing DC Power - Current Trouble

Description: A light bulb glows brightly when it's connected to a nearby battery but becomes much dimmer when the wires connecting it the battery grow longer. The solution to this problem is to use thicker wires.

Purpose: To show that wires are active components in a circuit and that thin wires carrying large currents waste lots of power.

Supplies:

1 12 V car battery
2 12 V lamps (about 80 W)
2 holders for the 12 V lamps
2 short wires (relatively thick gauge)
2 long, thin wires (at least 10 m long; we use 18 gauge speaker wire)
2 long, thick wires (same length as above; we use #10 gauge house wiring)

Procedure: Connect the car battery to the lamp using the short wires and observe that the lamp glows brightly. Discuss the fact that almost all the energy given to the current by the battery is deposited in the lamp's filament. The wires do waste some of the current's energy, but not enough to notice.

Now connect the second lamp to the same car battery with the long thin wires. This second lamp should be placed as far away as the wires will allow. It will also begin to glow, but not very brightly. Point out that while both lamps are identical, the long, thin wires are now wasting so much of the power they're carrying that there isn't much left for the distant lamp.

After pointing out that the power a wire wastes is proportional to the square of the current it carries and inversely proportion to its electric resistance, replace the long, thin wires with the long, thick wires. The distant bulb will now glow much more brightly. Discuss how using thick wires reduces the fraction of power wasted in the wires. Because copper is expensive, this is an expensive solution to the problem of long distance electric power distribution.

Explanation: Reducing the electric resistance of the wires carrying electric power is part of the solution to electric power distribution. A much more effective solution is to reduce the current involved by raising the voltages involved.

268. Alternating Current and Transformers

Description: An alternating current passes through an electromagnet. When a coil of wire with a light bulb attached to it is lowered over the pole piece of the electromagnet, the light bulb glows.

Purpose: To show that a transformer can transfer power from its primary circuit to its secondary circuit without any contact (or exchange of charge) between the two.

Supplies:

1 AC electromagnet with an iron-rod pole piece that extends vertically above the wire coil
1 coil of wire that forms a complete circuit with a small light bulb as part of that circuit

Procedure: Connect the AC electromagnet to the power line and turn it on. Point out that current is now flowing through the coil of the electromagnet, but that its direction of travel is reversing smoothly 120 times a second (or 100 times a second outside the United States). The electromagnet's magnetic poles are reversing directions with each reversal of the power line and these changes in the magnetic field near the electromagnet give rises to changing electric fields that circle the pole piece.

While there are no mobile electric charges near the pole piece, nothing happens. But now lower the coil of wire around the pole piece and watch the lamp begin to glow. Point out that the wire contains mobile electric charges that are pushed on by the electric fields around the pole piece. These electric fields do work on the mobile electric charges and the coil of wire becomes a source of electric power. This electric power is consumed by the light bulb. Note that there is no direct contact between the wire coil and the electromagnet—no charge or current moves between the primary coil and the secondary coil; only power is being transferred.

Explanation: The fluctuating magnetic field of the AC electromagnet creates a fluctuating electric field that circles the pole piece. When the coil of wire is lowered around that pole piece, the electric field pushes charges through the wire and does work on those charges. They experience a voltage rise as they flow around the coil (the more turns, the more voltage rise) and they deliver their energy to the light bulb. In the light bulb, these charges experience a voltage drop and they finally return to the coil to pick up more energy.

269. Step-Down Transformers

Description: A step-down transformer is used to heat a nail red hot.

Purpose: To show that a step-down transformer can take power that arrives as a modest current at a moderate voltage and use it to provide power to a second circuit as a large current at a small voltage.

Supplies:

1 power-line operated step-down transformer (a high current transformer—a soldering gun will work in a pinch)
2 nails
1 heavy gauge wires (as necessary)

Procedure: Connect one nail to each of the two secondary terminals of the step-down transformer. Touch the two nails together near their tip. Plug in the transformer and watch as the nails begin to glow red hot. If their temperatures become high enough, they will weld themselves together. Unplug the transformer and allow the nails to cool. If they have welded themselves together, show that this has happened.

Explanation: For the nails to consume enough electric power to reach red heat, they must have large currents flowing through them. The step-down transformer transfers power to a circuit that carries a large current of low energy (low voltage) charges and this large current is enough to heat the nails very hot.

270. Step-Up Transformers

Description: A step-up transformer is used to make a flaming arc that rises between two almost parallel vertical wires—a Jacob's ladder.

Purpose: To show that a step-up transformer can take power that arrives as a modest current at a moderate voltage and use it to provide power to a second circuit as a small current at a high voltage.

Supplies:

1 power-line operated step-up transformer (a high voltage transformer—a neon sign transformer works well)
2 copper rods or wires

Procedure: Connect one of the copper rods to each of the two secondary terminals of the step-up transformer. Bend the rods together so that they almost touch and then head vertically upward. Allow them to spread apart gradually as they rise upward. Be sure that the copper rods don't come near the case of the transformer or near anything else! When you're sure that everything (particularly people) is safely away from the transformer and the copper rods, plug in the transformer. A flaming arc will appear at the closest approach between the two rods and will then rise gradually upward until it breaks at the top of the rods. A new arc will appear at the bottom of the rods again and will begin to rise. If the arc fails to rise, you can help it start upward by blowing it upward, but be careful not to get near the transformer or rods.

Explanation: The step-up transformer is producing a small current of high energy (high voltage) charges. They have so much energy that they can leap through the air from one wire to the other, ionizing the air in the process. Once a path of ionized air forms, an arc, this arc becomes the natural path for subsequent charges to take between the copper rods. Because the arc consists of hot gases with low densities, it's lifted upward by the buoyant force until it breaks away from the top of the copper rods. A new arc then forms at the bottoms of the rods.

271. A Tesla Coil

Description: An air-core step-up transformer is used to produce long sparks.

Purpose: To show that a step-up transformer can take power that arrives as a modest current at a moderate voltage and use it to provide power to a second circuit as a very small current at a very high voltage.

Supplies:

- 1 telsa coil (commercial, or instructions on how to build one follow)

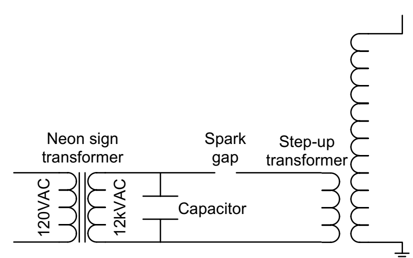
Constructing a Simple Tesla Coil: You'll need a neon sign transformer (about 12,000VAC output), one or more plate glass capacitors, a spark gap, and a cardboard or plastic pipe upon which to wind a very long coil of fine enamel-coated copper wire. You'll also need high voltage wire, rated to a voltage that's at least the voltage of the neon sign transformer.

To build the capacitor(s): glue aluminum foil to both sides of a large plate of heavy window glass (about 50 cm on a side). Leave at least 5 cm of open glass around the edges of the aluminum foil so that no arcs form around the edges.

To build the spark gap: mount two binding posts on an insulating support so that they're about 10 cm apart. Insert a sharpened copper rod into each binding post and bring the two tips to about 2 cm apart. You'll have to adjust this spacing to be sure that arcs form properly.

To build the main transformer: create the primary coil with 20 turns of high voltage wire. Support this wire on an insulating mount that gives it a diameter about 20 cm larger than that of the secondary coil. Now wind the secondary coil around the cardboard or plastic pipe. This pipe should be about 15 cm in diameter and about 1 to 1.5 m tall. Use 24 gauge enamel-coated copper wire to wind the secondary coil. You should be able to fit about 2,000 turns on the pipe, leaving about 5 cm at each end. The upper end of the secondary coil should be mounted so that it projects upward above the pipe. The pipe should sit vertically at the center of the primary coil. The primary coil should be at the base of the second coil.

Assembling the parts: unplug the neon sign transformer! The two secondary terminals of the neon sign transformer should be attached to the two sides of the capacitor. If you have more than one capacitor (the more capacitors—up to a maximum of 3—the higher the final voltage of the tesla coil), connect the capacitors in parallel. Keep all the wires well insulated and away from anything conducting, particularly other wires! Always use high voltage wire. Now connect one terminal of the spark gap to one secondary terminal of the neon sign transformer. Connect the other terminal of the spark gap to one side of the main primary coil. Connect the other side of the main primary coil to the other secondary terminal of the neon sign transformer. Ground the lower end of the main transformer secondary to a good earth ground.



To operate the Tesla coil: from a safe distance, plug in and turn on the neon sign transformer. If the spark gap doesn't begin to arc, immediately turn off the transformer and unplug it, then adjust the spark gap to have a narrower gap and try again. Once the spark gap fires, you should begin to see long sparks emerging from the top of the secondary coil. For the longest sparks, the spark gap should be adjusted (always unplug the neon sign transformer before adjusting it) so that it just barely fires during each half-cycle of the power line.

How it works: During each half cycle of the power line, the neon-sign transformer secondary moves charge from one side of the capacitor to the other until a large voltage difference appears across the capacitor. When this voltage difference becomes large enough to initiate a spark across the spark gap, it arcs and the capacitor becomes electrically connected to the primary coil of the main transformer. The capacitor and the primary coil then form a tank circuit, and charge sloshes back and forth from one surface of the capacitor to the other through the primary coil at radio frequencies (approximately 1 MHz). The changing magnetic field inside the primary coil induces current in the secondary coil of the main transformer. Because of its many turns, the voltage rise across the secondary coil of the transformer is enormous—between 100,000 V and 300,000 V, depending mostly on the number of capacitors in the circuit.

NOTICE: This Tesla coil uses dangerous voltages and should not be built or operated by anyone unfamiliar with safety precautions appropriate for the safe use of high voltages. The Tesla coil emits electromagnetic waves and may not comply with FCC regulations. It produces ozone gas, an irritating and toxic form of oxygen. Neither the author nor the publisher accepts any responsibility for health, regulatory, or other problems that arise from the construction and/or operation of this device.

Procedure: Turn on the Tesla coil and show that it produces a display of enormous sparks. Discuss the fact that because it has no iron core to store magnetic energy, it must operate at very high frequencies. The primary coil magnetizes empty space and the changing magnetization of empty space is enough to induce currents in the secondary coil. Note that the voltages involved in the Tesla coil are actually less than the voltages used in many high voltage transmission lines. Discuss the issues involved in keeping such high voltages from producing sparks and wasting power.

Explanation: A Tesla coil is an air core transformer that operates on very high frequency AC. The radio frequency current through the primary coil of the Tesla coil induces a radio frequency current in the secondary coil. Because there are far more turns in the secondary coil than in the primary coil, the Tesla coil acts as a step-up transformer and produces very high voltages.

272. Distributing AC Power - Transformers Save the Day

Description: A light bulb glows brightly when it's connected to a nearby AC power source but becomes much dimmer when the wires connecting it to the power source are longer. While thicker wires help, there is a better solution: step the voltage up for transmission through the original wires and step the voltage down before delivering power to the light bulb. After inserting two transformers into the system, the distant light bulb glows brightly.

Purpose: To show that wires carrying a certain amount of power lose less of it when that power takes the form of a small current of high energy (high voltage) charges.

Supplies:

- 3 identical transformers: primary 120 VAC, secondary 12 V, 15 A or more. If possible, these transformers should be mounted on boards with terminals that allow easy connections. One of the transformers should have a power cord attached to its primary windings. In all cases, the transformers should be insulated properly and handled carefully to avoid shocks or fires. Note: if you choose not to operate two lamps at once, you don't need such large transformers. With only one lamp, you can get by with 7 A transformers (12 V times 7 A is 84 W).
- 2 12 V lamps (about 80 W)
- 2 holder for the 12 V lamp
- 2 short wires (relatively thick gauge)
- 2 long, thin wires (at least 10 m long; we use 18 gauge speaker wire)
- 2 long, thick wires (same length as above; we use #10 gauge house wiring)

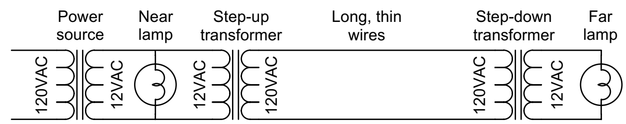
Procedure: Begin with the transformer that has a power cord. Use the short wires to connect the secondary of this transformer to the lamp and plug in that transformer. Observe that the lamp glows brightly. The students shouldn't concern themselves with this first transformer—they should think of it as a source of 12 VAC power. Discuss the fact that this alternating current can cause the bulb to light, even though it's stopping and reversing many times a second. Discuss the fact that almost all the energy given to the current by the AC power source is deposited in the lamp's filament. While the wires waste some of the current's energy, it’s not enough to notice.

Now connect the second lamp to the same power source (the 12 VAC supply) with the long thin wires. This second lamp should be placed as far away as the wires will allow. It will also glow, but not very brightly. Point out that while both lamps are identical, the long, thin wires are now wasting so much of the power they're carrying that there isn't much left for the distant lamp.

You can show, if you like, that replacing the long, thin wires with long, thick wires will solve the problem. However, you should then return to the thin wires. Now unplug the first transformer (for safety) and insert the two remaining transformers into the circuit. Place one transformer near the power source transformer and connect the secondary winding of this transformer to the secondary winding of the power source transformer. This added transformer will be the step-up transformer because it will convert a large current at 12 VAC into a small current at 120 VAC. Connect the two long, thin wires to the primary winding of this added transformer.

Now place the remaining transformer near the distant light bulb and attach the two long, thin wires to the primary winding of this transformer. Connect the secondary winding of this transformer to the distant light bulb. This third transformer will be the step-down transformer because it will convert a small current at 120 VAC into a large current at 12 VAC.

Starting with the 12 VAC from the power source transformer, there are 3 circuits: an initial 12 VAC circuit, a 120 VAC circuit that extends the length of the long, thin wires, and a final 12 VAC circuit. Now plug in the power source transformer and observe that both light bulbs, near and distant, glow equally brightly. The long, thin wires are now carrying a small current of high energy (high voltage) charges and are wasting relatively little power in the process. This demonstration shows how AC power permits the use of thin wires to carry electric power long distances with tolerable power loses.



Explanation: Even though the electric resistances of the long, thin wires is still high, they carry so little current that the power they consume (current squared times resistance) is still small.

Section 12.3 Electric Power Generation

273. Generating Electricity - A Coil and a Magnet

Description: When a magnet moves past a coil of wire, a current flows through the wire.

Purpose: To show that changing or moving magnetic fields can induce currents in electric conductors.

Supplies:

- 1 coil of wire
- 1 bar magnet
- 1 current meter (one that reads both positive and negative currents)

Procedure: Connect the two ends of the coil of wire to the two terminals of the current meter. Now move one pole of the bar magnet past the coil. You'll observe that the meter needle moves first one way and then the other. Show that as the pole approaches the coil, the needle moves one way and as the pole moves away from the coil, the needle moves the other way. Try reversing the magnet (use its other pole)—the effect will reverse.

Explanation: The changing magnetic field through the coil produces an electric field around it and this electric field pushes charges through the coil's windings. The meter registers this flowing current. The direction of current flow is determined by the direction in which the electric field points and that direction depends on how the magnetic field is changing.

274. Generating Electricity - A Coil and a Two-Color LED

Description: When a magnet moves past a large coil of wire, a current flows through it and illuminates an LED. The LED's color depends on which way the magnet moves and on which of its poles is being used.

Purpose: To show that moving a magnet past a conductor can cause a current to flow through that conductor.

Supplies:

- 1 large coil of wire (several hundred or even a thousand turns)
- 1 two-color LED (actually two different LEDs connected in parallel in the same package. One LED glows when the current flows one direction and the other LED glows when the current flows in the opposite direction. Alternatively, use two LEDs connected in parallel but in the opposite directions)
- 1 strong bar magnet

Procedure: Connect the LED to the two ends of the wire coil. Now hold the bar magnet in your hand and bring one of its poles toward the wire coil. The faster you move the magnet, the more effective it will be. The LED should light with one of its colors. Now pull the magnet out of the coil quickly. The LED should light with its other color. Repeat this process rapidly several times and point out that you are generating alternating current. If you were to attach the magnet to a spinning rotor, the LED would blink back and forth rapidly as the magnet swept by. Show that reversing the pole of the magnet reverses its effects.

Explanation: The changing magnetic field in the coil of wire induces currents in the coil. The coil is large enough (has enough turns) that these induced currents reach the high voltages (about 3 to 5 V) needed to power an LED.

275. An AC Generator

Description: You turn the crank of an AC generator and illuminate a light bulb. You show that it's much harder to turn the crank of the generator when current is flowing through the light bulb than when the circuit to the light bulb is open.

Purpose: To show how an AC generator works.

Supplies:

1 AC generator
1 suitable light bulb for the generator
1 light bulb holder
2 wires

Procedure: Connect the two terminals of the generator to the two terminals of the light bulb holder and light bulb. Turn the generator and show that the light bulb lights up. Allow a student to turn the generator and open and close the circuit to show that it's much harder to turn the generator while current is flowing and the generator is producing electric power.

