Complete Demonstration List

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1A: Measurements

1A10. Basic Units

Basic SI Units (1A10.10) -- a standard kilogram, a meter stick, and a stopwatch calibrated in seconds to demonstrate SI units of mass, length, and time.

Meter/Yard Stick (1A10.30) -- one side is marked off in millimeters and centimeters, the other in inches and feet.
Painted Meter Stick (1A10.30) -- painted with broad centimeter and decimeter marks for large class viewing.

Blank Meter Stick -- a meter stick painted white without divisions.

Stopwatch (1A10.40) -- large electric stopwatch reads down to 1/100th of a second.

Dubious Clocks (1A10.40) -- two large "clocks" without numbers mounted on the same vertical board. The clocks coincide at zero on each revolution, but differ in their readings elsewhere around the circle. The difference is subtle enough to encourage doubt as to which is "right." Shows that timing devices can be useful for some measurements but worthless for others.

One Liter Cube (1A10.50) -- a cube 10 centimeters on a side, disassembles into deciliter, centiliter, and milliliter subsections.

Liquid Measure -- various size glass beakers filled with colored water.

Spring Scales -- large faced dials with maximum readings of 20N, 40N, 100N, 5Kg, 10lbs, and 30lbs. Smaller scales with maximum readings from 250 to 2000 grams.

Pan Balance -- accurate to 0.1 gram.

1A20. Error and Accuracy

Gaussian Distribution (1A20.10) -- hundreds of tiny balls roll down through a gap and strike an array of pins below, bouncing between them and eventually landing in one of a number of slots below. The center slot will contain the greatest number of balls, and the number of balls in the outer slots will approximately follow a Gaussian distribution. The device sits on the overhead projector for class viewing.

Vernier Caliper (1A20.41) -- both a commercial caliper and a large-scale demo model are available.

Micrometer (1A20.41) -- show and tell.

1A30. Coordinate Systems

Chalkboard Globe (1A30.40) -- large globe surfaced with a black material that can be written on with chalk. Can be used to draw and discuss polar coordinates.

Acrylic Globe -- clear plastic globe has lines of latitude and longitude drawn on it for discussion of polar coordinate systems.

1A40. Vectors

Also see Force Board (1J30.50) listed in Section 1J30: Resolution of Forces.

Vector in Coordinate Frame (1A40.10) -- a three-dimensional stick-and-ball coordinate frame has a vector arrow emerging from the origin; the vector can be adjusted to any angle within the frame.

Folding Ruler (1A40.20) -- a folding carpenter's ruler.

Vector Components (1A40.13) -- a transparent grid with colored transparent arrows pivoting at the origin is used with the overhead projector to demonstrate the change in vector components with changes in vector angle or magnitude. Both angles with respect to
the x-axis and the corresponding x,y position of the vector tip may be read directly from the grid. Different length vectors are available.

**Sum Vector (1A40.31)** -- a pair of acrylic “vectors” make up two sides of a parallelogram, with a tape measure “vector” extending diagonally across the parallelogram to represent the sum of the vectors. Change the angle between the vectors and the length of the sum vector changes in accordance with the parallelogram rule.

**1A50. Math Topics**

**Radian Disc (1A50.10)** -- large disc marked off in radians, with a flexible strip of length r to show the derivation of the unit.

**1A60. Scaling**

"Powers of Ten" (1968) (1A60.10) -- A ten minute video which uses the notion of powers of ten to compare the relative sizes of objects in the universe, from clusters of galaxies to individual protons.

For a very neat java display see The Scale of the Universe 2.

**Scaling Bridge (1A60.30)** -- Two “bridges” made of thin sheet metal are exact duplicates of one another except that the larger is twice the size in every dimension. Two cylinders, in the same 1:2 proportions are placed on their corresponding bridges, which bend under the weight. Even though all dimensions are simply scaled up in a 1:2 ratio, the larger bridge bends more than twice as far as the smaller bridge, showing the effects of scaling on the relative strength of structures.

**Scaling Cubes (1A60.40)** -- Twenty-seven small wood cubes are stacked together to form a larger cube. The outside surface area of the large composite cube has been painted black, but the other faces of the small cubes are unpainted. Pull the composite cube apart and even though it is plain that the mass stays constant, the surface area is seen to be greatly increased - in addition to the black faces which are still visible, the unpainted faces of the smaller cubes have been added to the total surface area.

**Hoberman Sphere** -- plastic lattice “sphere” expands easily to three times its original diameter, 27 times its original volume. Can be repeatedly expanded and compressed with a simple pull or push of the hand.

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**1C: Motion In One Dimension**

**1C10. Velocity**

**Glider on Air Track (Constant Velocity) (1C10.25)** -- glider moves on a frictionless air track at constant velocity (except for the bounce at the end).

**Puck on Air Table** -- puck slides across a frictionless air table at constant velocity (except for bounces).

**1C20. Uniform Acceleration**

**Guinea and Feather (1C20.10)** -- two plastic tubes contain paper and an aluminum disc. Times of fall for the discs are compared when the tubes are at atmospheric pressure and when they are evacuated. A smaller glass model is also available. NOTE: We have a new 8 foot tall apparatus that requires prior training and practice before use.

**Different Mass Balls in Free Fall (Galileo’s Experiment) (1C20.15)** -- drop two balls of different mass side-by-side and they will strike the ground at almost the same time.
Glider on Inclined Air Track (Constant Acceleration) (1C20.30) -- uses an air track which is raised on one end to various heights, and gliders of different masses. If two (or more) gliders are released with one slightly behind the other they will accelerate at the same rate regardless of mass and will maintain their relative positions.