Explanation: The generator moves a magnet past a coil (or a coil past a magnet) and generates an alternating electric current in the coil and the circuit to which that coil is attached. In this case, the current flows back and forth through the light bulb and its filament becomes hot.

276. Two DC motors Connected in Parallel

Description: Two DC motors (with permanent magnets) are connected to one another by wires. When you turn one of the motors, the other motor also turns. Reversing the direction in which you turn the first motor reverses the direction in which the other motor turns.

Purpose: To show how a DC generator works.

Supplies:

2 DC motors (good bearings and permanent magnets are essential—we use two 12 V motors that are large and powerful; probably about 1/10 hp or so)
2 wires

Procedure: Connect the two DC motors together with the two wires so that you form one large circuit. Now spin the rotor of one of the motors and observe that the other motor spins. That's because you're generating electricity with the first motor (effectively a generator) and that electricity is powering the second motor. Do the same with the second motor and show that the two motors are interchangeable. Now show that reversing the direction in which you spin the first motor causes the second motor to reverse its direction of rotation. That's because the motors are acting as DC generators—they contain switching systems that ensure that the current flows in one direction that's determined only by the direction in which you spin the rotor. Similarly, the direction of current flow through a DC motor determines its direction of rotation.

Explanation: When you spin the rotor of the DC motor, you are moving a permanent magnet past a coil (or vice versa) and generating a current in that coil. A switching system inside the motor/generator changes the connections regularly so that current always flows in the same direction through the external portions of the circuit (as long as you don't reverse the direction in which the motor/generator's rotor is spinning). The DC electricity that you generate with the first motor/generator powers the second motor/generator, which turns in a direction determined by the direction of current flow through the circuit.

277. Hero's Engine

Description: Steam produced by water boiling in a spherical vessel emerges from that vessel through two arms that are arranged in a Z shape. As the arms push the steam in one direction, the steam pushes back and the vessel experiences a torque. It begins to spin rapidly.

Purpose: To show how steam can be used to create rotational motion (a primitive turbine-like heat engine).

Supplies:

1 Hero's engine (available from a scientific supply company)
1 suspension for the Hero's engine (preferably with a swivel clip)
1 gas burner
matches
water

Procedure: Partly fill the Hero's engine with water and install the cap. Suspend the Hero's engine from its support and place the burner beneath it. Ignite the burner and allow the water to boil. When steam begins to emerge from the arms of the Hero's engine, the reaction forces on the arms will produce a torque on the engine and it will begin to spin rapidly. Turn off the burner so that it doesn't get out of control.

Explanation: The ejected steam exerts a torque on the engine, which undergoes angular acceleration. The steam is doing work on the engine, converting a small amount of its thermal energy into work as heat flows from the hot steam to the colder room air. The Hero's engine is a simple heat engine.

278. An Air Turbine or Windmill

Description: You blow air from a compressed air line or tank at a turbine or fan and it begins to spin. With the turbine or fan attached to a generator, it produces electric power.

Purpose: To show that a high-pressure (or high-speed) fluid can be used to generate electricity.

Supplies:

1 turbine or fan assembly, attached to a generator
1 light bulb
1 light bulb holder
2 wires
1 hose
compressed air or a tank of high pressure gas

Procedure: Insert the bulb in the holder and use the two wires to connect it to the generator. Allow the air or gas to flow through hose and direct the stream of air or gas toward the turbine blades. The blades will begin to spin, turning the generator and generating electricity. The light bulb will illuminate.

Explanation: As the air or gas flows through the turbine blades, they experience lift forces. These lift forces produce torques on the blades about their central pivot and the blades begin to turn. They turn the generator, which produces electricity.

279. Diodes - One Way Devices for Current

Description: A battery and light bulb are connected in a circuit so that the bulb lights up. When a diode is inserted into the circuit in one direction, it has essentially no effect and the bulb remains bright. But when the diode is reversed, no current flows through the circuit and the bulb is dark.

Purpose: To show that a diode only carries current in one direction.

Supplies:

1 12 V battery
1 12 V light bulb
1 light bulb holder
1 power diode
3 wires

Procedure: Insert the light bulb in the holder and use two of the wires to connect the battery to the bulb. The bulb will glow brightly. Now insert the diode into the circuit so that the battery's positive terminal connects to the anode of the diode and the diode's cathode connects to the light bulb. The light bulb will continue to glow. Finally, reverse the diode's connection, so that its anode is connected to the light bulb and its cathode is connected to the positive terminal of the battery. The light bulb will be dark because no current will flow. Discuss the fact that the diode only permits current (positive charges) to flow from its anode to its cathode.

Explanation: When the diode is forward biased (its anode is positively charged and its cathode is negatively charged), conduction level electrons in the cathode's n-type semiconductor can approach the diode's p-n junction and leap across the junction into empty conduction levels in the anode's p-type semiconductor. The anode's positive charges can then meet the oncoming electrons so that there is a net flow of charge and current through the diode. But when the diode is reverse biased (its anode is negatively charged and its cathode is positively charged), the depletion region near the p-n junction widens and no charges cross the junction.

280. A Solar Cell

Description: A solar cell is connected to a small motor. When the cell is exposed to light, the motor turns.

Purpose: To show that a solar cell can produce electricity directly from light.

Supplies:

1 solar cell
1 ultra-low friction motor (specially designed for solar cell operation—available from a scientific supply company)
2 wires
1 100 W (or more) incandescent spot light

Procedure: Use the two wires to connect the solar cell to the motor. Now expose the solar cell to the bright light from the spot light. Current will begin flowing through the solar cell and receiving power. This power will be delivered to the motor and will cause it to turn.

Explanation: The solar cell is a specially designed diode. Light energy transfers electrons from the n-type semiconductor of the cathode to the p-type semiconductor of the anode. The anode becomes negatively charged and the cathode becomes positively charged. Since the electrons can't return through the diode's p-n junction, they flow through the circuit (including the motor). The light energy is causing this current flow and is powering the motor.

Section 12.4 Electric Motors

281. Hanging from an Electromagnet

Description: A strong electromagnet hangs for the ceiling. A steel surface is touched to it and it's turned on. The forces between the electromagnet and the steel are so strong that you can hang from the steel without pulling it away from the electromagnet.

Purpose: To demonstrate the tremendous forces that are possible with electromagnets.

Supplies:

1 strong, battery-powered electromagnet (available from scientific supply companies)
1 thick steel plate, the same diameter as the electromagnet
2 strong steel eyelets with threaded shafts
2 ropes

Procedure: Use a drill and tap to attach one of the eyelets to the back of the electromagnet and the other to the back of the steel plate. Attach the ropes to the eyelets and hang the electromagnet from the ceiling. Form a loop in the rope attached to the steel plate so that you can hold onto the rope tightly. Now touch the steel plate to the electromagnet and turn the electromagnet on. The plate will bind very strongly to the electromagnet. Pull downward on the steel plate to show that it can't be pulled away easily. Try hanging on the plate (though be prepared for it to pull away from the electromagnet). If the electromagnet is sufficiently strong, the plate will remain attached.

Explanation: Steel is a ferromagnetic metal, meaning that it contains magnetically ordered domains. When you bring the steel near the electromagnet, the steel's domains change size and reorient to give the steel its own magnetic poles. The steel's poles are opposite to those of the electromagnet and the two bind together strongly.

282. A Galvanometer

Description: When you send current through the coil of a galvanometer, the coil moves. It experiences a torque in the presence of a magnetic field.

Purpose: To show that the torque between a current-carrying coil and a fixed permanent magnet can cause that coil to turn.

Supplies:

1 galvanometer (or a coil of wire that's supported in a low-friction bearing and surrounded by permanent magnets)
1 battery
2 wires
1 resistor (to limit the current through the galvanometer, if necessary)

Procedure: Use the two wires to connect the battery to the galvanometer. If the galvanometer involves thin wires, you should include a current-limiting resistor in the circuit. As soon as you complete the circuit and current begins to flow through the galvanometer, its coil will become magnetic and will experience a torque due to its interactions with the surrounding magnets. However, it will turn only once and then settle down. Unlike a motor, the galvanometer coil has an equilibrium orientation into which it's able to settle.

Explanation: The galvanometer coil will turn to bring its magnetic poles as close as possible to the opposite poles of the surrounding permanent magnets.

283. A DC Motor

Description: A DC motor with a visible commutator turns rapidly as current passes through it from a battery.

Purpose: To show how a DC motor works.

Supplies:

1 DC motor demonstration, with a visible commutator
1 battery
2 wires

Procedure: Use the two wires to connect the DC motor to the battery. The motor will begin spinning. Reverse the battery and show that the motor turns the other way. Point out that the motor reverses because all the poles of the coil reverse but the permanent magnets that surround the coil remain unchanged. As a result, the torques on the rotor reverse and the motor spins backward. Stop the motor and discuss how the commutator reverses the flow of current through the coil just before the coil reaches its equilibrium orientation. This current reversal ensures that the coil keeps turning because the coil can never actually reach its equilibrium orientation.

Explanation: The battery provides power to the current that then flows through the coil of the motor. This current magnetizes the coil and causes the coil to experience a torque in the presence of the surrounding permanent magnets. The coil rotates so as to approach its equilibrium orientation within the permanent magnets, but before it arrives, the commutator causes the current through the coil to reverse and it must turn further. The coil never reaches an equilibrium orientation and continues to turn indefinitely.

284. A Very Simple DC Motor

Description: A tiny motor built right on top of a battery turns for hours without stopping.

Purpose: To illustrate just how easy it is to build an electric motor.

Supplies:

1 "D" battery
1 strong rubber band
2 large paper clips
1 square magnet, about 2 cm on a side and about 0.3 cm thick, with a north pole on one side and a south pole on the other.
enamel-coated copper wire, about #24 gauge
fine sandpaper
pliers
tape
1 small base

Procedure: One end of a paper clip has two metal loops. Locate this end of each clip and bend the outer loop over the inner loop so that you form an oval opening at that end of the paper clip. Place one of the modified paper clips at each end of the battery so that the two oval openings project outward from the same side of the battery. Hold the two paper clips in place with the rubber band. Lie the battery on its side so that the paper clips point directly upward and tape the battery to the base so that the battery won't roll. Use tape to attach the square magnet to the top of the battery, between the two paper clips.

Now wind a circular coil from the enamel-coated copper wire. You should form a coil about 2 cm in diameter that contains about 10 turns of wire. One end of the wire in the coil should extend about 3 cm to the left from the coil and the other end should extend about 3 cm to the right. Wrap the wire ends once or twice around the other 10 turns of wire before extending them outward, to help hold the coil together. You should end up with a wire ring that has an end wire extending leftward at 9 O'clock and another end wire extending rightward at 3 O'clock.

Sand away the insulation from one end wire but be careful with the other end wire. Hold the coil of wire so that the coil is in a vertical plane with the untouched end wire oriented horizontally. Lower that end wire onto a firm horizontal surface and sand away only the enamel that's on the upper half of the end wire. Leave the lower half enamel-coated.

Carefully insert the coil's end wires into the two oval loops of the two paper clips—one end wire into each oval—and let the end wires touch the paper clips. If the paper clips are touching the battery terminals and if the end wires of the wire coil are making contact with the paper clips, the coil should begin to move. You may have to spin the coil to get it started. Note that it will only spin properly in one direction, determined by the direction of current flow through the coil and the orientation of the magnet. The coil will spin as long as the electric connections are good and will operate for hours before depleting the battery's energy.

Explanation: Because of the partial insulation on the enamel wire, the coil is an electromagnet only for half its orientations. It is attracted or repelled by the magnet beneath it during half its rotation, but just as it gets to its equilibrium orientation, the current flow vanishes and it continues on for half a turn because of its rotational inertia. It continues to turn indefinitely.

285. Sophisticated DC Motors

Description: A DC motor that's attached to a variable-current power supply turns more rapidly as the current passing through it is increased. When the current passing through it is reversed, its direction of rotation reverses.

Purpose: To show that a DC motor's rotational speed increases as the current passing through it increases (assuming that its only load is friction) and that its direction of rotation reverses as the current through it reverses.

Supplies:

1 good quality DC motor
1 variable-current DC power supply
2 wires

Procedure: Use the two wires to connect the power supply to the motor. Show that as the current through the motor increases, so does its rotational speed. Show also that when you reverse the current passing through the motor, that its direction of rotation reverses.

Explanation: The rotational speed of the unloaded motor is limited by its ability to do work against sliding friction. The faster it turns, the more work it does each second and the more electric power it requires. Thus increasing the current passing through the motor and voltage drop of that current increases the power the motor receives and allows it to turn faster. Since reversing the current through the motor interchanges all the north and south poles of the motor's electromagnets, the torques in the motor reverse and it turns backwards.

286. A Simple Induction Motor

Description: An aluminum pizza platter or pie dish floats on water. When you move a strong magnet around in a circle above the platter, the platter begins to rotate with the magnet, even though the two aren't touching.

Purpose: To show how magnetic drag forces allow a magnet that's circling a conducting wheel to pull that wheel around with it.

Supplies:

1 aluminum pizza platter or pie dish
1 large, shallow container of water (large enough to float the aluminum dish in)
1 strong magnet

Procedure: Float the platter or dish in the water and stop it from turning. Now hold one pole of the magnet a few centimeters above the platter and begin to circle the outer edge of the platter with the magnet. The platter will experience angular acceleration and will begin to turn with the circling magnet.

Explanation: The moving magnet induces currents in the platter and makes that platter magnetic. The repulsive forces between the magnet and platter tend to push the platter out in front of the magnet. If you could continue this motion steadily enough, the platter would end up turning just a little more slowly than the magnet.

287. A Large Single-Phase Induction Motor

Description: A capacitor-start motor leaps into action when you turn it on and rotates steadily there after.

Purpose: To demonstrate the operation of a powerful induction motor.

Supplies:

1 large induction motor with a starting capacitor (1/2 hp or whatever you can find)

Procedure: Hold the induction motor in place (I use my foot) and plug it in. It will jump as its rotor begins to spin. Point out the raised ridge on its side. This ridge contains a capacitor that helps to create a magnetic pole in the stator that circles the rotor in a particular direction as the motor starts up. During its operation, the rotor turns almost as fast as the circling pole of the stator. Since the rate at which the stator's pole circles the rotor depends on the cycling of the power line, the motor's rotational speed is determined by the power line frequency. Many induction motors complete one full turn for every two cycles of the power line. These motors turn at almost 1800 rpm (almost 30 turns per second) in the United States or almost 1500 rpm in many other countries.

Explanation: The stator of the induction motor is built from electromagnets. The starting capacitor provides a delayed phase to some of the electromagnets during the starting process so that the magnetic poles of the stator circle the rotor in a particular direction. (Note for the experts: Once the rotor is turning properly, the delayed phase isn't needed any more. The poles of the stator are then driven directly from the single phase power and these poles oscillate back and forth rather than circling the rotor. However, these oscillating poles can be decomposed into pair of poles that circle with and against the direction in which the rotor is spinning. It turns out that the torque exerted on the rotor by the poles that are circling with the rotor are strongest and they keep the rotor turning steadily and powerfully forward.)

288. An Electric Fan

Description: The induction motor of an electric fan turns at 2 or 3 different speeds, as determined by the rotation rates of the poles on its stator.

Purpose: To show how varying the rotation speeds of the stator poles can change the rotation speed of an induction motor's rotor.

Supplies:

1 2- or 3-speed fan

Procedure: Show that the fan has two or three different speeds of rotation. These speeds are determined by how rapidly the poles of the stator circle the rotor.

Explanation: The faster the poles of the stator circle the rotor, the faster the rotor must turn to keep up with the circling poles.

289. A Shaded Pole Motor

Description: A copper disk that can turn on a bearing is held horizontally above the pole piece of an AC electromagnet. When the electromagnet is operating and another piece of copper shades half the pole piece from the copper disk, the disk begins to turn.

Purpose: To demonstrate another type of induction motor—a shaded pole motor.

Supplies:

1 copper disk, about 10 cm in diameter that turns about a central bearing
1 support for the copper disk and its bearing
1 AC electromagnet with a vertical pole piece that extends upward above the electromagnet
1 thick piece of highly conductive copper sheet (about 3 or 4 mm thick)

Procedure: Mount the copper disk horizontally above the pole piece of the AC electromagnet. The pole piece should end about 1 cm below one edge of the disk. Turn on the AC electromagnet and gradually slide the copper sheet on top of the pole piece until it covers half the pole piece. The edge of the strip should be aligned with the radius of the disk. The disk will begin turning so that its surface moves from above the uncovered portion of the pole piece to above the covered portion. If you shift the copper sheet to the other side of the pole piece, the disk will begin to turn the other way.

Explanation: The presence of the copper sheet above the pole piece delays the formation of a magnetic pole on the copper-shaded side of the pole piece. This delay occurs because the induced currents in the copper sheet temporarily shield the area above the sheet from the magnetic field of the pole piece. In effect, the pole moves from the unshaded portion of the pole piece to the shaded portion. The copper disk moves with this moving pole and it turns.

Follow-up: You can replace the disk and bearing with a copper ball that floats in water. The ball will begin to rotate when you cover half the pole piece with copper.

Section 12.5 Tape Recorders

290. Magnetic Domains

Description: An array of magnetic arrows (tiny compasses) forms aligned domains.

Purpose: To show that magnetic domains tend to form in any extended ferromagnetic system.

Supplies:

1 array of magnetic arrows (available from a scientific supply company)
1 bar magnet

Procedure: Set the array of magnetic arrows on the table and inspect its arrows. You'll find groups of nearby arrows that are aligned with one another, but overall they will have little or no average alignment. These local regions of alignment are analogous to the domains in a ferromagnetic solid.

Now bring one pole of the bar magnet near the edge of the array. The array will change so that virtually all of the arrows will be aligned. They will all point either toward or away from the pole of the bar magnet. You have magnetized the array—its domains have changed so that they have a net magnetic alignment.

Take the bar magnet away from the array and show that much of its magnetic alignment remains. The array is permanently magnetized.

Finally, wave the bar magnet across the array carefully and gradually move it farther and farther away until it has no more effect. The array will once more consist of small aligned domains that have no average overall alignment. You have demagnetized the array.

Explanation: If all the magnetic arrows were to point in the same direction, the array would be a large magnet and would have considerable magnetic potential energy. The array normally lowers its energy by breaking up into domains and allowing the magnetizations of these domains to cancel one another. But when you bring the strong external magnetic field near the array, you force it into alignment. Even when you take away the external magnet, the array remains aligned—it needs a disturbance to break up into domains once again. When you jiggle the magnet nearby, you create this disturbance and the array breaks up into domains.

291. A Magnet and Steel Nails

Description: Steel nails normally don't stick to one another. But when you touch the pole of a permanent magnet to one of the nails, the nail becomes a magnet. When this nail touches another nail, that nail becomes magnetic, and so on. When you remove the permanent magnet, the nails slowly lose most of their magnetizations.

Purpose: To show how the presence of a strong magnetic pole magnetizes steel or iron.

Supplies:

- 1 bar magnet
- 3 or more steel nails

Procedure: First show that the nails don't normally stick to one another. Then touch the north pole of the bar magnet to a nail. The nail will stick to the bar magnet because it will become magnetized. The presence of the nearby north pole rearranges the magnetic domains inside the steel so that their south poles all point toward the north pole of the permanent magnet. As a result, the other end of the nail becomes a north pole. Show that this nail can magnetize another nail it touches in a similar manner. Form a chain of nails dangling from the bar magnet.

Finally, remove the bar magnet from the first nail. The chain of nails will slowly fall apart as the domains in the nails gradually return to their original random orientations. A few domains won't return to normal, so the nails will remain slightly magnetized as a result of their exposure to the bar magnet.

Explanation: Iron and most steels contain magnetic domains. Until these materials are exposed to magnetic fields, the domains are randomly aligned and their magnetization cancel one another. However, when these materials are exposed to magnetic fields, the domains grow or shrink until the materials exhibit substantial overall magnetizations. These magnetizations only remain while the external magnetic fields persist. The domains in very pure iron rearrange easily when the external fields vanish, so that very pure iron completely loses its magnetization. But in steels, the impurities in the crystals prevent the domains from rearranging so easily. Steel is a little harder to magnetize when an external magnetic pole approaches it and it doesn't demagnetize completely when the external magnet is taken away.

292. Aluminum and Copper are Non-Magnetic

Description: While steel sticks to a bar magnet, aluminum and copper do not.

Purpose: To show that most metals are non-magnetic (they are not ferromagnetic).

Supplies:

- 1 strip of steel (not stainless steel!)
- 1 strip of copper
- 1 strip of aluminum
- 1 bar magnet

Procedure: Show that steel sticks to the bar magnet while copper and aluminum do not.

Explanation: The steel contains magnetic domains that can be aligned by the proximity of a strong magnetic pole. The copper and aluminum have no magnetic domain structure at all, so a nearby magnetic pole has no effect on their internal magnetic structures.

293. Domain Flipping in a Piece of Soft Iron

Description: An iron rod sits in a coil of wire that's attached to a sensitive audio amplifier. As a bar magnet is brought up to the iron, the domains inside the iron flip into alignment with the magnet. These flipping domains induce currents in the coil of wire and create a "shoop" sound from the amplifier's speakers.

Purpose: To show that the domains in iron flip when the iron is magnetized.

Supplies:

1 iron rod
1 coil of wire
1 preamplifier, amplifier, and speaker
1 bar magnet

Procedure: Connect the coil of wire to the preamplifier, amplifier, and speaker. Insert the iron rod inside the coil. Turn on the amplifiers and slowly bring one pole of the magnet up to the iron rod. You will hear a "shoop" sound emerge from the speaker. Each component of the "shoop" corresponds to a domain flipping in the iron rod. Since there are so many domains and they flip at random moments between the start to the finish, their overall sound is the "shoop" sound. If you reverse the bar magnet, you can repeat the experiment and hear the "shoop" again.

Explanation: Each time you magnetize the iron, the domains in the iron rod align with the bar magnet. Their rearrangement creates a changing magnetic field through the coil and induces a current in its wire.

294. Reversing the Magnetization of a "Permanent" Magnet

Description: A bar magnet is inserted in a magnetizer and its poles are permanently reversed. A second trip through the magnetizer flips its poles back to normal.

Purpose: To show that the poles of a "permanent" magnet can be reversed during the magnetization process.

Supplies:

2 bar magnets, with their ends clearly labeled north and south (or red and white)
1 horizontal swivel mount for one of the bar magnets
1 bar magnet magnetizer (available from a scientific supply company)

Procedure: Support one of the bar magnets on the swivel mount. Hold the other magnet in your hand and show that the opposite poles of the two magnets attract and the like poles repel. Now insert the magnet that you have in your hand into the magnetizer and magnetize it backwards! When you again hold it in your hand, its "north" pole will attract the north pole of the magnet in the swivel. Show that the poles of the hand-held magnet are completely reversed. Finally, reinsert the magnet into the magnetizer and magnetize it properly. Show that its poles are back to normal.

Explanation: A permanent magnet is a material that, once magnetized in a certain direction, remains magnetized in that direction. While the factory may have magnetized the bar magnet in a particular direction, you can reverse that direction if you have the right equipment (typically a coil of wire and a highly charged capacitor).

295. Sprinkling Iron Fillings on a Credit Card

Description: You sprinkle iron filings on the magnetic strip of a credit card. The filings align in patterns, indicating that there is a pattern to the magnetization of the permanent magnet particles in the magnetic strip.

Purpose: To show how the magnetization of a credit card strip contains information.

Supplies:

1 credit card (this test is non-destructive; you can clean off the credit card and it will still work)
1 shaker of iron filings (finely ground)

Procedure: Sprinkle iron filings on the magnetic strip of a credit card and gently tap the card to allow the loose filings to slip away. You'll see a pattern to the filings that shows that there is a pattern to the magnetization of the magnetic strip.

Explanation: The magnetic strip of a credit card is like a very coarse magnetic tape. The magnetic patterns on the credit card strip are so huge that you can see them with your eye, or at least with a magnifying glass.

296. A Simple Tape Player

Description: You construct of simple tape player by inserting an iron rod in a coil of wire that's attached to an amplifier and speaker. You then pull a long refrigerator magnet strip across the iron "playback head" and hear a humming sound from the speaker. The faster you pull the strip across the iron rod, the higher the pitch of the hum.

Purpose: To demonstrate how a tape recorder plays back a tape.

Supplies:

1 long magnetic strip (a long refrigerator magnet or a magnetic strip for a office organizational bulletin board)
1 iron rod
1 coil of wire
1 preamplifier, amplifier, and speaker

Procedure: Connect the coil of wire to the preamplifier, amplifier, and speaker. Insert the iron rod into the coil. Turn on the amplifiers and draw the long magnetic strip across the iron rod. A humming sound will emerge from the speaker. The faster you move the magnetic strip, the higher the pitch of the hum. Point out that the magnetic strip has many poles on it and that they reverse every few millimeters (you can show this with iron fillings if you like). As you pull the strip across the iron rod, the iron's magnetization reverses periodically and it induces fluctuating currents in the coil of wire. The amplifiers and speaker use this fluctuating current to produce the humming sound.

Explanation: Just as in a magnetic tape that has recorded sound on it, the magnetic strip has a fluctuating magnetization on its surface. As you draw it across the "playback head," the amplifiers and speaker produce a fluctuating air pressure that is the humming sound.

297. A Reconstructed Tape Recorder

Description: A piece of magnetic tape slides across the playback head of a tape recorder. The amplifier and speaker of the tape recorder reproduce the sound.

Purpose: To show how the parts of a tape recorder work.

Supplies:

1 cassette tape recorder (to be disassembled)
1 cassette tape
parts, time, and perseverance

Procedure: Extract the playback head of the tape recorder (or a tape player) and mount it and the preamplifier on a board that allows them to be inserted into the center of a cassette cartridge so that the head touches the tape. Position a variable speed motor so that it will pull the tape through the cassette tape cartridge at a steady, slow speed. Connect the playback head and preamplifier to an amplifier and speaker.

Now start the tape moving through the cartridge and bring the playback head into contact with the tape as the tape moves through the middle of the tape cartridge. The speaker will reproduce the sound recorded on the tape. Getting all of this working correctly takes a little time and energy, but it's pretty satisfying when it works. It really helps demystify tape recorders.

Explanation: The moving tape induces currents in the playback head and these currents are amplified and delivered to the speaker to reproduce the sound.

Follow-up: Tape player kits exist and can be modified to make it easy to see how the tape recorder works.

Section 13.1 Audio Amplifiers

You may wish to repeat the Ohm's law demonstration from Section 12.2 to show how a resistor impedes the flow of electric current and the capacitor demonstration from Section 1.4 to show how a capacitor stores separated electric charge.

298. The Current from a Microphone

Description: The current from a microphone is displayed on an oscilloscope while you make various sounds.

Purpose: To show how the air pressure fluctuations at the microphone are represented by current fluctuations in the circuit to which the microphone is attached.

Supplies:

1 microphone (with power supply, if necessary)
1 oscilloscope
wires

Procedure: Connect the microphone to the input of the oscilloscope and turn both on. Set the oscilloscope trigger so that a clear trace appears on the screen when you make a single-pitch sound (a whistle, for example). Point out that the oscilloscope displays the current in the circuit on the vertical axis (with zero appearing at the center of the screen, so that excursions below the center of the screen represent reversals of the current) and that time is the horizontal axis. Note that broad fluctuations in the trace represent low frequency sounds and low frequency alternating currents. Note also that narrow (rapid) fluctuations in the trace represent high frequency sounds and high frequency alternating currents. Show that larger volumes produce larger amplitude alternating currents.

Explanation: The microphone produces currents that are proportional to changes in air pressure. As sound reaches the microphone, the rising and falling air pressures are represented by the microphone as forward and backward currents through the circuit connected to the microphone.

299. A Speaker

Description: A variable-amplitude 60 Hz current flows into a large speaker that rest horizontally on the table. Several marbles in the cone of that speaker begin to leap up and down.

Purpose: To show how a speaker uses an alternating current to produce sound.

Supplies:

1 large (woofer) speaker, without a cabinet
1 low-voltage transformer (12 VAC, 5 A or so)
1 variable-voltage autotransformer (a Variac)
3 or more marbles
wires

Procedure: Connect the primary of the low-voltage transformer to the output of the variable-voltage autotransformer. Connect the secondary of the low-voltage transformer to the speaker. Plug in the autotransformer and slowly turn up its voltage. The speaker should begin to hum more and more loudly. Put the marbles in the speaker and allow them to bounce up and down. Discuss the motion of the speaker cone as the alternating current in its coil flows back and forth. Discuss how this motion produces compressions and rarefactions of the air; thus producing sound.

Explanation: The AC current flowing through the secondary coil of the low-voltage transformer and the coil of the speaker magnetizes the coil of the speaker and causes it to be alternately attracted and repelled by the speaker's permanent magnet. The speaker's paper cone is connected to its coil and both move toward and away from the speaker's permanent magnet. This motion causes the marbles to jump about.

300. A MOSFET

Description: You show that a tiny amount of electric charge (delivered with your finger) on the gate of a MOSFET can control the flow of a large amount of electric current between its source and drain. The MOSFET controls a light bulb.

Purpose: To show how charge affects the conductivity of a MOSFET and allows it to control the current flowing in a circuit.

Supplies:

1 n-channel enhancement-mode MOSFET with a suitable current and voltage rating (I have usually used Motorola MTP1N50 MOSFETs, which are rated at 1 A (hence the "1") and 500 V (hence the "50"). However, if you want to use a high current bulb, an MTP10N40E would be appropriate—10 A at 400 V. In any case, be prepared to replace the MOSFET once in a while when you damage it with static electricity. It just happens.
1 12 V light bulb (less than 1 A if you use a 1 A MOSFET, but can be higher current if you use a more powerful MOSFET)
1 light bulb holder
1 12 V battery
wires

Procedure: Before handling the MOSFET, always touch an earth ground to remove any charge you may have accumulated! Insert the light bulb in the holder. Connect the positive terminal of the battery to one terminal of the light bulb holder. Connect the other terminal of the light bulb holder to the drain of the MOSFET. Connect the source of the MOSFET to the negative terminal of the battery. Now you're ready to begin switching the light on and off.

To turn the light on, touch one hand to the positive terminal of the battery and then touch your other hand to the gate of the MOSFET (in that order! If you touch the MOSFET first, you may have excess charge on you and may destroy the MOSFET!). Positive charge will flow onto the gate of the MOSFET and it will conduct current. The light bulb will turn on.

To turn the light off, touch one hand to the negative terminal of the battery and then touch your other hand to the gate of the MOSFET (again battery first!). Positive charge will flow off the gate of the MOSFET and it will stop conducting current. The light bulb will turn off.

Since the charge (or lack of charge) will remain on the gate while you are not touching it, the light will remain on or off indefinitely while you leave the gate alone.

Explanation: When positive charge is present on the gate of the MOSFET, electrons are attracted into the normally p-type semiconductor of the channel and the channel becomes effectively n-type semiconductor. Because both the source and drain are already n-type semiconductor, the p-n junction between the source and channel and between the channel and drain vanish and the entire MOSFET acts like a piece of n-type semiconductor. Current can flow through it from the source to the drain. However, when the positive charge is removed from the gate, the channel becomes p-type again, the p-n junctions reappear and current can't flow through the MOSFET anymore.

301. An Audio Amplifier

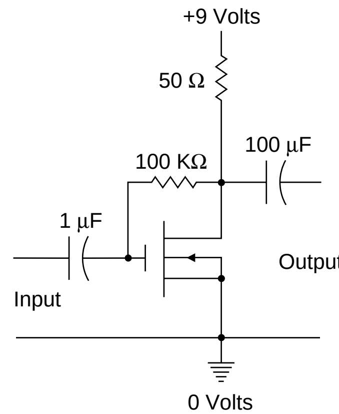
Description: You build a simple audio amplifier and use it to amplifier sound from a small tape or CD player so that it can be reproduced by a reasonably large speaker. The amplifier is so sensitive that you can act as part of the wiring connecting the tape or CD player to the input portion of the amplifier.

Purpose: To show how an audio amplifier works.

Supplies:

- 1 n-channel enhancement-mode MOSFET with a suitable current and voltage rating (I have usually used Motorola MTP1N50 MOSFETs, which are rated at 1 A (hence the "1") and 500 V (hence the "50"). However, an MOSFET that's capable of handling more current would also be fine. Be prepared to replace the MOSFET if you burn it out.
- 1 1 µF capacitor (20 V or higher)
- 1 100 µF capacitor (20 V or higher)
- 1 100 KΩ resistor
- 1 50 Ω resistor (2 Watt)
- 1 9 V battery or an equivalent power supply
- 1 speaker (8 Ω or 4 Ω)
- 1 small tape or CD player
- wires

Procedure: Construct the amplifier shown in the figure below (also Fig. 13.1.9 in the book). I do it on a giant, homemade bread board with the components already mounted on cards with pins that plug into the breadboard. Each component is labeled with its symbol so that when the amplifier is complete, it looks like the figure below.



Be careful as you assemble the amplifier not to burn out the MOSFET. It should be inserted last and you should touch earth ground (and ground the rest of the amplifier, at least briefly) before you touch the MOSFET.

When the amplifier is complete, connect the speaker to its output wires (on the right) and the tape player or CD player to the input wires (on the left). If you now turn on the tape player or CD player, sound will come out of the speaker. Discuss how alternating currents in the input circuit cause charge to flow on and off the gate of the MOSFET. Discuss how charge on the gate of the MOSFET controls the current flowing between its source and drain. Discuss how the MOSFET diverts current that flows down from the battery's positive terminal through the 50 Ω resistor and keeps that current from flowing to the speaker. By alternately diverting and not-diverting this current from the 50 Ω resistor, the MOSFET produces an fluctuating current in its output circuit and through the speaker. The speaker produces sound.