Incline with Flashing Lights (1C20.41) -- a large metal ball is electrically released and rolls down an inclined straight track with lights and marks at spacings of 0,1,4,9,16,25, and 36 units (1 unit = 8cm). The lights flash simultaneously once per second. Due to the increasing velocity of the ball it will travel farther and farther between flashes and will be directly atop a light at each flash. After the ball has been rolled, a set of magnetic tape strips may be pulled off the track and moved to a large magnetic graph board to make graphs of position, velocity, and acceleration vs. time for the ball.

1C30. Measuring g
Timed Free Fall (1C30.10) -- an electromagnet drops a ball from fixed heights of 1 and 2 meters. A clock starts upon release and stops when the ball strikes a cup at the bottom. Time of fall is 0.45 sec. for 1 meter and 0.64 sec. for 2 meters. Values of "g" can be found for each case and compared.

Reaction Time (1C30.55) -- hold a meter stick between a student's fingers and drop the meter stick. The reaction time of the student is found from the distance which the meter stick falls before the student can catch it.

Water Dropper for Freefall -- a beaker with a dropper spout releases single drops which fall about two meters into a bucket. Drop rate is adjusted until a new drop is just beginning to fall as the last one strikes the bucket - the time between drops is then equal to the time of fall. By timing ten drops and dividing the total time by ten an accurate measurement of the time of fall can be obtained, and the value of "g" can be derived.

1D: Motion In Two Dimensions
1D10. Displacement in Two Dimensions
Cycloid Generator (1D10.20) -- a large cylinder with lights at different distances from the center rolls along the lecture desk. With the room lights off, the path of each light is seen to be a cycloid.

1D15. Velocity, Position, and Acceleration
Sliding Weights on Right Triangle (1D15.41) -- a vertical board supports a taut-wire right triangle with the hypotenuse in the vertical plane. Each wire side has a brass ball sliding on it. When the hypotenuse is vertical, a ball released from the top of the hypotenuse falls a distance d with an acceleration of g. A ball released from the top of the upper side wire travels a distance d \cos \theta with an acceleration of g \cos \theta, where \theta equals the angle of tilt of the side wire from the vertical. Thus if both balls are released simultaneously, both strike the bottom of their respective sides simultaneously. The same holds for the hypotenuse and bottom side wire (with sin \theta replacing cos \theta).

1D40. Motion of the Center of Mass
Air Table Center of Mass (1D40.22) -- a rectangular acrylic plate has three fluorescent dots. One is in the center, and two differently-colored dots are off to either side. Spin the plate across the air table and the center dot will move in a straight line while the other dots circle around it. Add a weight to either end and the center of mass moves to the dot closest to the weight, so the plate will now spin around that dot as it floats across the table.
Pendulum Glider (1D40.50) -- a metal-armed pendulum with a heavy bob is mounted atop an air track glider so that the center of mass of the glider/pendulum system is located partway along the pendulum arm; that spot is marked with a fluorescent disc. When the glider/pendulum is set oscillating on the track, both the glider and pendulum bob swing back and forth, but the center of mass as marked by the disc stays still (or moves smoothly down the track if the glider is given a push). Since the eye is easily confused by the motion of the glider, the room lights are turned off and the motion of the fluorescent disc is viewed under UV.

Inchworm (1D40.55) -- two gliders fastened together with a long strip of spring steel are set on the air track. Give one glider a push and it will move until it reaches the end of the steel strip, when it will exert a force on the second glider and set it into motion. The reaction force exerted by the second glider will bring the first to a halt. Then the second glider strikes the first and the cycle begins again; the two gliders “inchworm” down the track.

1D50. Central Forces

Ball on String (1D50.20) -- a ball on string may be swung around to show the basics of circular motion. Run the string through a handheld tube, start the ball spinning with all the string out, and then pull the string through the tube to decrease the radius of the ball's rotation - the ball will gain angular velocity to conserve angular momentum. Weights may be supported on the end of the string to show the centrifugal force.

Conical Pendulum (1D50.25) -- string and weight pendulum swung in a circle.

Roundup (Tilt-a-Whirl) (1D50.30) -- a horizontal disc rotating at about 2 rev/s has a small section of vertical “wall” at one point on its periphery. Because of centrifugal force, a small object placed on the wall will cling there rather than falling down.

Whirling Bucket of Water (1D50.40) -- a bucket containing a few inches of water is swung in a vertical circle without spilling the water. Critical rotational frequency can be approached from the high end if you don't mind taking a chance. For a drier version, try the same effect with the Ball on String, above.

Greek Waiter’s Tray -- a small circular plastic plate hangs from three strings tied symmetrically to its edge. The three strings are tied together at the top so that the plate hangs horizontally beneath them. A small glass of water is placed at the center of the plate. The plate can now be swung around in any direction, and the surface of the water in the glass will always stay parallel to the plate. The plate can also be swung overhead without spilling a drop. Waiters in Greece use similar trays to ferry drinks to tables and are able to turn tight corners without spilling.

Coin on Coat Hanger (1D50.45) -- a wire coat hanger is bent so that the loop is elongated and narrow. The hanger is suspended from a finger, and a coin is balanced on the end of the hook. When the hanger is twirled in a circle centrifugal force holds the coin against the tip and keeps it in place. Not as difficult as it sounds, but practice first.

Bicycle Wheel -- a bicycle wheel with handles; can be spun up with a string wrapped around the hub.

Bicycle Wheel with Arrows -- a bicycle wheel with cardboard velocity and acceleration vectors for one point on the perimeter. An angular velocity/momentum vector is also available for placement along the axis of spin.

Arrow Disk -- a wooden disc with an arrow showing one direction of rotation and an arrow along the axis showing the direction of the angular momentum vector for that spin direction.