For a display of how sensitive the MOSFET is to charge, disconnect one of the input wires from the tape or CD player and use your hands to remake the connection. Enough current will flow through you to allow the amplifier to play the music.

Explanation: Current in the input circuit controls the charge on the MOSFET's gate and the MOSFET controls the current flowing through the speaker.

Section 13.2 Computers

302. Series and Parallel Circuits

Description: You create a circuit with a battery and bulb, in which two switches are in series. Both switches must be closed simultaneously before current will flow and the lamp will light. You then arrange the switches in parallel and either switch can close the circuit.

Purpose: To show the differences between series and parallel arrangements for switches.

Supplies:

2 switches (knife switches, if possible)
1 12 V battery
1 12 V bulb
1 bulb holder
wires

Procedure: Connect the battery and bulb in a complete circuit and show that the bulb lights up. Now insert one switch into the circuit and show that it must be closed in order for the bulb to light. Add a second switch in series with the first switch and show that both switches must be closed for the bulb to light.

Now disconnect the second switch and reinsert it in parallel with the first switch. Show that closing either switch causes the bulb to light. Discuss how in a series arrangement, the same current must flow through both devices to reach its destination. Discuss how in a parallel arrangement, current can flow through either device to reach its destination.

Explanation: In general, two devices in series experience the same current but their overall voltage drop is the sum of their individual voltage drops. Two devices in parallel experience the same voltage drop, but their overall current is the sum of their individual currents.

303. A Simple CMOS Inverter

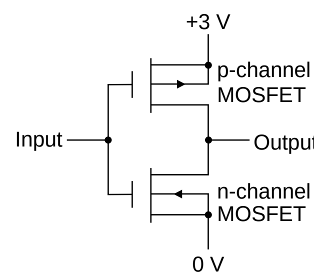
Description: You build a simple CMOS inverter. You then show that when you deliver positive charge to its input, it delivers negative charge to its output and vice versa.

Purpose: To show how an inverter works.

Supplies:

1 n-channel enhancement-mode MOSFET with a suitable current and voltage rating (I have usually used Motorola MTP1N50 MOSFETs, which are rated at 1 A (hence the "1") and 500 V (hence the "50"). Be prepared to replace the MOSFET if you burn it out.
1 p-channel enhancement-mode MOSFET with a suitable current and voltage rating (I have usually used Motorola MTP2P50 MOSFETs, which are rated at 2 A (hence the "2") and 500 V (hence the "50"). Be prepared to replace the MOSFET if you burn it out.
1 9 V battery
1 voltmeter or equivalent
wire

Procedure: Connect the two MOSFETs according to the figure below (also Fig. 13.2.6 of the book), but use the 9 V battery as the supply, rather than the 3 V shown (the power MOSFETs need 9 V rather than 3 V). The upper MOSFET is the p-channel MOSFET and its source is connected to the positive terminal of the 9 V battery. Be careful to ground yourself and the components before working with them. Attach the voltmeter to the output to monitor its voltage (and charge).



To deliver positive charge to the input of this inverter, touch one hand to the positive terminal of the battery and then touch your other hand to the input wire. The output will go to 0 V (negative charge).

To deliver negative charge to the input of this inverter, touch one hand to the negative terminal of the battery and then touch your other hand to the input wire. The output will go to 9 V (positive charge).

Explanation: This CMOS inverter is using the charge delivered to its input to control two MOSFETs. The MOSFETs are arranged so that positive charges on their gates turns on the n-channel MOSFET and it delivers negative charge to the output. Negative charges on their gates turns on the p-channel MOSFET and it delivers positive charge to the output.

304. A Simple CMOS NAND Gate

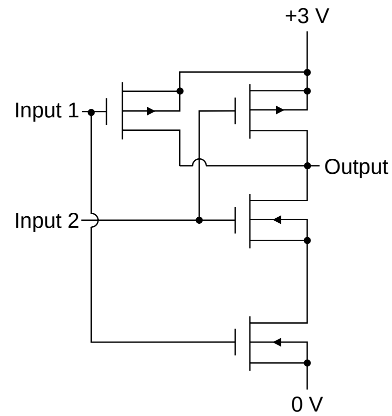
Description: You build a simple CMOS NAND gate. You then show that when you deliver positive charge to both of its inputs, it delivers negative charge to its output. If either input has negative charge on it, it delivers positive charge to its output.

Purpose: To show how a computer gate works.

Supplies:

2 n-channel enhancement-mode MOSFETs with a suitable current and voltage rating (I have usually used Motorola MTP1N50 MOSFETs, which are rated at 1 A (hence the "1") and 500 V (hence the "50"). Be prepared to replace the MOSFET if you burn it out.
2 p-channel enhancement-mode MOSFETs with a suitable current and voltage rating (I have usually used Motorola MTP2P50 MOSFETs, which are rated at 2 A (hence the "2") and 500 V (hence the "50"). Be prepared to replace the MOSFET if you burn it out.
1 9 V battery
1 voltmeter or equivalent
wire

Procedure: Connect the four MOSFETs according to the figure below (also Fig. 13.2.8 of the book), but use the 9 V battery as the supply, rather than the 3 V shown (the power MOSFETs need 9 V rather than 3 V). The upper MOSFETs are the p-channel MOSFETs and their sources are connected to the positive terminal of the 9 V battery. Be careful to ground yourself and the components before working with them. Attach the voltmeter to the output to monitor its voltage (and charge).



To deliver positive charge to an input of this gate, touch one hand to the positive terminal of the battery and then touch your other hand to the input wire. To deliver negative charge to an input of this gate, touch one hand to the negative terminal of the battery and then touch your other hand to the input wire. Don't reverse the touch order or you will zap the MOSFETs!

When both inputs are positively charged, the output will be negative (0 V). When either input is negatively charged, the output will be positive (9 V).

Explanation: This CMOS NAND gate is using the charge delivered to its inputs to control four MOSFETs. The two p-channel MOSFETs are arranged in parallel and deliver positive charge to the output when either input is negatively charged. The two n-channel MOSFETs are arranged in series and deliver negative charge to the output when both inputs are positively charged. This arrangement gives the output a NAND relationship to the inputs.

Section 14.1 Radio

To remind the students about resonant systems and resonant energy transfer, you might want to revisit the demonstration of resonant energy transfer to a pendulum in Section 9.2. To remind students about transverse waves, you might want to repeat the demonstration of transverse waves on a Slinky in Section 10.1.

305. A Tank Circuit

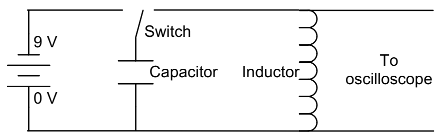
Description: You charge a capacitor and then connect it to an inductor to form a tank circuit. As shown by an oscilloscope, the charge sloshes back and forth through the tank circuit in a natural resonance.

Purpose: To show that a tank circuit has a natural electronic resonance.

Supplies:

1 large non-electrolytic capacitor (a low-loss capacitor)
1 large inductor (a low-loss inductor)
1 battery
1 oscilloscope (preferably a storage oscilloscope so that you can view the trace for a long time)
1 single-pole double-throw (SPDT) switch
wires

Procedure: Connect the components as shown in the figure below. When the switch is in one position, the battery will charge the capacitor. When the switch is in the other position, the capacitor will be connected to the inductor to form a tank circuit. Keep the electric resistance of the components low to allow the charge to oscillate back and forth through the tank circuit for a long time.



To do the demonstration, first charge the capacitor and then flip the switch to form the tank circuit. The charge will oscillate in the tank circuit and the oscilloscope will display the changing voltages across the capacitor and inductor as they evolve in time. Remember to identify the two axes of the oscilloscope to the students, who will find the device unfamiliar.

Explanation: Charging the capacitor gives it electrostatic potential energy. This energy will become magnetic energy in the inductor when the capacitor sends its separated charges through the inductor. The inductor will use this magnetic energy to recharge the capacitor upside down. The process then repeats. The oscilloscope displays a history of this alternating current flow.

306. A Radio Transmitter and a Nearby Antenna

Description: A small radio transmitter emits radio waves from its short vertical antenna. A nearby antenna receives those radio waves and uses their power to light a light bulb.

Purpose: To show that radio waves travel through empty space and carry power with them.

Supplies:

- 1 simple radio transmitter with a short vertical antenna (because of the short antenna, the transmitter must operate in the 100+ MHz range. Be sure not to violate any FCC regulations.
- 1 simple radio antenna that's tuned to receive the transmission (it's length should be twice that of the transmitting antenna). The antenna should consist of two halves and a light bulb should connect its lower half to its upper half.

Procedure: Turn on the radio transmitter so that charge begins to oscillate up and down its antenna. Hold the receiving antenna vertically, a meter or so away. The light bulb will glow. The moving charge on the transmitting antenna is causing charge to move on the receiving antenna. This moving charge deposits energy in the filament of the bulb and the bulb glows.

Now show that the effect diminishes as you move the receiving antenna away from the transmitting antenna—the electromagnetic fields from the transmitting antenna spread out and become weaker with distance.

Finally, hold the receiving antenna horizontally and show that the bulb doesn't light at all. That's because the electromagnetic waves from the vertically oriented transmitting antenna are vertically polarized and a horizontally oriented receiving antenna can only receive horizontally polarized waves. A vertically polarized radio wave will push charge up and down on an antenna, not sideways. Since the charges on the horizontal receiving antenna can't move up and down, no current flows in the receiving antenna.

Explanation: The electromagnetic fields from the transmitting antenna are causing currents to flow in the receiving antenna. These currents heat the filament of the bulb red hot.

307. Transmitting Radio Waves

Description: You turn on a radio transmitter and the static on an FM receiver suddenly disappears—the receiver is silent. When you then begin to FM modulate the transmitted wave, the receiver begins to emit sound.

Purpose: To show how radio waves are transmitted and received and to show how modulating those waves allows them to carry sound information.

Supplies:

- 1 radio transmitter that works in the normal FM band and that can be FM modulated by a small input signal
- 1 transmitting antenna
- 1 tape or CD player to FM modulate the radio transmitter
- 1 FM radio receiver without any mute (if it receives no transmission, you should hear static)

Procedure: Attach the transmitting antenna to the transmitter and turn on the transmitter. Tune the receiver until you find the silent transmission. Show that when you turn off the transmitter, the receiver begins to look for a transmission and you hear the hiss of "static." Now turn on the transmitter and attach the tape player or CD player to it (or even a microphone).

Turn on the tape player or CD player. The receiver should begin to reproduce the sound.

Explanation: The unmodulated radio wave represents a silent period in an FM transmission. But when you begin to shift the frequency of the radio wave back and forth, the FM receiver recognizes these shifts and uses them to shift the air pressure at its speaker back and forth. You then hear sound.

Follow-up: Try a similar experiment with AM modulation. However, the wavelengths involved in normal AM transmission are very long and the antennas become more complicated. Still, you can work with antennas that are too short if you don't care about perfection. If you AM modulate a radio transmission in the AM band range, an AM receiver will pick it up and produce sound.

308. The Wavelength of a Radio Wave (Actually a Microwave)

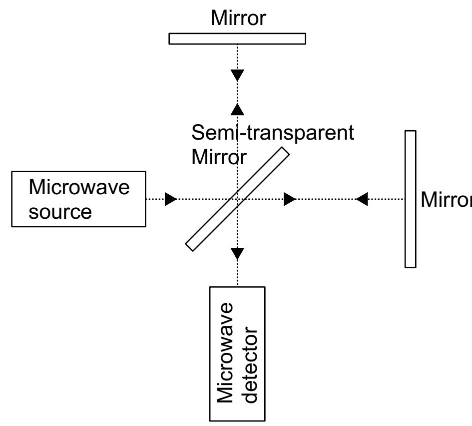
Description: You move one arm of a Michelson Interferometer and determine the wavelength of the microwave emerging from a microwave source.

Purpose: To show that electromagnetic waves really do have wavelengths and that these wavelengths can be measured.

Supplies:

- 1 microwave source
- 1 microwave detector
- 2 microwave mirrors (actually just aluminum plates with bases so that they stand on a table)
- 1 semi-transparent microwave mirror (50% transmission and 50% reflection)

Procedure: Assemble the components to form a Michelson interferometer (see the figure below). The microwave source and the microwave detectors should be 90° from each other around the central semi-transparent mirror.



In operation, half of the wave emerging from the microwave source will bounce off one mirror and half will bounce off the other mirror. When the two partial waves recombine on their way to the detector, they can interfere constructively or destructively, depending on the relative lengths of their trips on the different arms of the interferometer.

If you slowly change the length of one of the legs, the strength of the microwave at the detector will vary up and down. Moving a mirror half a wavelength of the microwave will cause one complete cycle of variation (e.g. from strong to weak and back to strong). If you measure the distance you must move the mirror to complete one full cycle, and double that distance, you have the wavelength of the microwave.

Explanation: Adding half a wavelength to one arm of the interferometer causes the partial-wave in that arm to travel one wavelength further (it covers the added distance twice). Adding a full wavelength to the travel of a partial-wave leaves that partial-wave unchanged.

309. The Polarization of a Radio Wave (Actually a Microwave)

Description: You insert a collection of isolated, parallel metal rods into the microwave traveling from a source to a detector. When the rods are oriented in one direction, the microwave is unaffected, but when the rods are turned 90°, the microwave no longer reaches the detector.

Purpose: To show that radio waves and microwaves are typically polarized.

Supplies:

- 1 microwave source
- 1 microwave detector

1 microwave polarizer (a collection of thin metal rods mounted in an insulating holder so that they are all parallel to one another and about 1 cm apart)

Procedure: Place the microwave source and the microwave detector about 50 cm apart and point them toward one another. Turn them on and detect the strong microwave traveling from the source to the detector. Now insert the polarizer between the two. Observe that when the rods are oriented in one way (either vertically or horizontally), they permit the microwave to travel unimpeded. But when the rods are rotated 90°, they prevent the microwave from reaching the detector. They reflect it. The microwave is polarized in the direction of the rods in this second orientation.

Explanation: When the rods are oriented along the microwave's polarization, charge can move along the rods in response to the microwave's electric field. This movement of charge reflects the microwave.

Section 14.2 Television

310. Fluorescence

Description: Various materials are exposed to ultraviolet light and glow different colors.

Purpose: To demonstrate fluorescence.

Supplies:

1 ultraviolet lamp
fluorescent dyes and materials of various colors

Procedure: Turn on the ultraviolet lamp and show that you can't see its light. Point out that normal materials remain dark when exposed to only ultraviolet light. Now put the various fluorescent materials in the ultraviolet light and observe that they begin to emit visible light of various colors. Discuss the fact that this light is new light, radiated by the dyes and materials using energy they obtained from the ultraviolet light.

Explanation: A fluorescent material absorbs a photon of ultraviolet light and emits a new photon of light. While the new photon can have all of the energy of the original photon, so that it's just a new version of the original photon, the fluorescence that we observe most often involves the emission of a lower-energy photon—usually a visible photon. The missing energy usually becomes thermal energy.

311. Fluorescence Caused by Electron Impact

Description: A beam of electrons in a simple cathode ray tube causes the phosphor coating on the inside of the tube to glow (probably green).

Purpose: To show that energy from a beam of electrons can cause fluorescence.

Supplies:

1 simple cathode ray tube and its power supply

Procedure: Turn on the cathode ray tube and show that the impact of electrons on its phosphor screen causes that screen to emit light. The electrons are providing energy to the phosphors and they turn that energy into visible light.

Explanation: Phosphors can produce light whenever they are shifted to electronically excited states. Whether that excitation is the result of exposure to high energy light photons or the result of collisions with particles, the phosphors produce light.

312. Deflecting a Beam of Electrons with Electric Fields

Description: An electrostatic field created by a static generator deflects a beam of electrons in a cathode ray tube.

Purpose: To show that a beam of electrons accelerates in response to electric fields.

Supplies:

1 simple cathode ray tube and its power supply
2 metal plates with insulating supports
2 wires
1 Wimshurst static generator

Procedure: Touch the two contacts of the Wimshurst generator together to be sure that it doesn't have any stored charge. Use the wires to connect its two contacts to the two plates, being sure that the wires aren't near anything conductive or near one another. Position the plates at the sides of the cathode ray tube. Turn on the cathode ray tube. Separate the two contacts of the Wimshurst generator and turn its crank to generate static electricity. As charge builds up on the plates, the beam of electrons in the cathode ray tube will steer toward the positively charged plate.

Explanation: The beam of negatively charged electrons is attracted toward the positively charged plate and repelled by the negatively charged plate. The electrons accelerate toward the positive plate and the beam is deflected.

313. Deflecting a Beam of Electrons with Magnetic Fields

Description: A magnetic field created by a hand-held magnet deflects a beam of electrons in a cathode ray tube.

Purpose: To show that a beam of moving electrons accelerates in the presence of magnetic fields.