Centripetal Acceleration Vector -- a set of magnetic vector arrows that can be used to show the center-pointing nature of the
acceleration vector for uniform circular motion. A long radius vector extends from the center out to the circumference. A velocity vector is placed perpendicular to the tip of the R vector, then left in position as the R vector is shifted slightly to a different angular position. A new V vector is then placed perpendicular to the tip of the R vector at its new position. You now have V vectors for two different angular positions of the radius vector; slide one atop the other and place an acceleration vector between the tips of the two V vectors. The acceleration vector is seen to point to the center of the circle.

Rotating Chain (1D50.70) -- a loop of brass chain fits snugly on a spinning wooden disk driven by a high-speed motor. The chain is cautiously forced off the disk with a wooden stick and maintains its circular shape as it rolls across the lecture table; it will bounce off an obstacle as though it were a rigid hoop.

Rotating Disk with Erasers -- a hand rotator spins a horizontal disk with a smooth surface. Chalk board erasers with various surfaces are placed on the disk, which is rotated slowly until the erasers slide off; how long this takes depends on rotation speed, distance from the center, and eraser surface. A metal disc hooked to the center of the spinning disc with a rubber band shows qualitatively how the stretch due to centrifugal force increases with rotational velocity.

1D52. Deformation by Central Forces

Flattening Earth (1D52.10) -- a flexible hoop becomes oblate when rotated.

Water Paraboloid of Revolution (1D52.20) -- vertical glass cylinder in a motorized spinner contains colored water; upon rotation the surface of the water forms a paraboloid.

Water and Mercury in Globe (1D52.35) -- a glass globe containing colored water and mercury is spun in a motorized rotator. The mercury forms an equatorial band around the globe with the colored water above and below it.

Rotating Rubber Wheel (1D52.61) -- a spoked rubber wheel is rotated at high speed with a motor and expands outward slightly from centrifugal force. Its motion can be frozen with a variable strobe.

1D55. Centrifugal Escape

Circle with Gap on Overhead (1D55.10) -- A ball is rolled around the inside of an open circle on the overhead. Students predict where the ball will go when it reaches the opening.

Spinning Disk with Water (1D55.23) -- a lucite disk is spun by hand on the overhead and sprinkled with drops of colored water. The droplets flying off leave tangential tracks on the overhead screen.

1D60. Projectile Motion

Vertical Gun on Cart (1D60.10) -- a vertical spring cannon is mounted to a cart running on a horizontal track. The cannon shoots a small sphere vertically while the cart rolls along. Since the cart travels at (nearly) constant velocity, the ball goes up and falls back into the cannon’s top, staying directly above the cannon while in the air. Caution: Lift the cart when returning to the start position or you can bend the trigger.

Vertical Gun on Accelerated Car (1D60.16) -- same as above (1D60.10), but the car is accelerated either by tipping the track or using a mass on a string.

Drop/Shooter (1D60.20) -- a spring gun shoots a pool ball horizontally while simultaneously dropping another ball vertically. Both balls strike the floor simultaneously with a loud “click.” Have a student volunteer catch the projected ball after the first bounce, while
you catch the dropped ball (the second bounce is not simultaneous due to different elastic coefficients, etc).

**Monkey Gun (1D60.32)** -- a blowgun pipe points at a "monkey" (plastic bottle filled with shot) hanging from an electromagnet. A wooden plug is blown out of the pipe, displacing a strip of aluminum foil and opening the electromagnet circuit. Thus the monkey begins to fall the instant the "bullet" leaves the tube, but the bullet is falling also and will strike the monkey regardless of the curvature of its path. Blow hard and the monkey will be hit just after release; blow softly and the monkey will be hit closer to the floor.

**Range Gun (1D60.40)** -- a variable angle range gun shoots a small wooden ball at various angles to the horizontal and the distance traveled is noted. A large digital stopclock can be used to show times.

**Air Table Parabola (1D60.55)** -- large air table is tilted along one axis to produce a gravitational "down" with very low acceleration. Pucks skinned across the table go through all the normal motions of objects under gravitational acceleration (parabolic trajectories, etc), but much more slowly. A video camera and projector can be used to show the view from above.

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**1E: Relative Motion**

**1E10. Moving Reference Frames**

**Bulldozer on Plastic Sheet (1D or 2D) (1E10.10)** -- one battery powered bulldozer runs at a constant speed across the lecture table while a second runs across on a large sheet of plastic. Push or pull on the plastic sheet to show how velocities add vectorially to give a resultant velocity. This can be done in one dimension or two; or used for frames of reference discussions.

"Frames of Reference" (1960) (1E10.20) -- an excellent film (black & white, 1960, approx 28 minutes) showing the apparent motion of objects with respect to various inertial and non-inertial frames of reference. Available on laserdisc or as an MPEG file from archive.org.

**1E20. Rotating Reference Frames**

**Foucault Pendulum (1E20.10)** -- large pendulum hung from the atrium in the A-wing rotates its plane of swing about 11 degrees in one hour. An explanatory plaque is mounted on the wall opposite the pendulum.

**Foucault Pendulum Model (1E20.20)** -- overhead projection model of Foucault pendulum sits on a rotating plastic disc representing the Earth. Rotate the disc while the pendulum is swinging, and the plane of swing stays constant.

**1E30. Coriolis Effect**

**Coriolis Effect (1E30.28)** -- a ball rolls down a track onto a rotating disc and draws curved lines along the surface, even though the ball is moving in a straight line as seen from an inertial frame of reference.

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**1F: Newton's First Law**

**1F10. Measuring Inertia**

**Inertial Balance (1F10.11)** -- a platform is supported by two strips of spring steel, leaving it free to oscillate horizontally. Two blocks of similar appearance but different mass are placed on the platform; the lighter block oscillates at a higher frequency than the heavier block.