Supplies:

1 simple cathode ray tube and its power supply
1 strong bar magnet

Procedure: Turn on the cathode ray tube and then hold the bar magnet near its face. The spot formed when the electrons hit the phosphors will move, indicating that the magnetic field has deflected the electron beam.

Explanation: Moving electrons experience a transverse force when they move through a magnetic field. While this force is at right angles to their velocities and does no work on the electrons, it does alter their trajectories.

314. Deflecting a Beam of Electrons with a Magnetic Field - in a Black and White Television Set

Description: You hold a strong magnet up to a black and white television set and the picture distorts.

Purpose: To show that the television set is using a beam of electrons to form its image and to show that this beam of electrons can be steered by a magnetic field.

Supplies:

1 black and white television set (or an old color television set, if you don't mind spoiling it or are willing and able to demagnetize its shadow mask after the demonstration)
1 strong bar magnet

Procedure: Turn on the television and obtain a clear picture. Now bring the bar magnet up to the surface of the screen and show that the image distorts. If you're using a color television, the colors will also shift because the electrons no longer travel in their usual paths through the shadow mask. The effect will vanish when you remove the bar magnet from a black and white set, but the image may remain distorted or color-shifted on a color set. To "repair" a color television set, you need to demagnetize its shadow mask with a large AC demagnetizing coil.

Explanation: Moving electrons inside the television's picture tube are deflected by their passage through the extra magnetic field and they hit the screen at unintended positions.

315. Mixing the Primary Colors of Light

Description: By mixing various amounts of red, green, and blue light, you can make people perceive any possible color.

Purpose: To show how the primary colors of light can be mixed (as they are in a television) to make us see any possible color.

Supplies:

3 light sources of variable brightness
1 red filter
1 blue filter
1 green filter

Procedure: Place the three filters over the three light sources and partially overlap their beams on a white screen. Show that by adjusting their relative intensities, you can form various colors in their overlapping regions. When red and green are mixed evenly, you see yellow. When green and blue are mixed evenly, you see cyan. When red and blue are mixed evenly, you see magenta. And when all three are mixed evenly, you see white.

Explanation: Our eyes are really only sensitive to three types of light: red, green, and blue. While wavelengths of naturally occurring light that fall in between the wavelengths of pure red, pure green, and pure blue light cause us to see intermediate colors, we can be tricked into seeing those colors by the proper mixture of these primary colors of light.

Section 14.3 Microwave Ovens

316. Heating a Fluid of Molecular Dipoles with a Changing Field

Description: An array of magnetic arrows (tiny compasses) jitters back and forth as you move a magnet nearby.

Purpose: To show that you can add energy to a fluid of dipoles by causing those dipoles to turn back and forth with a changing electric or magnetic field.

Supplies:

1 array of magnetic arrows (available from a scientific supply company)
1 bar magnet

Procedure: Place the array of magnetic arrows on the table and allow it to settle. Point out that this array represents a fluid that's at low temperature. Each arrow is a molecule in that fluid. To "heat up" the array, wave the bar magnet back and forth near its surface. The arrows will twist back and forth. As they do, they will interact with one another and some of them will start spinning and jittering wildly, even when you take the bar magnet away. The array now represents a fluid that's at a higher temperature.

Explanation: In a real fluid containing molecules that have dipoles (normally electric dipoles), a changing field will cause those molecules to turn back and forth and rub against one another. This rubbing causes them to become hotter and raises the temperature of the fluid.

317. Resonant Cavities - For Sound

Description: You hold a vibrating tuning fork in front of an acoustic cavity that's resonant at the same frequency as the tuning fork. The air in the cavity begins to vibrate loudly.

Purpose: To demonstrate the existence of resonant cavities for sound waves. (This is as an analogy to resonant cavities for electromagnetic waves.)

Supplies:

1 resonant acoustic cavity (available from a scientific supply company)
1 tuning fork (resonant at the same frequency as the cavity)
1 tuning fork mallet

Procedure: Strike the tuning fork and note that it doesn't emit much sound—it doesn't compress or rarefy the air very effectively. Now hold the vibrating tuning fork in front of the resonant cavity so that it can begin to transfer its energy to the air in the cavity. The cavity will emit a much louder tone.

Explanation: The tuning fork's vibrational energy moves to the air in the acoustic cavity by resonant energy transfer. In a microwave oven's magnetron, resonant energy transfer continuously adds energy to the electromagnetic waves inside the magnetron's cavities.

318. Boiling Water in an Ice Cup

Description: A small amount of water is poured into a depression in a large ice cube and the ice cube is placed in a microwave oven. After a few moments, the water begins to boil, even though the ice is still largely intact.

Purpose: To show that water is a much more efficient absorber of microwaves than is ice.

Supplies:

1 large plastic container - a cube about 20 cm on a side
1 small plastic container - a bowl about 8 cm in diameter
1 heavy weight
water

Procedure: Boil some water and allow it to cool to room temperature (boiling eliminates dissolved gases that would otherwise form white bubbles in the ice cube). Put the water into the large container, filling it about ¾ of the way and place the water in the freezer. You may need to insulate it so that it freezes slowly and doesn't crack during the freezing process.

When frozen, remove the container from the freezer and allow it to warm until it reaches its melting temperature. Place the small container on top of the ice, in the center of the container, and place the weight inside the container. Add about 2 cm of ice water to the large container. The weight in the small container should keep that container pressed against the ice and should keep the ice from floating up in the large container.

Return the container to the freezer until the whole ice cube is frozen. Remove the ice cube from the large container and remove the small container from the ice cube. Place the ice cube on a ceramic plate and return it and the plate to the freezer so that they're cold.

When you're ready to do the experiment, transfer the plate and the ice cube to the microwave oven, pour hot water into the depression in the ice cube and turn on the microwave oven. The water will heat much faster than the ice will melt and, if you're fortunate, the water will begin to boil before the ice cube cracks or melts. Even if something goes wrong, it will be clear that the water absorbs far more microwave power than does the ice.

Explanation: The water molecules in the ice are held rigidly in place and can't rotate in response to the microwave electric fields. The water molecules in the liquid water respond easily and absorb most of the microwave power. The water thus heats up while the ice does not. Putting the ice on the cold plate allows its bottom surface to remain solid, since contact with the bottom of the oven would normally melt the ice there.

Section 15.1 Sunlight

319. Sunspots Aren't Really Dark

Description: The filament of an uncoated light bulb appears dark against the bright background of a light box or an overhead projector's light source. But when the light box or overhead projector are turned off, the filament is glowing reasonably brightly—just not as brightly as the background was.

Purpose: To show that while sunspots are relatively cool spots on the sun's surface, they are still very hot and are still radiating lots of thermal energy.

Supplies:

1 clear light bulb
1 variable-voltage transformer (an autotransformer such as a Variac)
1 light box or overhead projector

Procedure: Place the clear light bulb in front of the light box or on the overhead projector. Its filament will appear dark against the bright background. Now connect the bulb to the variable-voltage transformer and begin to turn up the current through the bulb. Eventually, the filament will appear about as bright as the background. Reduce the current so that the bulb appears noticeably darker than the background. Finally, turn off the light box or projector and observe that the filament is actually still glowing brightly. It just wasn't as bright as the background.

Explanation: Sunspots are relatively cool regions on the sun's surface. They appear dark only because they aren't as bright as the surrounding sun surface, but they are still extremely bright sources of light.

320. The Blue Sky and the Red Sunset

Description: You shine light from a slide projector through a tank of clear water. A bright, white circle appears on the screen beyond. But after you add a chemical to the water, the circle gradually reddens, like the setting sun. The colors of light scattered by the water also change gradually from blue, like the sky, to various shades of purple, like those visible at sunset.

Purpose: To show why the sky is blue and why sunsets are red.

Supplies:

1 aquarium tank
1 slide projector
1 projection screen
1 cardboard "slide" with a circular hole
water at room temperature
sodium thiosulfate ("hypo")
sulfuric acid
1 stirring stick

Procedure: Dissolve 15 ml (1 tablespoon) of sodium thiosulfate (a white powder) into 16 liters of water in the aquarium. Stir to dissolve the powder. Insert the cardboard circle slide into the slide projector and direct the projector's beam of light through the long direction of the aquarium and onto the screen. You should see a bright, white disk and the water should look essentially clear. Now add 50 ml of sulfuric acid to the aquarium and stir to mix. Allow the water to settle for a few seconds and everything should look as it was.

But about 2 minutes later, the water will begin to have a blue appearance—tiny transparent particles will be forming in it that will Rayleigh scatter blue light. The disk on the screen will begin to look yellowish. By about 3½ minutes, the disk will look decidedly yellow and by about 4½ minutes, it will be full red. Throughout this period, the colors of light scattering from the aquarium will progress from blue to various shades of purple and pink, just as at sunset.

The recipe scales, so that if your aquarium needs more or less water, just scale the sodium thiosulfate and sulfuric acid accordingly. To make the reaction proceed faster, increase the concentrations of the two chemicals. If you double both of them, everything will happen roughly 4 times as fast. Be sure to dispose of the acidic solution properly when you're done.

Explanation: The chemical reaction that occurs in the water forms tiny clear particles that gradually grow in size. As they do, they become more and more effective at Rayleigh scattering light. While the particles are very small, blue light is scattered more effectively than red light, so the red light makes it through the aquarium to the screen and the blue light is scattered about the room.

321. Refraction

Description: A beam of light passes through glass or plastic surfaces and bends as is does.

Purpose: To demonstrate that refraction occurs when light changes speeds.

Supplies:

1 source of light rays
1 glass or plastic prism

Procedure: Show that a beam of light bends when it encounters a glass or plastic surface at anything but normal incidence. Show that light bends toward the normal as it enters glass or plastic, and bends away from the normal as it leaves.

Explanation: Light slows down as it enters glass, plastic, or water, and speeds up as it leaves. These changes in speed affect the propagation of light at the interfaces between materials and cause that light to bend.

322. Reflection

Description: A beam of light partially reflects from the surfaces of glass or plastic.

Purpose: To demonstrate that partial reflection occurs when light changes speeds.

Supplies:

1 source of light rays
1 glass or plastic sheet or rectangle

Procedure: Show that a beam of light partially reflects from each surface between air and glass or plastic.

Explanation: Light slows down as it enters glass, plastic, or water, and speeds up as it leaves. These changes in speed (or more generally, impedance mismatches) cause partial reflections of the light waves. For typical optical materials, the reflections are about 4% from each surface.

323. Dispersion

Description: A beam of light bends as it passes through a glass or plastic prism, but the different colors in the white light bend differently and a rainbow forms on the screen where the beam finally hits.

Purpose: To show that lights of different colors travel at different speeds in materials (dispersion) and thus experience unequal refraction.

Supplies:

1 source of white light rays
1 glass or plastic prism—60° angles, if possible
1 projection screen or another white surface

Procedure: Direct the beam of light through the prism at a shallow angle so that the light bends severely on both entry and exit from the prism. Have the beam then impinge on the projection screen. The violet portions of the spectrum will bend more than the red portions, so the light will appear as a rainbow on the screen.

Explanation: The charges in most materials respond more easily to high frequency, short wavelength light (violets) than they do to low frequency, low wavelength light (reds). As a result, violet light slows down more in materials than does red light. Violet light thus experiences more refraction than red light and the colors travel different paths to the screen.

324. Polarizing Glasses

Description: You show that glare, the sunlight reflected at shallow angles by horizontal surfaces, is mostly horizontally polarized. Polarizing sunglasses block this glare rather effectively.

Purpose: To show why polarizing sunglasses are helpful at blocking sunlight that reflects upward from horizontal surfaces.

Supplies:

1 light source (a slide projector)
1 glossy non-metallic horizontal surface, such a table with a layer of clear glossy varnish
1 large polarizing sheet
1 pair of polarizing sunglasses

Procedure: Direct the light source so that it reflects at a shallow angle from the glossy horizontal surface. Place the polarizing sheet in the reflected light and show that most of the light is blocked when the polarizing sheet is turned to absorb horizontally polarized light. Show that the sunglasses are also built to absorb horizontally polarized light and thus to block glare of this type.

Explanation: Light partially reflects from transparent materials, but the fraction of light that reflects depends on the light's polarization. If the light is polarized across the surface (e.g., horizontally polarized light hitting a horizontal surface), the reflection is stronger than if the light were polarized into the surface (e.g., vertically polarized light hitting a horizontal surface). Polarizing sunglasses recognize this preferential reflection of horizontally polarized light from horizontal surfaces. By blocking all horizontally polarized light, they eliminate most glare.

325. The Polarization of the Blue Sky

Description: While the Blue Sky and Red Sunset demonstration is proceeding (see above), you hold a polarizing sheet in front of the aquarium tank and observe that the blue light emerging from the water is mostly vertically polarized.

Purpose: To show that blue light from the sky is somewhat polarized.

Supplies:

- 1 aquarium tank
- 1 slide projector
- 1 projection screen
- 1 cardboard "slide" with a circular hole
- water at room temperature
- sodium thiosulfate ("hypo")
- sulfuric acid
- 1 stirring stick
- 1 polarizing sheet

Procedure: Repeat the Blue Sky and Red Sunset demonstration (or perform this demonstration at the same time as that other demonstration—a little tricky, unfortunately). Hold the polarizing sheet on the side surface of the aquarium and show that the blue light you see through it is much brighter when the sheet is permitting vertically polarized light to pass than when it's permitting horizontally polarized light to pass.

Explanation: Photons of vertically polarized light from the slide projector are much more likely to scatter 90° in the horizontal plane than are horizontally polarized photons. That's because a vertically polarized photon causes vertical oscillations of charges in the particles in the water and these vertical oscillations of charge radiate vertically polarized waves into the horizontal plane. A horizontally polarized photon from the slide projector will make charges in the particles oscillate horizontally, and those charges won't radiate at all in the direction of the polarizing sheet.

326. Soap Bubbles and Interference

Description: You blow soap bubbles on the surface of a sheet of white plastic laying on an overhead projector. The soap bubbles exhibit beautiful colors in a darkened room.

Purpose: To show interference effects in soap bubbles.

Supplies:

- 1 overhead projector
- 1 sheet of thin white plastic or a plastic diffuser
- soap bubble mix
- 1 drinking straw or bubble wand

Procedure: Place the plastic sheet on the surface of the overhead projector and turn on the projector. Wet the surface of the plastic sheet with bubble solution and blow one or more large bubbles on its surface. In a darkened room, the bubble will appear brightly colored.

Explanation: Light waves partially reflect from each surface of the soap film and can bounce about inside the film several times before emerging. When these partial waves join together, they may interfere destructively or constructively, depending on their wavelengths and on how far they have traveled through the soap film before joining together. The partial waves of some wavelengths will join together in constructive interference and these wavelengths will appear bright. Other wavelengths will experience destructive interference and won't be visible. Since only some wavelengths experience constructive interference, the soap film appears brightly colored. The film tends to be thicker at the bottom than at the top, so the colors vary with position.

327. White Sugar and Clear Rock Candy

Description: You show that while large sugar crystals (rock candy) appear clear, a pile of tiny sugar crystals appears white.

Purpose: To show that when light travels through many interfaces between clear materials, the light is reflected and scattered, and the materials appear white.

Supplies:

- granulated sugar
- rock candy

Procedure: Show that the rock candy is clear and that the granulated sugar is white, despite the fact that both are the same chemical. In fact, you might crush the rock candy to make white granulated sugar.

Explanation: Each time light travels from air into sugar or from sugar into air, some of that light reflects. While these transitions occur only occasionally in rock candy, they occur frequently in a pile of granulated sugar. With enough reflections from randomly oriented sugar surfaces, the pile of granulated sugar appears white.

Section 15.2 Fluorescent Lamps

You might revisit the fluorescence demonstration from Section 14.2.

328. Gas Discharges

Description: A vertical glass tube emits a bright line of light as an electric discharge occurs inside it. The colors of this discharge depend on the type of gas inside that tube. A CCD camera views the tube through a diffraction grating and displays a series of bright spectral lines.

Purpose: To show the spectral lines of a gas discharge.

Supplies:

1 set of gas discharge lamps and a high-voltage power supply
1 CCD color camera and monitor
1 transmission diffraction grating

Procedure: Mount one of the discharge lamps vertically in the power supply and turn it on. Note that the gas is producing light because its atoms are being excited by a stream of high-energy electrons. When one of these electrons collides with a gas atom, that atom may be shifted to an electronically excited state and may subsequently emit a photon of light. The wavelength and color of that light are determined by the atomic structure of the atom.

To see the specific wavelengths of light, use the CCD camera to observe the discharge through the diffraction grating. With the camera aimed properly to one side, you should see a series of spectral lines that sweep from violets to reds across the screen of the monitor. (If you need to attenuate the light from the tube, try two crossed polarizers.) Turn off the high-voltage supply and change the tube to one with a different gas. Show that the spectral lines are unique to the particular gas.

Explanation: The electronic structures of the different atoms depend on the charges of their nuclei and, consequently, to the numbers of electrons they have. In the dark, electronically excited atoms tend to emit their excess energy as light and return to their ground electronic states.