**Foam Rock (1F10.25)** -- one of those fake rubber rocks that can be used to show students their expectations about the inertia of
heavy objects. This lightweight “rock” can be propelled across the table with a small flick of the fingers, which would not be true of an actual (heavy) rock.

1F20. Inertia of Rest

**Inertia Ball (1F20.10)** -- a heavy mass is suspended between two loops of string. A steady pull on the bottom loop will break the upper string, while a quick jerk will break only the lower string (due to the high inertia of the mass).

**Ball and Card (1F20.34)** -- a marble sits on a small card, which is flicked away by a spring steel launcher. The card flies away, but the marble drops straight down into a catcher. Not very large, so it is not easily visible in large rooms.

**Table Setting (1F20.30)** -- plates and glasses with colored water on a paper table cloth. With one swift downward snap the table cloth is removed from under the tableware with no breakage. Easy to do, but practice first.

**Pipe on Paper (1F20.33)** -- large brass pipe rests vertically on a sheet of brown paper. The paper is snapped out from underneath the pipe - if done quickly enough, the pipe remains standing.

**Eggs and Pie Pan (1F20.35)** -- Three raw eggs perch atop cardboard cylinders sitting on a pizza pan. The pan sits on three water-filled beakers with a beaker directly under each egg. The pie pan is knocked out by a broom (check on technique!), but the eggs drop straight down into the beakers of water.

**Shifted Air Track (1F20.50)** -- a level air track is shifted side-to-side beneath a glider. With the air turned off, the glider follows the track. With the air turned on, the glider stays still as the track is shifted due to a lack of accelerating forces.

**Shingles** -- a thin wood shingle perched over the end of the table is struck a rapid blow with a stick. The overhanging end of the shingle breaks off because the inertia of the end on the table is high enough to prevent rapid motion.

1F30. Inertia of Motion

**Air Track and Glider (1F30.10)** -- a glider at rest or in motion on an air track will maintain that state due to lack of external forces (except for the bounce at the end of the track).

**Air Table (1F30.11)** -- similar to the constant velocity air track listed above, but with air jets blowing from beneath a plastic disc.

**Hovercraft** -- a toy hovercraft can be pushed along the table with the power off to show the effect of friction on its motion. It stops immediately when you stop pushing. Then turn it on and give it the same push and it will glide the length of the table since the friction has been removed.

1G: Newton's Second Law

1G10. Force, Mass, and Acceleration

**Uniform Acceleration with Air Track Glider and Weights (1G10.10)** -- gliders on a level air track are accelerated with string, pulley, and weights (large paper clips, approx. 3 grams apiece).

**Air Track Glider and Spring (1G10.16)** -- a light spring attached to a glider allows the application of a constant force (checked by spring extension against a marker stick) and resulting acceleration.
Accelerate a Heavy Cart with Spring or Spring Scale -- a small wheeled cart is pulled along the table with a spring or spring scale at various accelerations to show the relationship between force and acceleration. The spring will give a smoother indication of a constant force (the scale bounces) but cannot give quantitative results. Weights may be added to vary the cart's mass.

Acceleration Car (1G10.21) -- a cart is accelerated along a track by a constant force from weights on the end of a string/pulley arrangement. Weights are stored on the back of the rolling car and are moved to the weight hanger when a greater accelerating force is desired - in this way the total mass being accelerated (cart + weight hanger + weights) stays constant while the accelerating force is changed. Cart is timed for one meter of travel for different forces and the force/acceleration relation is obtained. Total system mass may also be changed.

Atwood's Machine (1G10.40) -- equal masses are attached to either end of a cord running over a pulley. Small riders can be added to one of the hanging masses to unbalance to weights and accelerate the system. A stopclock and a two meter stick can be used to show that acceleration is proportional to the unbalanced force.

Table Slingshot with Cart -- a rolling cart is fired along the table from a rubber tubing "slingshot" to show basic acceleration due to a force.

1G20. Accelerated Reference Frames

Candle in Dropped Jar (1G20.10) -- light candle, enclose in quart jar and place it on lecture table. Note the 10 second burning time Repeat lighting candle and closing jar lid, then drop the jar 2 meters into a box in a dark room. Note the suffocation of the flame en-route due to lack of convection currents in freefall.

Dropped Slinky (1B20.45) -- hold a slinky so some of it extends downward, then drop it to show the contraction.

Local Vertical on Tilted Air Track (1G20.70) -- an acrylic and water accelerometer is bolted to the top of an air track glider. The surface of the colored water is perpendicular to the gravitational gradient at all times. The glider is placed at the top of a tilted air track with the air turned off, and the water surface is seen to be horizontal, and thus angled with respect to the track. Turn the air blower on, and as the glider begins its descent the water surface quickly becomes parallel to the track and remains so for the rest of the trip.

Accelerometers (1G20.76) -- two types: a glass jar containing water and a lead fishing sinker on a string, and the same type of jar with a tethered bobber floating underwater. At rest, or at constant velocity, the supporting strings of both are vertical, but under acceleration they move away from the vertical (in opposite directions).

1G30. Complex Systems

1H: Newton's Third Law
Also see Section 1N20: Conservation of Linear Momentum.

1H10. Action and Reaction

Fan Car with Sail (1H10.20) -- small commercial cart with onboard fan and removable "sail." Cart will not move at all with the sail perpendicular to the fan breeze, but moves well with the sail removed.

1H11. Recoil
1J: Statics Of Rigid Bodies

1J10. Finding Center of Gravity

Irregular Objects (1J10.12) -- a piece of wood of irregular shape is hung on a metal pin from various points around its edge. Since the center of mass is directly beneath the point of support in each case, one can find it by using a plumb bob to draw vertical lines from two or more points of support - the lines intersect at the center of mass.

Meter Stick on Fingers (1J10.30) -- rest a meter stick on two widely-spaced fingers, then bring fingers together - they will always meet at the center regardless of initial position. The finger closest to the center at any time always supports the greater weight, so its frictional force is greater and it moves more slowly.

1J11. Exceeding Center of Gravity

Leaning Tower of Pisa (1J11.10) -- a model tower leans on a slanted base and is stable until a cap is added to the top; that shifts the center of mass outside the base and the tower topples.

Double Cone on Incline (1J11.50) -- two wood rails fastened together at a small angle form an incline; a cylinder will roll down the incline but a double cone will roll "up" the incline because the spreading of the rails allows it to lower its center of mass by moving in that direction.

1J20. Stable, Unstable, and Neutral Equilibrium

Stability (1J20.11) -- a cone, a cylinder, and a sphere are used to discuss stability and equilibria. The sphere has neutral stability. The cone and cylinder are either in neutral, stable or unstable equilibria depending on how they rest on a surface.

Clown on Tightrope (1J20.45) -- a toy clown with weighted rods as arms rides a unicycle down a length of thin string. The clown is stable because the center of mass is below the rope.

Chair on Pedestal (1J20.51) -- a wooden chair with weighted legs balances on a pointed rod; since the center of mass is below the point of support the chair is stable and may be knocked around without being upset.

1J30. Resolution of Forces

Load on Removable Incline (1J30.10) -- a cart rests against a block on an incline. The cart can be supported parallel to the incline by a weight strung over a pulley, which is equal to the component of gravitational force in that direction. The block can now be removed. Another weight is used to balance the component of gravity perpendicular to the incline; the incline can now also be removed, and the cart remains in place.

Clothesline (1J30.25) -- a long taut line can be significantly displaced at its center with a small sideways force. Both the sideways force and rope tension can be displayed on spring scales.

Boom and Weight (1J30.40) -- a long boom is hinged at the end of a table and supported by a cable. A large spring scale indicates the force on the cable. The apparatus can have the boom horizontal or the cable horizontal. Various weights can be hung from the end of the boom.

Force Board (1J30.50) -- three strings are tied together to a common point, with their other ends passing over three pulleys and supporting three weights. Two different combinations of weights and string angles are available that will leave the common point in
equilibrium under the three forces.

1J40. Static Torque

Torque Bar (1J40.10) -- a T-shaped wooden rod with screw eyes spaced along its length. A weight is hooked to an eye and lifted off the table by twisting your wrists. The farther from your wrists the weight is, the harder it gets. Good for student participation.

Balancing Meter Stick (1J40.20) -- a meter stick which pivots at the center is supplied with masses which may be attached to the stick at various points to achieve different equilibria. Masses and distances are all simple 1:2:3 ratios for ease of calculation in class.

Hinge Board (1J40.21) -- a long thin board with knobs at intervals is attached to the table by a hinge. Lift the board at different distances from the hinge with a spring scale, and observe the force required.

Torque Wheel (1J40.25) -- a wheel with coaxial pulleys of 5, 10, 15, and 20 cm to show static equilibrium of combinations of weights at various radii.

Bridge and Truck (1J40.40) -- a long wooden board with position markings is supported at each end by a kitchen scale. A 10 lb. toy truck is rolled to different positions along the bridge while the forces at each end of the bridge are indicated by the scales.

Roberval Balance (1J40.50) -- a simple balance is shown to be sensitive to the position of the weights, while the Roberval balance is not.

Crank and Axle -- wooden axle with a radius \( r \) is cranked by a handle with a length of \( 6r \). A rope is wrapped around the axle, and a weight hung on the rope can be balanced by a smaller weight on the crank.

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1K: Applications Of Newton's Laws

1K10. Dynamic Torque

Ladder Demo (1K10.20) -- a model ladder is positioned as though it were leaning against a wall, but is actually supported by three spring scales that provide the horizontal "wall" force and the horizontal and vertical "floor" forces needed to keep the ladder in equilibrium. A weight can be hung from various rungs of the ladder to vary the forces, which are read directly off the scales.

Large Spool with Wrapped Ribbon (1K10.30) -- a large spool has a ribbon wrapped around its axle several times so that it will come off the bottom of the axle's shank as the spool rolls along the table. The spool will either roll clockwise, counter-clockwise, or slide without rolling, depending on the angle at which the ribbon is pulled. Using an imaginary line drawn from the point of contact with the table to the spool's rotational center as a reference line, one can determine whether the spool will slide or roll and in what direction. If this line and the pull along the string (extended) intersect above the point of the spool's surface contact, the spool will rotate clockwise. If the intersection is below the surface, the spool will rotate counter-clockwise. If they intersect at the point of contact the wheel will slide along the table without rolling.

Loaded Disc Rolls Uphill (1K10.50) -- a wooden disc has a lead weight hidden near one edge, so its center of mass is away from the center of the disc. If it is placed on an incline with the lead weight on the uphill side of the incline, it will roll uphill slightly because that lowers its center of mass.

1K20. Friction
The Drill and Dowel (4B60.55) and Cork Popper (4B60.70) have been moved to Section 4: Thermodynamics.

Four Surface Incline (1K20.10) -- a board is covered with strips of four different materials (Teflon, sandpaper, bare wood, and rubber) that run down the length of the board. Identical brass blocks are placed at the end of each, and the end of the board near the blocks is slowly lifted up. As the tilt increases, the blocks will slide down the strip in order of the different coefficients of friction.

Area Dependence of Friction (Plank and Weights with Spring Scale) (1K20.20) -- pull a 2x12 plank along a level table at constant speed with a spring scale. Friction is approximately independent of which face the plank is sliding on (narrow or wide) and the plank's velocity. Add masses to increase frictional force.