329. The White Fluorescence of the Phosphors in a Fluorescent Lamp

Description: You exposed the phosphors from a fluorescent lamp to ultraviolet light and they glow with white light.

Purpose: To show how the phosphors in a fluorescent lamp convert the ultraviolet light from the mercury atoms into visible light.

Supplies:

1 ultraviolet lamp (ideally a short wavelength mercury lamp)
phosphors removed from a fluorescent lamp

Procedure: Collect the phosphors from inside a fluorescent lamp. (While there is a tiny amount of mercury trapped in these phosphors, they are otherwise nontoxic. If you like, you can eliminate the mercury by baking the phosphors gently in a well-ventilated area.) Expose these phosphors to ultraviolet light and observe that they emit white light.

Explanation: The phosphors are a mix of different materials that glow with a spectrum that mimics that of sunlight.

Follow-up: You could compare the lights from the four standard lamp styles: regular and deluxe cold and warm whites.

330. Different Fluorescent Fixtures

Description: You turn on several different types of fluorescent fixtures to show how they initiate and control their gas discharges.

Purpose: To show the various techniques for starting and sustaining the discharges inside fluorescent lamps.

Supplies:

1 manual preheat lamp (you must push one button—typically a red button—and the lamp starts when you release the button)
1 automatic preheat lamp (the lamp blinks on several times before it glows continuously)
1 rapid start lamp (it starts shortly after you turn it on, without blinking, and may be dimmed in some cases—if you can find a dimmable lamp, that's ideal)
1 instant start lamp (it starts immediately as you turn it on and its tubes have only one pin at each end)

Procedure: Demonstrate the 4 lamps one at a time (if you can find all of them).

The manual preheat lamp starts only after you release the preheat button. Note that as you press the preheat button, the ends of the tubes (the filaments) glow red hot. When the filaments are hot enough and you release the preheat button, the discharge will start when you release the button and the discharge will keep the filaments hot enough to provide the free electrons needed to sustain the discharge.

The automatic preheat lamp uses a starter device (often a little metal can) to do the same job that you would have done with the preheat button had it been a manual fixture. The filaments are first heated red hot and then the discharge is tried. The starter device usually tries to start the discharge several times before it actually starts properly. That's why the discharge blinks before becoming continuous.

The rapid start lamp continuously heats the filaments, both before and while the discharge is operating. When you turn on the lamp, the ballast immediately begins to heat the filaments and the discharge starts smoothly (though with a little flickering) as soon as the filaments are hot enough. Because the filaments are always kept hot enough to emit electrons, even when the discharge is weak, a rapid start lamp can be dimmed.

The instant start lamp uses high voltage to start the discharge operating. It turns on immediately.

Explanation: To sustain a discharge in a fluorescent tube, electrons must be emitted from its ends so that current can flow through the tube. The free electrons are normally released by hot electrodes (filaments) at the ends of the tube. There are different techniques for heating these electrodes.

331. A High Pressure Mercury Lamp

Description: You turn on a high pressure mercury lamp and watch the color of its light and its brightness evolve. It starts with a dim violet glow and gradually develops a brilliant blue-white light.

Purpose: To show how the pressure of gas in a mercury discharge changes the spectrum of light emitted by that discharge.

Supplies:

1 high pressure mercury lamp (available from a hardware store)
1 CCD color camera and monitor
1 transmission diffraction grating

Procedure: Place the diffraction grating in front of the CCD camera and aim the CCD camera to one side of the high pressure mercury lamp so that it will observe the dispersed colors of the lamp. Now turn on the lamp. The discharge will begin as a dim violet glow—the pressure of mercury gas in the lamp is low and the light it emits is mostly invisible ultraviolet; the same ultraviolet that's used in a fluorescent lamp. But as the lamp warms up and more mercury atoms enter the vapor, the lamp will begin to emit a rich spectrum of colors and its light will appear blue-white. Watch the monitor and see how new spectral lines continue to appear. The lamp probably contains metal-halides to improve its whiteness, so some of the lines are due to those added materials.

Explanation: At low pressures, the mercury atoms in a gas discharge emit mostly the mercury resonance radiation at 254 nm. But at higher pressures and densities, the 254 nm light experiences radiation trapping—it goes from one atom to the next and is virtually unable to escape from the dense gas. New spectral lines that are able to escape from the gas begin to appear, including many that correspond to forbidden transitions—transitions that can't occur in isolated atoms but that are allowed during collisions.

332. A High Pressure Sodium Vapor Lamp

Description: You turn on a high pressure sodium vapor lamp and watch the color of its light and its brightness evolve. It starts with a dim orange-violet glow and gradually develops a brilliant orange-white light.

Purpose: To show how the pressure of gas in a sodium vapor discharge affects the spectrum of light emitted by that discharge.

Supplies:

1 high pressure sodium vapor lamp (available from a hardware store)
1 CCD color camera and monitor
1 transmission diffraction grating

Procedure: Place the diffraction grating in front of the CCD camera and aim the CCD camera to one side of the high pressure sodium-vapor lamp so that it will observe the dispersed colors of the lamp. Now turn on the lamp. The discharge will begin as a dim violet-orange glow—the pressure of sodium atoms in the lamp is extremely low and you are seeing mostly light emitted by gases added to start the discharge. But as the lamp warms up and more sodium atoms enter the vapor, the lamp will begin to emit bright orange light. At still higher densities and pressures, the orange light will smooth out into an orange-white light. If you watch the spectrum evolve on the monitor of the CCD camera, you'll see that the bright orange line that first appears when the discharge has just begun to warm up becomes broader and broader and develops a dark center.

Explanation: At low pressures, the sodium atoms in a gas discharge emit mostly sodium resonance radiation at 590 nm. But at higher pressures and densities, the 590 nm light experiences radiation trapping—it goes from one atom to the next and is virtually unable to escape from the dense gas. However, light emitted by excited sodium atoms during collisions is shifted from its normal wavelengths and has a much better chance of escaping from the gas. That's why the 590 nm line broadens and develops a dark center—light right at 590 nm can't get out of the discharge, but collision-broadened light that isn't right at 590 nm can get out. Other spectral lines also appear as the density of sodium atoms increases and the lamp stops being such a monochromatic orange.

Section 15.3 Lasers

333. An Open Helium Neon Laser

Description: You observe the spectral lines in the gas discharge of a helium neon laser (or a neon discharge lamp). Only one of these spectral lines is present in the laser light emerging from a helium-neon laser.

Purpose: To show that, of the spectra lines in the neon atom, only one of them is selected for amplification in a normal helium neon laser.

Supplies:

1 red helium-neon laser with an exposed discharge tube (if available; else a neon gas discharge lamp and a normal red helium-neon laser)
1 CCD color camera and monitor
1 transmission diffraction grating

Procedure: Turn on the helium-neon laser (or the gas discharge lamp) and observe its spectral lines with the CCD camera and the diffraction grating. Now look at the laser line and identify the spectral line in the neon discharge that's being amplified to form the laser line.

Explanation: The helium neon laser is amplifying light from neon's spectral line at 632.8 nm. An elevated population of excited neon atoms is being created by a collisional energy transfer from excited helium atoms and the excited neon atoms are amplifying this 632.8 nm light to form a laser beam.

334. The Coherence of Laser Light

Description: You observe the patterns produced when laser light passes through slits and screens.

Purpose: To show that because laser light is coherent, it exhibits dramatic interference effects.

Supplies:

1 continuous-wave visible laser
slits (single, double, etc.)
screens (fine mesh)

Procedure: Place the slits and screens in front of the laser beam, one at a time, and discuss the patterns that form on the wall beyond. Point out that such patterns normally don't form with spontaneous or thermal lights because these other forms of light don't have the coherence needed to exhibit strong interference effects.

Explanation: The photons leaving a laser are copies of one or a small number of original photons. Because of the identical character of the photons, they can interfere not only with themselves but also with one another. This broad flexibility with interference in laser beams makes it possible to see some remarkable effects.

Section 16.1 Photographic Cameras

In a large lecture hall, you may want to observe the images that are formed in these demonstrations with a camera and display them on a monitor.

335. Forming a Real Image

Description: While the light from a light bulb alone causes a diffuse illumination of a white screen, the addition of a converging lens can form an inverted image of the light bulb on the screen.

Purpose: To show how a converging lens forms a real image.

Supplies:

1 light bulb (or another bright, identifiable object)
1 white screen or ground-glass screen
1 converging lens (about 50 mm in diameter, with a focal length of about 250 mm or so)
1 optics bench (optional—otherwise just use lens and component holders)

Procedure: Place the light bulb and the white screen about twice the focal length of the lens apart and turn on the light bulb. Only a diffuse illumination will appear on the screen. Now insert the converging lens midway between the bulb and screen and move the lens back and forth until a sharp real image of the bulb appears on the screen. Point out how refraction at the surfaces of the lens is bending all the light from one point on the bulb together to a single point on the screen. Show that blocking part of the lens with your hand simply dims the image—because each portion of the lens is sending light rays from all parts of the bulb to their appropriate positions of the screen.

Explanation: The converging lens takes the diverging light rays that emerge from a particular point on the bulb and bends them so that they converge to a particular point of the screen. But even if the screen weren't there, the real image would form in space and you could find it with your hand or with a piece of photographic film.

336. How a Lens Works

Description: You use black board optics (or camera table optics) to show how a converging lens bends light rays together and can thus form a real image of an object.

Purpose: To show how refraction at the surfaces of a converging lens bends light rays toward one another.

Supplies:

1 set of black board optics or camera table optics

Procedure: Begin with several parallel light rays heading from left to right. Show that inserting a converging lens into these rays causes them to bend toward one another. Point out that there is one point at which all the bent rays meet.

If possible, repeat this experiment with a spray of diverging light rays that come from one point in the light source. Show that the converging lens still brings these rays together, but the convergence is delayed.

Explanation: A converging lens brings formerly parallel light rays together at its focal length. It can also bring formerly mildly diverging light rays together somewhat beyond its focal length.

337. The Importance of a Lens's Focal Length

Description: The real image formed on a screen by a long focal length lens is larger and dimmer than the real image formed by a short focal length lens of the same diameter.

Purpose: To show how a lens's focal length affects the brightness and size of the image it forms.

Supplies:

1 light bulb (or another bright, identifiable object)
1 white screen
1 short focal length converging lens (about 50 mm in diameter, with a focal length of about 25 mm or so)
1 long focal length converging lens (about 50 mm in diameter, with a focal length of about 100 mm or so)
1 optics bench (optional—otherwise just use lens and component holders)

Procedure: Place the light bulb and the white screen about 2 m apart and insert the short focal length lens about 25 mm away from the screen. Move the lens back and forth until a sharp real image of the bulb appears on the screen. Point out how small that real image is and how bright it is.

Now remove the short focal length lens and replace it with the long focal length lens. Place this new lens about 100 mm from the screen and move it back and forth until a sharp image forms. Point out how much larger that real image is than the previous one and how much dimmer it is. Discuss the decreased curvature of the surfaces of the long focal length lens and how this delays the focus.

Explanation: With more distance over which to travel before it focuses, the light can spread farther away from the axis of the lens and create a larger (and dimmer) real image.

338. Depth of Focus

Description: A large-diameter converging lens forms real images of three different light bulbs at three different distances from the lens. Only one of these images is sharply focused on a screen at a time. But when a small aperture is inserted over the lens, allowing only its central portion to form the image, all three images are in focus at once.

Purpose: To show how a lens's aperture affects its depth of focus.

Supplies:

- 3 light bulb (or other bright, identifiable objects)
- 1 white screen
- 1 large diameter converging lens—a magnifying lens will work (about 100 mm in diameter, with a focal length of about 200 mm or so)
- 1 optics bench (optional—otherwise just use lens and component holders)
- 1 cardboard aperture, about 20 mm in diameter (or even less; a variable aperture is even better)

Procedure: Place the three light bulbs at various distances from the white screen (none closer than 1 m) and insert the lens about 100 mm away from the screen. Move the lens back and forth until a sharp real image of the middle distance bulb appears on the screen. Point out that the images of the other two bulbs also appear, but that they are out of focus. Shift the lens to bring the other light bulbs into focus, one at a time, and note that you can't bring all three into focus at once.

Now insert the narrow aperture in front of the lens and show that, while the images have become dimmer, they are all essentially in focus on the screen.

Explanation: When only rays that pass through the center of the lens are allowed to reach the screen, they are so nearly converged well in front of and behind the true focus, that the precise distance between the lens and the screen isn't very important. Everything appears in focus. But when the whole lens is active, rays converging from the edges of the lens are badly out of place in front of and behind the true focus and the patterns of light observed before or after the true focus are badly blurred.

339. Mixing the Primary Colors of Pigment

Description: You show 4 transparent sheets containing fractions of a color image. One sheet bears magenta pigments, another cyan, another yellow, and the last black. When these sheets are stacked, they reveal a full color image.

Purpose: To show how the primary colors of pigment can be combined to form full color images (as is done in photographic film).

Supplies:

- 1 set of color separation transparencies from a newspaper print shop (or generated with a color printer and software that can make color separations)

Procedure: Show the four separate sheets of transparent material. Point out that the magenta sheet contains a dye that absorbs green light wherever green light isn't wanted in the final image, that the yellow sheet contains a dye that absorbs blue light wherever blue light isn't wanted in the final image, that the cyan sheet contains a dye that absorbs red light wherever red light isn't wanted in the final image, and that the black sheet helps to darken parts of the image that should be particularly dark (black dye isn't present in color photography, but saves the printers from having to use extremely large quantities of costly colored dyes). Now overlap all the sheets and show that they combine to form a full color image. By controlling where you see red, green, and blue lights, these dye layers can make you see any possible color.

Explanation: Each layer absorbs one of the primary colors of light. Together, these layers can turn white light into any specific arrangement of red, green, and blue lights and thus make you perceive any possible color.

Section 16.2 Telescopes and Microscopes

Before the demonstration about virtual images, I repeat the demonstration about real images from Section 16.1. Then I can combine the two demonstrations to form the Keplerian telescope that follows.

340. Forming a Virtual Image

Description: You hold a magnifying glass in front of a picture and see an enlarged virtual image of that picture. This image appears behind the lens, so you can't put your fingers in it the way you can with a real image.

Purpose: To show how a converging lens forms a virtual image of a very nearby object.

Supplies:

1 picture
1 magnifying glass (or another converging lens)

Procedure: Hold the magnifying glass a short distance in front of the picture and show that a virtual image of the picture appears. Point out that the image is larger than the picture and that it's located on the same side of the lens as the picture. You can't touch the virtual image. The virtual image is also upright, in contrast to a real image, which is inverted.

Explanation: The converging lens takes the diverging light rays that emerge from a particular point on the picture and bends them so that they don't diverge quite as fast. You see them as coming from a more distant but much larger virtual image.

341. A Keplerian Telescope

Description: You use a magnifying glass to allow close inspection of the real image formed by a converging lens, thus producing a Keplerian telescope.

Purpose: To show how two converging lenses can form a simple telescope.

Supplies:

1 light bulb (or another bright, identifiable object)
1 converging lens (about 50 mm in diameter, with a focal length of about 250 mm or so)
1 magnifying glass (or another converging lens)
1 optics bench (optional—otherwise just use lens and component holders)

Procedure: Place the light bulb several meters from the first converging lens and locate the real image of this light bulb that the first lens forms. You can use your hand to find the pattern of light in space because you can touch a real image.

Now take the magnifying glass and use it to produce an enlarged virtual image of that real image. You may want to observe this real image with a television camera and monitor so that everyone can see it.

Explanation: The first lens forms a real image of the light bulb and the second lens allows you to make a close (magnified) inspection of that image. The final virtual image is inverted because it's an upright virtual image of an inverted real image.

342. Forming a Virtual Image with a Mirror

Description: You look at an object in a mirror and notice that what you see is a virtual image.

Purpose: To show that mirrors can form virtual images.

Supplies:

1 mirror
1 light bulb (or another object)

Procedure: Place the light bulb a short distance in front of the mirror and observe the image that the mirror forms. This image is located on the other side of the mirror from the object, where you can't touch it. It's thus a virtual image.

Explanation: The mirror bends the light rays so that they appear to come from an object that's located behind the mirror, the same distance behind the mirror as the object is in front of the mirror.

343. Forming a Virtual Image with a Curved Mirror

Description: You look at an object in a curved mirror and notice that what you see is an enlarged virtual image.

Purpose: To show that curved mirrors can form enlarged virtual images.

Supplies:

1 concave mirror
1 light bulb (or another object)

Procedure: Place the light bulb a short distance in front of the mirror and observe the enlarged virtual image that the mirror forms.

Explanation: The mirror bends the light rays so that they appear to come from an object that's located behind the mirror. This virtual image is located at a greater distance behind the mirror than the object is in front of the mirror. This virtual image is also greatly enlarged relative to the object.

344. Forming a Real Image with a Curved Mirror

Description: Light from a distant light bulb reflects from a curved mirror and forms an inverted real image.

Purpose: To show that curved mirrors can form real images.

Supplies:

1 concave mirror
1 light bulb (or another object)
1 ground-glass screen

Procedure: Place the light bulb a long distance in front of the mirror (perhaps in the back of the darkened room) and observe the real image that the mirror forms on a nearby ground glass screen.

Explanation: The mirror bends the mildly diverging light rays from the distant bulb so that they converge together on the screen. The real image that forms on the screen is inverted in this process.

Follow-up: Use a magnifying glass to inspect the real image, thereby creating a reflecting telescope. Also, insert apertures in front of the mirror so that you use less of the mirror. Show that the real image darkens but remains complete. Point out that one of the values of a large aperture is light-gathering ability. Large mirrors collect more light and do their jobs faster.

345. The Importance of Large Apertures - Diffraction

Description: A laser beam is sent through a series of progressively smaller pinholes. With each smaller size, the resulting beam spreads outward more strongly.

Purpose: To show that sending light through an aperture causes it to spread outward (and that this spreading limits the resolution of a telescope).

Supplies:

1 laser beam with a good quality beam (a helium-neon laser is probably better than a solid state laser pointer. In principle, you want a clean TEM00 mode from the laser.)
1 set of pinholes
1 screen

Procedure: Direct the beam from the laser at the screen and notice how small the beam spot is. Now insert the pinholes into the beam, one at a time. As these holes get smaller, not only does the light spot get dimmer—it also gets wider.

Explanation: The light propagates as a wave. When the wave is force to go through a narrow aperture, it naturally spreads out in its subsequent travels. The narrower the aperture, the more rapidly the wave spreads. In a telescope, making the light go through the aperture defined by the mirror's diameter causes the light spread and limits the telescope's ability to resolve nearby stars.

Section 16.3 Compact Disc Players

346. Putting Sound on Light (Analog Version)

Description: The signal from a tape player is used to modulate the light outputs of a flashlight and a laser pointer. This light strikes an optical sensor that's connected to an amplifier and speaker, and the sound is heard.

Purpose: To show that light can carry sound information (albeit in analog form in this demonstration).

Supplies:

1 flashlight
1 laser pointer
1 large inductor (a 5 cm diameter coil of about 100 turns of insulated copper wire will do)
1 tape player
1 light sensor that's AC coupled to an amplifier and speaker

Procedure: Modify the flashlight's circuit so that, in addition to passing through its batteries and bulb, its current must also pass through the inductor. Attach the output wires from the tape player's headphone jack to the two sides of the inductor. Shine the light from the flashlight onto the light sensor and turn on the tape player. You will hear sound from the speaker. Repeat this same procedure with the laser pointer. Some laser pointers have pocket clips that also act as their switches. All you have to do in this case is to insert the inductor between the clip and the case of the pointer.

Explanation: The inductor carries the DC current needed to maintain operation of the light bulb or laser. But the tape player superimposes an AC current onto the DC current passing through the bulb or laser and its light output fluctuates accordingly. The light sensor detects these fluctuations and uses them to reproduce the sound.

347. Total Internal Reflection

Description: You use black board optics (or camera table optics) to show how light that tries to escape from a clear medium into air at a glancing angle is totally reflected from the interface.

Purpose: To show how total internal reflection works.

Supplies:

1 set of black board optics or camera table optics

Procedure: Send a light ray into the wide face of a right-angle prism. Show that as this light tries to exit the prism through the narrow face, it's at least partially reflected and that the emerging beam is bent dangerously close to the surface of that face. When the prism's angle is adjusted far enough in one direction, the emerging beam vanishes altogether and the beam is perfectly reflected from the surface.

Explanation: When light speeds up as it moves from one medium to another, it bends away from the normal to the surface. As the angle of incidence on the interface becomes more shallow, the outgoing beam bends more and more toward the surface between the media. At a shallow enough angle, the light no longer emerges from the first medium at all—it's totally internally reflected.

Follow-up: Send light rays upward through a container of water and watch how they exit from the water's surface. The light rays that travel almost directly upward escape without difficulty, but those that strike the water a glancing blow simply reflect—they experience total internal reflection.

348. Light Following a Stream of Water

Description: A beam of laser light shines into the stream of water leaving a container. The light follows the water as the water arcs downward and illuminates the spot where the water hits a basin.

Purpose: To show that light can become trapped in a medium by total internal reflection.

Supplies:

1 laser or laser pointer (a flashlight and a converging lens will also work)
1 clear beaker with a pipe attached to its side near its bottom
1 cork for the pipe
1 basin to catch the water
water

Procedure: Insert the cork in the beaker's pipe and fill the beaker with water. Shine the laser beam through the beaker so that it travels through the pipe and hits the cork. Now remove the cork and allow the water to flow in an arc into the basin. The laser light will follow the water all the way to the basin.

Explanation: The laser light encounters the surfaces of the water stream at such shallow angles that it experiences total internal reflection. Unable to escape from the water, the beam travels with it all the way to the basin.

349. Birefringence in Calcite

Description: You place a piece of cardboard with a small hole in it on an overhead projector. One circle of light appears on the screen. But when you put a calcite crystal on top of the hole, two separate circles of light are visible. With a polarizing sheet, you determine that the two circles of light have different polarizations. The calcite crystal is handling those two polarizations differently.

Purpose: To show that some materials allow the two polarizations of light to travel at different speeds.

Supplies:

1 overhead projector
1 screen
1 cardboard sheet with a small (3 mm) hole punched in it
1 calcite crystal
1 polarizing sheet

Procedure: Place the cardboard sheet on the overhead projector and form a clear image of the hole on the screen. Now place the calcite crystal on top of the hole and observe that two different circles of light are present on the screen. Rotate the calcite crystal and see that they move relative to one another—their separation is evidently related to the structure and orientation of the calcite crystal. Now use the polarizing sheet to show that the two circles of light have different polarizations.

Explanation: The electrons in a calcite crystal can move more easily in some directions than in other directions. As a result, calcite slows one polarization of light more than the other. It thus bends one polarization of light more than other upon entry and exit, and this different bending leads to the spatial separation of the two circles of light.

Follow-up: If you have a calcite-based polarizing beam splitter, show how it uses both calcite's ability to bend the two polarizations differently and total internal reflection to separate the two polarizations of light from one another completely.

Section 17.1 Knives and Steel

You might want to repeat the breaking a penny demonstration from Section 6.1 to show how reduced temperature prevents dislocations from moving and makes some metals hard and brittle.

350. Hardening and Annealing a Steel Nail

Description: You try to bend a hardened steel nail and it breaks. You take an identical nail, heat it red hot, and let it cool slowly. It then bends rather than breaking. You straighten this nail and reheat it. However, this time you plunge the red hot nail into water to harden it. Now it breaks rather than bending.

Purpose: To show how heat treatment hardens carbon steels.

Supplies:

- 2 high carbon nails (masonry nails—we have found a supply of flat-sided masonry nails that work very well. They are very hard and very brittle. That's what you want.)
- 1 propane torch
- matches
- 1 container of water
- 1 vise
- 1 pliers
- 1 tongs
- safety glasses

Procedure: Clamp one of the nails in the vise and try to bend it with the pliers. Instead of bending, it will break. Now take the second nail in the tongs and heat it red hot with the torch. Allow it to cool gradually until it's at room temperature (a minute or two). Now clamp it in the vise and try to bend it with the pliers. It will bend without breaking. Straighten it back out and hold it in the tongs. Reheat it red hot and this time plunge it into the water. This rapid cooling will harden the steel. When you return it to the vise and try to bend it, it will break.

Explanation: The steel is hard because it contains tiny particles of hard cementite (iron carbide) scattered throughout its ferrite crystals (iron). When you try to bend this hard steel, the cementite particles keep the ferrite crystals from undergoing plastic deformation (slip) and the nail breaks. But when you heat and slowly cool the steel, the carbon that dissolves in the hot steel has time to migrate out of the ferrite crystals. The steel is then a soft mixture of large ferrite crystals and a few large cementite crystals. It bends easily because the ferrite crystals have no tiny cementite particles in them to prevent them from undergoing plastic deformation.

351. Different Steels

Description: You compare the properties of several different steel alloys.

Purpose: To show how small compositional changes and changes in processing can have substantial effects on the characteristics of steels.

Supplies:

- 1 piece of low-carbon steel (common steel)
- 1 piece of high-carbon steel (tool steel)
- 1 piece of 18-8 stainless steel
- 1 magnet
- 1 plastic container of hydrochloric acid

Procedure: Discuss the compositional differences between the steels. Show that the high-carbon steel can cut the low-carbon steel because the former is much harder than the latter. Show that both the carbon steels are magnetic while the stainless steel is not. Show that the carbon steels react with hydrochloric acid while the stainless steel does not.

Explanation: The high-carbon steel is harder than the low-carbon steel because it contains a large proportion of iron carbide particles (and perhaps other slip-inhibiting inclusions). The stainless steel is chemically inert because of its high content of chromium and nickel atoms.

Section 17.2 Windows and Glass

352. Melting Glass - Quartz vs. Soda-Lime Glass

Description: You try to melt quartz glass tubing unsuccessfully while soda-lime glass tubing melts easily.

Purpose: To show that the addition of soda and lime to quartz glass dramatically reduces its melting and softening temperatures.

Supplies:

1 piece of quartz glass (or Vycor glass) tubing or rod
1 piece of soda-lime glass tubing or rod
1 gas burner or propane torch
matches

Procedure: Try to melt the quartz glass tube with the burner or torch. You will be unable to do so. Now try to melt the soda-lime glass tube. It will melt and flow easily.

Explanation: Adding the soda and lime to the quartz makes it much easier to work with. The sodium ions terminate the covalent networks that are the basis for quartz glasses and weaken those networks. As a result, soda-lime glasses are softer and melt more easily than pure quartz glass. In fact, soda-lime glasses are eutectics—they melt at temperatures below the melting points of the chemicals from which they are made.

353. Thermal Shock and Glass

Description: You show that heating soda-lime glass rapidly causes it to crack from the stresses of uneven thermal expansion. Borosilicate glass doesn't suffer such problems. Quartz glass can handle rapid heating well, too. Upon rapid cooling in cold water, even the borosilicate glass may break. But quartz glass is still unaffected.

Purpose: To show that thermal expansion and contraction can cause glasses to tear apart during uneven heating and cooling.

Supplies:

1 glass slide (soda-lime glass)
1 pyrex tube or dish
1 quartz glass tube (or Vycor glass)
1 propane torch
matches
1 container of water
safety glasses

Procedure: Heat the glass slide rapidly with the torch. It will crack or shatter. Now heat the pyrex tube or dish. Unless you heat it particularly quickly in one spot, it should survive. Now heat the quartz tube. You can't damage it with heat.

Next reheat the pyrex tube or dish and plunge it into cold water. It will almost certainly crack or shatter. Try the same with the quartz tube. It will survive without injury.

Explanation: Soda-lime glass is soft and has a large coefficient of volume expansion. When you heat part of it rapidly, the heated part expands. The heated and unheated parts of the glass exert tremendous stresses on one another and they tear the weak glass apart. Borosilicate glasses are still structurally weak, but they have much smaller coefficients of volume expansion. The heated and unheated parts are less able to tear one another apart. However, very rapid temperature changes (as occur when hot glass is plunged into water) still cause the glass to tear itself apart. Quartz glass is so strong and has such a small coefficient of volume expansion that it's very hard to injure with thermal shock.

354. The Disappearing Glass Container

Description: You pour salad oil into a clear container that has a Pyrex or Kimax item inside it. The item appears to vanish.

Purpose: To show that there are no reflections when light moves between two materials with the same index of refraction.

Supplies:

1 bottle of salad oil (Wesson works well)
1 Pyrex or Kimax flask or beaker
1 clear container

Procedure: Put the flask or beaker in the container and observe that it's plainly visible. Now pour the salad oil into the container and into the flask or beaker. The flask or beaker will become essentially invisible.

Explanation: The indices of refraction of the salad oil and borosilicate glasses are almost identical. With no change of speed upon entry or exit from the flask or beaker, light doesn't refract or reflect, and you can't tell that the flask or beaker is there.

355. Tempered Glass - A Bologna Bottle

Description: You use a peculiar glass bottle to pound in a nail. You then drop a tiny chip of sharp crystal into the bottle and it falls apart.

Purpose: To show that the surface stresses experienced by glass determine its resistance to tearing and breakage.

Supplies:

1 bologna bottle (available from a scientific supply company, at non-negligible expense. Sargent-Welch charged $41 for them recently. Still, they are remarkable.)
1 piece of wood
1 nail with a large head (just to be safe)
safety glasses

Procedure: Hold the neck of the bologna bottle and tap the nail into the wood with the side of the round bottle. Having demonstrated that the outside of the bottle is extremely tough, hold the bottle upright over a garbage can and drop the crystal chip that came with the bottle into the neck of the bottle. When this chip hits the inside bottom of the bottle, the bottle will tear itself apart and its pieces will drop into the garbage can.

Explanation: The bottle is tempered in such a way that the outside surface is experiencing compression and the inside surface is experiencing tensile stress. Since it's very hard to start a tear in a layer that is being compressed, it's hard to tear the outside of the bologna bottle. But the inside is under tension and the slightest injury to it will cause the surface to tear itself to shreds.

356. Tempered Glass - Rupert Drops

Description: When you break the tail of a small glass drop, the drop crumbles into dust.

Purpose: To show that tempered glass exhibits dicing fracture when its compressed outer skin is broken.

Supplies:

2 or 3 Rupert drops (available from a scientific supply company)
1 needle-nosed pliers
cloth gloves
safety glasses

Procedure: Hold a Rupert drop in your gloved hand and break off its tail with the pliers. If the drop has been properly tempered (I've had mixed luck), it will tear itself to powder. You may have to try more than one to observe this self-destruction.

Explanation: The Rupert drops are tempered glass—their outer surfaces are under compression while their insides are under tension. When you break through the compressed surface layer and expose the tense inner portion of the drop, it tears itself apart.

357. Glass Fibers

Description: You heat the middle of a glass rod until it softens and then pull its ends away from one another. A glass fiber forms in between the ends. This fiber is relatively flexible and extremely strong for its size.

Purpose: To show how glass fibers are formed.

Supplies:

1 glass rod
1 gas burner
matches
safety glasses

Procedure: Light the burner and hold the middle of the glass rod over the flame. When the glass has softened significantly, pull the two ends of the rod away from one another in a smooth and steady motion. Stop when you have stretched the rod to about 1 m long. Allow the pieces to cool briefly. Show that the glass fiber is flexible (don't bend it too far or it will break!). Be careful with the hot ends of the glass until they've had enough time to cool completely. Be careful with eyes.

Explanation: The glass fiber's strength comes in part because of its relative lack of defects on its surface. With so little surface on any given length of fiber, there are only a couple of sites for a tear to begin as you bend the fiber.

Section 17.3 Plastics

Many of the demonstrations listed in this section are standard experiments done by students of organic chemistry. You may be able to obtain the materials for these experiments from your local chemistry department already prepared and ready to go.

358. Natural Polymers

Description: You display several natural polymers.

Purpose: To show that polymers (plastics) are common in nature.

Supplies:

- 1 sheet of paper (cellulose)
- 1 rubber band (rubber)
- 1 piece of wool
- 1 piece of silk
- 1 box of cornstarch

Procedure: Simply point out that each of these materials consists of extremely long molecules that are used to give structure and function to biological systems.

Explanation: Cellulose and starch are both sugar polymers. Rubber is a polymer of isoprene monomers. Wool and silk are both protein polymers.

359. Cellulose Derivatives

Description: You show that a piece of nitrocellulose (celluloid) is quite clear and tough, but that it burns nicely. A piece of cellulose acetate (acetate plastic) is much more practical.

Purpose: To show some of the early synthetic plastics.

Supplies:

- 1 piece of clear nitrocellulose sheet (can be made by allowing collodion to dry on a sheet of shiny aluminum foil. Because the ether solvent in collodion is dangerously flammable, you should only do this drying in a fume hood or outdoors. Be careful!)
- 1 piece of cellulose acetate plastic
- tongs
- matches
- water (in case of fire)

Procedure: Show that the nitrocellulose (celluloid) sheet is clear and flexible. But then hold it in the tongs and light it with a match. The nitrocellulose will burn rapidly and leave no ash. Note that relatively nonflammable cellulose acetate replaced nitrocellulose.

Explanation: Both nitrocellulose and cellulose acetate can be reshaped in ways that cellulose itself cannot. However, nitrocellulose is extremely flammable (in its highly nitrated form it's a high explosive and the principle component of smokeless powder), so cellulose acetate is a safer choice. It also ages less and is less susceptible to light damage.

360. Reptation in Wet Cornstarch

Description: A mixture of cornstarch and water appears liquid-like when you stir it slowly but feels hard when you poke it suddenly or try to throw it abruptly out of its container.

Purpose: To show that the long molecules of cornstarch moves slowly past one another (reptation) in a solution. If you try to deform the solution quickly, the cornstarch molecules won't permit it to flow. Only if you're patient will it behave as a liquid.