Incline with Sliding Blocks (1K20.35) -- blocks with different surfaces are placed one after another on an inclined board, which is slowly raised until the block just begins to slide down. The tangent of the incline angle at that point equals the coefficient of static friction between the incline and the block.

Incline and Block with Tacky Wax -- qualitative demonstration of a large coefficient of friction. Similar to the incline described above.

1K30. Pressure

Bed of Nails (1K30.10) -- lie down on a bed of nails and let the demo staff smash a cinder block. NOTE: Please see us first before requesting this.

1L: Gravity

1L10. Universal Gravitational Constant

Cavendish Balance Film (1L10.10) -- a short time lapse movie and animation of the Cavendish balance experiment. Note: This is much shorter and easier to do than the full experiment.

Cavendish Balance Model (1L10.20) -- a large-scale open model of the Cavendish balance.

Cavendish Balance Experiment (1L10.30) -- standard Cavendish balance can measure the value of G to about 10% within a class period. Note: We need at least one week notice! See us beforehand for literature, etc.

1L20. Orbits

Gravitational Well Model (1L20.10) -- a sheet of fabric is stretched over a large horizontal loop and then distorted by placing a heavy ball in the center. Smaller balls can then be made to orbit around the potential well. Note: See also Marbles and Funnel (1Q40.70).

Conic Sections (1L20.40) -- A dissectible cone is cut several ways to give a circle, ellipse, parabola, and hyperbola.

Ellipse Drawing Board (1L20.51) -- an acrylic board with two nails and string on the overhead projector.

Orrery -- A motorized model of the solar system.

1M: Work And Energy
1M10. Work

**Pile Driver with Nails (1M10.20)** -- Five nails sit side-by-side with just their tips driven into a piece of wood. Masses slide down a rod and strike the heads of the nails one by one, driving them into the wood. The penetration depths of the nails are compared on the overhead projector as an indicator of the energy released in four different configurations (two different heights and two masses) versus the control nail. Note: See also Pile Driver with Foam Rubber (1N10.30).

1M20. Simple Machines

**Examples of Simple Machines (1M20.01)** -- block and tackle, crow bar, differential pulley, hammer, inclined plane, screw jack, scissors model, lever, and windlass.

**Pulleys and Mechanical Advantage (1M20.10)** -- pulleys rigged in different configurations to show mechanical advantage.

**Block and Tackle** -- lift 50 lbs. with 14 lbs. of force on a spring scale.

**4:1 Ratio Pulleys** -- two pulleys with a 4:1 diameter ratio are bound together on a common axis. A weight on the large pulley is balanced by four times as much weight on the smaller.

**Levers (1M20.40)** -- a meter stick pivots on a knife edge which may be clamped anywhere on the stick. A weight is hung on a moveable hanger on the stick, which is then used as a lever by pulling with a spring scale either: on the other side of the fulcrum (Class I lever); on the same side of the fulcrum (Class II); or between the weight and fulcrum (Class III). Mechanical advantage can be shown.

**Artificial Arm (1M20.45)** -- aluminum and plastic "arm" has a working elbow joint and "tendons" to show the lever principles involved in arm motion. Lift a weight, throw a ball, etc.

1M30. Non-Conservative Forces

1M40. Conservation of Energy

**Ball on Table** -- a ball can be rolled along the lecture table to discuss gravitational equipotential surfaces, or dropped over the edge to demonstrate a change in potential.

**Bowling Ball Pendulum (1M40.10)** -- a bowling ball hangs on a long cord from the ceiling; position head against wall, raise bowling ball to nose, and release with no initial velocity. Ball will swing back almost to your nose. WARNING: Don't move!!

**Galileo's Pendulum (1M40.15)** -- a pendulum swings in front of a white board with horizontal marks. The string strikes a stationary peg positioned halfway down the length of the pendulum, which stops the top half of the string and shortens the pendulum, but the bob always rises to the initial height.

**Loop the Loop (1M40.20)** -- an aluminum track is bent so that a straight downhill section leads into a large vertical circular loop which terminates with another uphill incline. A ball rolls down the incline and around the loop and up the other incline. This demonstration can be used for the discussion of energy conservation and of the minimum speed for safe passage of the ball at the top point of the circle.

**Energy Well Track (1M40.25)** -- a ball rolls down an incline and up a shorter hill on the other side. If the ball's beginning height is below a given mark, the ball will not have enough energy to roll up and over the hill, but will instead roll back and forth between the two inclines.
Triple Track (1M40.33) -- three inclined tracks each have the same downward slope, but different uphill angles on the other side. A ball rolled down each track in turn reaches the bottom then rolls up the other side to the same height in each case, despite the different slopes.

Ballistic Pendulum (1M40.41) -- A commercial ballistic pendulum apparatus that fires a ball bearing into a swinging arm catch mechanism. For show and tell only.

Maxwell's Yo-Yo (Maxwell's Wheel) (1M40.50) -- essentially a large yo-yo in a slightly different configuration. When released, it will unspool, bottom out, and then wind itself back up close to the release height.

X2 Energy Dependence of a Spring (1M40.63) -- compression spring at the bottom of a tilted air track fires a glider up the track. Spring compressions of 1, 2, and 3 units produce rise heights of 1, 4, and 9 units respectively (compression units are smaller than rise height units).

Spring Ping Pong Gun (1M40.64) -- small spring powered toy gun shoots ping-pong balls into the air after you provide the energy to compress the spring. You can also use a heavier wooden ball with the same input energy.

Spring Jumper (1M40.67) -- a small jumping toy which shows that a spring may contain enough energy to launch itself (and a lot more) into the air.

High Bounce Paradox (1M40.91) -- sort of a racquetball that's been cut in half. Secretly invert the curve of the ball with your hand. When dropped, the ball will pop back upon colliding with the floor, releasing the stored energy you put in and making it bounce higher than the release height. Ask students to explain what's wrong with this picture.

1M50. Mechanical Power
The Falling Weight Generator (5K40.85) and Army Surplus Generator (5K40.80) have been moved to Section 5: Electricity and Magnetism.

Prony Brake (1M50.10) -- student cranks on the handle for one minute against a constant frictional force. Knowing the drum diameter, the number of turns (and thus distance traveled), the force, and the time, horsepower can be calculated (about 0.25 hp max).

1N: Linear Momentum And Collisions
1N10. Impulse and Thrust
Egg in a Sheet (1N10.20) -- a raw egg is thrown into a loosely-hanging sheet and decelerates without breaking. The same egg may then be broken by dropping it into a beaker. Impulse is actually greater with the sheet, but the beaker produces a greater force over a shorter time and cracks the egg.

Musket and Wax Bullet -- an old muzzle loader is used to fire a 4 gram wax bullet into a thin board, splitting the board. The high velocity of the bullet gives it a lot of momentum and kinetic energy despite its low mass.

Pile Driver with Foam (1N10.30) -- a pile driver drops a mass onto a plastic strip and cracks it, but not if a piece of foam is placed on the board. Same impulse, different force and time. Note: See also Pile Driver with Nails (1M10.20).
1N20. Conservation of Linear Momentum

**Reaction Carts** -- two wheeled carts, one with a spring-loaded plunger, are tied together with a string. The string is burned, and the two carts are pushed apart by the spring and roll away with equal and opposite momentum (see below). A large weight can be added to one cart to increase mass.

**See-Saw Center of Mass (1N20.10)** -- the Reaction Carts described above are balanced on a long see-saw board so that their center of mass is directly above the fulcrum. The board is horizontal and stable. When the string between the carts is burned, they spring apart with equal and opposite momenta, so the center of mass remains above the fulcrum and the board remains balanced (until one cart strikes the end of the board). Most dramatic with different mass carts.

**Radio Control Car on Rolling Board (Dog on Boat) (1N20.15)** -- a radio-controlled car sits on top of a short board that is mounted on wheels. Moving the car forward moves the board backward, and vice-versa. There are some external forces from the board's wheels, so it's not perfect, but it shows the effect well.

**Reaction Gliders on Air Track (1N20.20)** -- two gliders which spring apart with equal and opposite momenta when the string between them is burned. Mass ratio can be 1:1, 2:1, or 3:1.

1N21. Mass and Momentum Transfer

1N22. Rockets

**Rocket Wagon with Fire Extinguisher (1N22.10)** -- the exhaust from a CO2 fire extinguisher is vented out a tube at the back of a red wagon. Instructor sits on the wagon, fires the extinguisher, and accelerates across the room. "And all this science, I don't understand / It's just my job, five days a week / A rocket man, a rocket man" - Elton John. Note: Please come early for the pre-flight safety lecture.

**Water Rocket (1N22.20)** -- plastic water rocket uses pressurized air as a driving force. The amount of lift varies greatly with the selection of the exhaust: air exhaust will barely move the rocket (low mass transfer), but water exhaust can easily send the rocket to the ceiling.

**CO2 Rotator (1N22.33)** -- a CO2 cartridge is inserted in a cylinder at the end of a rotation arm. When the end of the cartridge is punctured, the escaping CO2 spins the arm in a circle.

1N30. Collisions in One Dimension

**Eleven Pool Balls (1N30.10)** -- eleven pool balls are suspended bifilarly in a straight line. One or more balls can be separated together and released to collide with the remaining balls. The same number of balls fly off other end.

**Collision Balls (Various Masses) (1N30.20)** -- two balls are suspended side by side on bifilaments so that one may be swung out and released to strike the other. Available in mass ratios of 1:1, 1:3, and 1:80. Velcro may be used on the 1:1 balls to produce inelastic collisions.

**Click-Clack Balls** -- two plastic balls are mounted on swing arms that move around a common axis, which has a handle. Hold the handle and move it in a small circle - each ball will swing around in a circle in turn, striking the other ball. The moving ball stops and the other takes off in a recurring cycle.

**Elastic and Inelastic Collisions on the Air Track (1N30.30)** -- air track gliders are collided and transfer of momentum discussed. Gliders may be equal or unequal masses. Elastic collisions are achieved with spring or magnet bumpers, inelastic with putty.
Compression Spring with Air Glider -- an air track glider is sent sailing into a compression spring at one end of the track. The ensuing exchange of energies is rather quick but can be followed.

Double Ball Drop (1N30.60) -- a tennis ball and basketball are dropped with one on top of the other.

Air Track High Bounce (1N30.65) -- similar to dropping a light ball atop a heavy ball for a high bounce (see previous demo), but much easier to perform. A light glider rests atop a heavy glider on a tilted track, partway up the track. Release them together, and after striking the bottom the light glider will bounce up to three or four times the original release height.

Astro-Blaster -- a set of five rubber balls of diminishing size are threaded on a common rod through holes in their middles. The balls are free to slide on the rod, but only the top (smallest) ball is free to come off the rod. If the stack of balls is dropped on the floor, the ratio of the ball masses is such that most of the momentum and energy of the four lower balls is transferred into the top ball during the collision with the floor. The top ball flies off the stick to a much greater height than the drop height.

1N40. Collisions in Two Dimensions

Collisions on an Air Table (1N40.20) -- two dimensional collisions between pucks having equal or unequal masses, elastic collisions using magnetic pucks, inelastic collisions using Velcro-edged pucks. A video camera and projector can be used to show the view from above.

Colliding Coins -- using overhead projector. Flick one dime to slide and strike a second dime obliquely, and note approximate perpendicularity of subsequent paths. Note: The air table works much better.