Supplies:

- 2 plastic cups
- 1 stirring stick
- cornstarch
- water

Procedure: Half fill one of the cups with cornstarch and gradually add water to it, stirring carefully with each addition. After you have added a modest amount of water, the entire powder will be wet and it will begin to flow as you stir slowly. (Don't add too much water—be patient and stir carefully.) When the whole mixture behaves like a very thick liquid when you stir slowly, it's ready.

First show that you can pour the "liquid" from one cup to the other. You'll see that it doesn't quite pour normally…it tends to crack as it pours. Next show that if you poke it quickly with your finger, it feels hard and doesn't get your finger wet. Finally, hold the cup by its bottom and try to throw its contents at someone. The mixture will remain in the cup as long as your motion is very rapid.

Explanation: The cornstarch mixture flows slowly because it must wait for the long molecules to disentangle themselves in order to change its shape. This disentanglement is done through reptation of the molecules and depends on their thermal energies and thermal motions. When presented with large, sudden stresses, the mixture resists deformation. But with time, it flows to relieve those stress.

361. Glue Putty

Description: You mix white glue, water, and borax to create a soft putty that flows slowly like a liquid but that tears when exposed to sudden large stresses.

Purpose: To show that the long molecules in glue take time to disconnect from one another and to disentangle themselves. With patience, the material will flow but when stressed suddenly, it tears.

Supplies:

- 1 large mixing container
- 1 smaller container
- 1 measuring cup
- 1 stirring stick
- white glue
- borax
- water

Procedure: In the large container, mix about 125 ml of glue and 125 ml of water. In the small container, dissolve 5 ml of borax powder in about 125 ml of water. Slowly add the borax solution to the glue, stirring as you do. The glue will congeal into a blob of glue putty. If you knead this material carefully and add the right amount of the borax solution, it will be soft and relatively non-sticky. Show that with time the putty will drip from your hands or flatten itself into a puddle, but that if you pull on it suddenly, it will tear into pieces. Is this material solid or liquid? How does time enter into the answer to that question?

Explanation: The borax molecules form hydrogen bonded bridges between the long molecules of the glue and effectively tie the whole mass of molecules together into one big molecule—like weak vulcanization. The water molecules that originally plasticized the glue are caught up in this network of molecules. Because the hydrogen bonds are relatively easy to break, the mass can rearrange and flow if you wait.

362. Slime

Description: You mix solutions of poly(vinyl alcohol) and sodium borate together to get a gooey glob of slimy plastic. Like glue putty, this material flows slowly like a liquid but tears like a solid when exposed to sudden large stresses.

Purpose: To show that the long molecules in poly(vinyl alcohol) take time to disconnect from one another and to disentangle themselves. With patience, the material will flow but when stressed suddenly, it tears.

Supplies:

- poly(vinyl alcohol) (a white powdery substance available from a chemical supply company)
- sodium borate
- water
- 1 heated magnetic stirrer
- several containers
- 1 stirring stick

Procedure: Dissolve 4 grams of poly(vinyl alcohol) in 100 ml of water (this recipe can be scaled up). You will have to heat the water to about 70° C and stir it with a magnetic stirrer for an hour or two. You may want to filter the resulting solution through a strainer because some of the material just won't dissolve, no matter how long you wait. In a second container, dissolve 4 grams of sodium borate in 100 ml of water.

To form the slime, slowly stir some of the sodium borate solution into the poly(vinyl alcohol) solution—about 5 to 10 ml of the sodium borate solution will be enough. The mixture will form a gooey elastic material, commonly called "slime."

Explanation: The borate ions in the sodium borate solution form hydrogen bonded bridges between the long poly(vinyl alcohol) molecules—like weak vulcanization. A vast network of molecules forms and the water is caught up on that network. Because the hydrogen bonds are relatively easy to break, the mass can rearrange and flow if you wait.

363. Making Plexiglas

Description: You add a tiny amount of catalyst to a test tube of methyl methacrylate and heat it to about 90° C. About 20 minutes later, the test tube is full of solid poly(methyl methacrylate) or Plexiglas.

Purpose: To demonstrate a common polymerization process.

Supplies:

- methyl methacrylate (an irritating chemical that makes your eyes tear. Use only in good ventilation.)
- benzoyl peroxide (a contact explosive—never keep more than a tiny bit around and never let it come in contact with metals. Use only ceramic or glass containers or scoops. This stuff is potentially bad news. It's used frequently in chemistry departments for this very reaction. It's also used in acne medications.)
- 1 large test tube
- 1 glass stirring rod
- 1 hot water bath (at about 90° C—don't let it boil because the methyl methacrylate will also boil and pop out of the test tube…I spoiled a good jacket with this stuff several years back)
- safety glasses

Procedure: Half-fill the test tube with methyl methacrylate and add a pea-sized amount of benzoyl peroxide (which acts as a catalyst for the polymerization). Stir. Place the test tube in the hot water bath and cook the mixture for about 20 minutes at about 90° C. The test tube will then contain a nearly solid, clear mass that will harden completely when you allow it to cool. You have made a glassy plastic called poly(methyl methacrylate), Plexiglas, or Lucite.

Explanation: The benzoyl peroxide forms free radicals that initiate the polymerization of the methyl methacrylate molecules. With the help of thermal energy, the monomers are consumed and long molecules are formed.

364. Epoxy

Description: You mix two liquids and stir them together. About 5 minutes later, you have a solid material.

Purpose: To demonstrate that polymerizations are common in high performance adhesives. (Students are remarkably unaware of any glues besides superglue and white glue. They don't understand that superglue polymerizes and doesn't simply dry the way white glue does.)

Supplies:

- 1 single-use pouch of 5 minute epoxy
- 1 stirring stick
- 1 piece of cardboard

Procedure: Tear off the end of the 5 minute epoxy pouch and squeeze both liquids onto the cardboard. Stir the mixture until it's uniform and leave the stick in it. About 5 minutes later, it will be completely hard. Discuss the fact that the glue has not "dried," that it has polymerized into a clear plastic. All of the atoms that were in the package are still present, but the molecules have joined together into giant chains that are no longer mobile. The plastic is in the glassy regime.

Explanation: During polymerization the epoxy rings that are present in the resin molecules open and link together, forming long chain molecules that are a glassy solid at room temperature.

365. Superglue

Description: You squeeze a few drops of superglue (cyanoacrylate monomer) onto a smooth metal surface and press a second smooth metal surface against it. About 1 minute later, it's difficult to separate those surfaces—they are joined by long polymer molecules.

Purpose: To demonstrate a polymerization that proceeds simply in the presence of moisture.

Supplies:

- 2 pieces of smooth, flat metal
- 1 tube of cyanoacrylate glue (superglue)

Procedure: Squeeze a few drops of the glue onto one of the metal pieces and press the second metal piece on top. Rub the pieces against one another to distribute the glue. Leave them pressed against one another for about a minute and then show that they have bonded together.

Explanation: The cyanoacrylate monomer in this polymerization is quite similar to the methyl methacrylate monomer used to form Plexiglas. However, cyanoacrylate will polymerize just in the presence of moisture. Since moisture is everywhere, all you need to do is squeeze it out onto a surface and it will begin to polymerize. Like Plexiglas, this cyanoacrylate plastic is glassy at room temperature.

366. Plastics Fail by Tearing - Piercing a Balloon

Description: To show that plastics fail when a tear propagates through them, you carefully insert a sharpened knitting needle all the way through a balloon. You carefully work the needle between the molecules of rubber, so that you don't start a tear, and the needle don't pop the balloon.

Purpose: To show that polymers break by tearing.

Supplies:

1 good-quality latex rubber balloon
1 sharpened knitting needle (or another needle-sharp thin rod with smooth polished edges)
oil

Procedure: Inflate the balloon and tie it off. Place a drop of oil near the nipple portion of the balloon (where the stresses on its surface aren't as high as elsewhere and the rubber is relatively thick). Carefully insert the needle through the oil drop and into the rubber. Twisting the needle helps it find its way between the rubber molecules. Once you have the needle inside the balloon, aim it at the bump at the other end (another region of relatively low stress). Carefully push the needle through that area of the balloon so that it comes out the other side. You will then have a balloon with a knitting needle passing all the way through it.

Explanation: As long as you don't start a tear, the rubber will tolerate the insertion of the needle between its molecules.

367. Nylon

Description: You pour a solution of adipic chloride in cylcohexane onto a solution of 1,6-hexanediamine in water. A film forms at the interface between the two and you catch this film with a copper wire. You then pull out the film as a long, continuous piece of Nylon–6,6.

Purpose: To show how nylon is made from two monomers that form a copolymer.

Supplies:

5% solution of 1,6-hexanediamine in water
5% adipic chloride in cyclohexane
20% sodium hydroxide in water
1 clean 100 ml beaker
1 clean copper wire
rubber gloves
safety glasses

Procedure: Put about 20 ml of the 1,6-hexanediamine solution in the beaker and add about 20 drops of the sodium hydroxide solution. Now carefully pour about 20 ml of the adipic chloride solution down the inside of the beaker so that it floats neatly on top of the other liquid. A film of nylon will appear at the interface between the two layers. Bend the copper wire into a hook and lift that film out of the liquid. You'll be able to pull out a continuous strand of nylon almost indefinitely. Having fresh solutions helps because pure chemicals gives the longest and strongest nylon molecules.

Explanation: 1,6-hexanediamine is a two-ended base while adipic chloride is essentially a two-ended acid. The base and acid ends join in a nearly endless chain molecule when the two chemical are brought together.

368. Polyurethane Foam

Description: You mix two liquids together in a cup and then wait. In a few moments, a dark foam rises up in the cup and pours over its sides. In a minute, you have a hard mushroom of polyurethane foam.

Purpose: To show how polyurethane foam is made.

Supplies:

polyurethane foam kit (two chemicals that mix to form polyurethane foam—from a hardware or hobby store)
1 paper or plastic cup
1 stirring stick

Procedure: Pour equal quantities of the two chemicals into the paper cup (or follow the directions on the kit). The paper cup should be about ¼ full when you're done. Stir. In about 20 seconds, the mixture will foam up and begin to overflow the cup. A minute later, it will be hard to the touch.

Explanation: During its polymerization reaction, the chemicals release carbon dioxide gas. This gas inflates the hardening plastic and turns it into a foam. Polyurethane is glassy at room temperature, giving the foam a firm character.

369. High-Strength Polymers

Description: You step into a loop at the end of normal plastic rope that's attached to the ceiling and the rope stretches considerably as it begins to support your weight. You then step into a loop at the end of a high-strength rope that's also attached to the ceiling. It doesn't stretch noticeably.

Purpose: To show how straight-chain polymers (either liquid crystal materials like Kevlar or artificially oriented materials like Spectra polyethylene) have enormous tensile strengths and barely stretch at all.

Supplies:

1 polypropylene rope (about a quarter inch diameter)
1 Spectra or Kevlar rope of the same diameter

Procedure: Suspend both ropes from the ceiling and tie loops in them near the ground. When you step into the loop of the polypropylene rope, the rope will stretch considerably. But when you step in the loop of the Spectra or Kevlar rope, it won't stretch. You'll feel like you just stepped onto a steel cable. You can bounce all you like, but nothing will happen.

Explanation: The molecules in Spectra and Kevlar are all aligned straight so they all work together to support your weight. Moreover, because they are already aligned straight, the rope can't stretch without actually stretching or breaking the molecules. Normal ropes stretch because the molecules are bent or coiled and they can unwind to give the rope some additional length.

Section 18.1 Nuclear Weapons

370. Hopping Toys

Description: You press the top and base of a spring-loaded toy together. After a few seconds, the suction cup that holds them together releases and the toy leaps into the air.

Purpose: To show that there are systems in which a strong, short-ranged attractive force can temporarily keep that system together, despite the presence of a weaker but much longer ranged repulsive force.

Supplies:

1 hopping toy (sold in various games and given away as premiums by some stores and restaurants—they have a spring between their top and base and a leaky suction cup that will temporarily keep the spring compressed when you squeeze the top and base together)

Procedure: Discuss the two forces in the toy: a relatively long-ranged repulsion (the spring) and a relatively short-ranged attraction. Squeeze the toy together and point out that you are doing work as you push the parts together—they are storing energy in the long-ranged repulsive force (potential energy). When the suction cup catches, point out that the short-ranged attractive force has now taken over and will keep the toy together.

However, there is a leak in the suction cup, so that it eventually lets go. When that occurs, the toy hops. The energy needed for the hop comes from energy you stored in it when you first squeezed its parts together.

Explanation: The spring is analogous to the long-ranged electrostatic repulsion between protons in a nucleus. The suction cup is analogous to the short-ranged attractive nuclear force that holds the protons together once they touch. The leakiness of the suction cup is analogous to the quantum tunneling that permits the nucleus to fall apart in spontaneous fission.

Follow-up: Squeeze together several of these toys at once and arrange them so that, when one jumps, it hits the others and causes them to "fission"—a chain reaction.

371. Radioactive Decay

Description: You hold a Geiger counter near various radioactive sources and listen to the random nature of their decays.

Purpose: To show that radioactive decay is a random, spontaneous event.

Supplies:

1 or more radioactive sources (appropriate licensing, training, and safety precautions must be followed)
1 Geiger counter

Procedure: Use the Geiger counter to monitor the decays of the various radioactive sources. Point out that the nuclei in these sources were given excess energy long ago, either in a star explosion (a supernova) billions of years ago or at a nuclear reactor facility in more recent years. This excess energy has been stored in the nuclei ever since but they haven't been able to release it because of various competitions between forces. Occasionally quantum tunneling allows one of the forces to win out over another and one of these nuclei spontaneous decays. It then releases some or all of its excess energy and the Geiger counter detects its energetic fragments. Point out that there is absolutely no way to predict when a particular nucleus will decay. The best one can do is make a statistical prediction that a certain fraction of the nuclei will decay during a certain time. If you look at enough nuclei, such statistical predictions will be quite accurate.

Explanation: In the case of spontaneous fission, the Coulomb repulsion is defeating the nuclear force because of tunneling effects. In the decays of other common radioactive sources, relatively isolated neutrons may be converting to protons, electrons, and antineutrinos (so-called "beta decay"). In still other sources, helium nuclei may be emitted (so-called "alpha decay").

372. A Mousetrap Nuclear Explosion

Description: You drop a small rubber ball into a field of set mousetraps, each loaded with two rubber balls. After bouncing around briefly, the rubber ball trips a mousetrap and the whole collection suddenly "explodes" in a shower of bouncing balls.

Purpose: To show how a chain reaction occurs.

Supplies:

- 32 mousetraps
- 65 or more small rubber balls
- 1 board
- 1 clear plastic rectangular top with a small hole on the top center (it should accommodate all 32 mousetraps, closely spaced, and have a height of about 30 cm so that the balls have some room to move)

Procedure: Set each of the mousetraps and place them close together on the board. Very carefully put one rubber ball on each side of the flip wire so that when the mousetrap trips, both balls will be thrown into the air. When all 32 mousetraps are set and loaded with balls, carefully place the plastic cover on top of them. When everything is ready, drop one of the remaining rubber balls through the hole in the plastic top. The ball may bounce once or twice, but it will probably trip a mousetrap sooner or later. When it does, the whole collection of mousetraps will explode into action. Discuss how this result resembles an explosive chain reaction in fissionable nuclei. When the Pandemonium is over, you might note that one or two mousetraps remain untripped. That would be consistent with a nuclear explosion, where some of the nuclei survive despite the violent activity around them.

Explanation: The average mousetrap "induced fission" yields three rubber balls (the original ball is still available). With such a rapid increase in the number of rubber balls bouncing in the box, the explosive chain reaction proceeds quickly.

Section 18.2 Nuclear Reactors

373. Radiation and Shielding

Description: You hold a Geiger counter near various radioactive sources and listen to their decays. When you insert certain materials between the sources and the Geiger counter, the counts diminish, indicating that the particles released by the decays are being blocked by the materials.

Purpose: To show that certain materials block the fragments of radioactive decays and can thus be used to control radiation and induced nuclear reactions.

Supplies:

- 1 or more radioactive sources (appropriate licensing, training, and safety precautions must be followed)
- 1 Geiger counter
- shielding materials, ranging from cardboard for beta decays to lead sheets for more energetic particles

Procedure: Use the Geiger counter to monitor the decays of the various radioactive sources. Then insert the shielding materials between the sources and the Geiger counter to show that the decay fragments can be block (absorbed or reflected) by these materials.

Explanation: The electrons from beta decays are easy to block because the low-mass electrons are easily deflected. But more massive alpha particles must encounter the nuclei of massive atoms such as lead to deflect them from their paths. Gamma rays are also stopped only by large atoms because they interact most strongly with the tightly bound inner electrons of those giant atoms.

Section 19.1 Medical Imaging and Radiation

I haven't developed any demonstrations for this section yet and continue to rely on show-and-tell materials (X-ray images, CAT scans, MRI images, etc.).