1Q: Rotational Dynamics

1Q10. Moment of Inertia

Moment of Inertia Rods (1Q10.10) -- two long rods have the same but have different mass distributions (either concentrated at the center or at the two ends). The instructor spins the rod with the mass at the center, while a student spins the rods with the mass at the ends.

Rolling Bodies (Discs, Hoops, and Sphere on Incline) (1Q10.31) -- two equal mass and size cylinders with different mass distributions are rolled down an incline simultaneously and the difference in translational velocity is noted. Also a hoop and disc of equal mass, and sphere and cylinder of equal radius and similar mass.

Soup Cans on Incline (1Q10.50) -- two soup cans, one filled with a solid consistency soup and the other with a broth, are raced down an incline. The solid soup is forced to roll with the can so its translational velocity is lower - the broth wins.

1Q20. Rotational Energy

Angular Acceleration Machine (1Q20.10) -- a flat bar free to rotate about its center is accelerated by the torque provided by a string-wrapped disc and hanging weight. Two weights attached to the bar may be removed, placed close to the center of the bar or at the ends of the bar for three different moments of inertia. Accelerating weights may be varied, and can be hung on either a 5 cm or 10 cm disc to change torque - observe varying angular accelerations.

Spool Wheel on Incline (1Q20.30) -- a spool wheel with a small hub and large outer discs rolls down an incline on the hub. When it nears the bottom of the incline the large outer discs touch down and the wheel rolls on the discs instead of the hub. Since points on
the edge of the outer discs have a much greater translational velocity than points on the hub, the wheel as a whole gains translational velocity. To compensate, it loses rotational velocity because total energy is conserved.

**Bicycle Wheel on Incline with Lockable Hub (1Q20.35)** -- a bicycle wheel with a center hub that can be left free to rotate or locked to the wheel rolls down an incline on the hub. When the hub is locked, a large amount of energy must go into the angular momentum of the wheel as it rolls, so the translational velocity is much lower than with the hub free.

**Falling Chimney / Hinged Stick and Ball / Faster Than g (1Q20.50)** -- Two boards are fixed together by a hinge at one end so as to allow them to fold together. One board is laid flat on the table and the other board is propped up by a stick, with a ball balanced on a golf tee attached to the end of the board. When the stick is pulled away and the board is released to free fall, it is torqued about the hinge and rotates as it falls. Thus, the rotation force causes the end below the ball to accelerate faster than the ball and the ball falls into the cup.

**1Q30. Transfer of Angular Momentum**

**Satelite De-Rotator (1Q30.25)** -- a large disc has two smaller discs held tight to its outer edge by retractable lever arms. The smaller discs are also attached by long cables to a freely rotating hub on the spin axis of the large disc. The weights of the discs and the length of the cables has been adjusted so that the moment of inertia of the small discs rotating on the long cables is equal to that of the large disc with small discs attached. The large disc is spun up with the small discs attached, then a lever is pulled that allows the small discs to fly free on their cables. As they fly free, they are forced by constraints on the cables to achieve the same angular velocity as the large disc; and since their moments of inertia are equal, the small discs take up all the angular momentum of the larger disc, stopping it completely.

**1Q40. Conservation of Angular Momentum**

**Rotating Stool and Weights (1Q40.10)** -- sit on a rotating stool holding a dumbbell in each hand; pulling the dumbbells inward will increase your angular velocity, letting them out will decrease it.

**Rotating Stool and Long Bar (1Q40.15)** -- same rotating stool as above; a long hand-held metal rod twisted in one direction will twist the instructor the opposite way. Weights can be added to the bar for a greater effect.

**Watt's Governor (1Q40.23)** -- a small model of Watt's governor is spun on a hand cranked rotator.

**Rotating Stool and Bicycle Wheel (1Q40.30)** -- sit on a rotation stool holding a spinning bicycle wheel in your hands. Tip the wheel and the stool will rotate to conserve the angular momentum of the system.

**Train on Circular Track (1Q40.40)** -- a windup train sits on a circular track which is free to rotate. Start the train and the track will rotate in the direction opposite the train's travel, then both will stop when the train runs down (there is occasionally a little spin left over due to friction in the bearings). Note: This demo is not currently operational.

**Wheel and Brake (1Q40.45)** -- a spinning bicycle wheel is contained in a framework that is free to rotate in the same direction as the wheel. A braking device mounted to the framework is held open by a string; burn the string and the brake clamps down on the wheel, transferring angular momentum from the wheel to the frame and making both rotate together at a lower velocity.

**Marbles and Funnel (1Q40.70)** -- marbles are rolled down a short inclined tube which enters tangentially into a large glass funnel mounted with axis vertical. The marbles spiral downward and rapidly increase their rate of rotation, due to conservation of angular momentum. Finally they reach an equilibrium level where they revolve in a horizontal plane, gradually dropping lower as friction slows
them down.

Air Rotator with Deflectors (1Q40.82) -- a rotating bar has tangential air jets at the ends of the arms and attached deflectors which may be swung into the air streams. If the deflectors are out of the air streams the device will rotate like a garden sprinkler. If the deflectors are in, and air velocity is low, no rotation is observed because the reaction force of the air leaving the jet is balanced by the force of the air striking the deflectors. If the air velocity is increased beyond a certain level, however, many of the air molecules striking the deflectors will bounce backwards instead of flowing smoothly off to the sides. This increases the momentum transfer to the deflectors and the device will rotate in the same direction as the air streams.

Please also see Heron's Engine (or Hero's Engine) (4F30.01) in Section 4: Thermodynamics.

1Q50. Gyros

Handheld Gyroscope -- a gimbal-mounted gyro will maintain its axis of rotation when it is moved around the room.

Gyro with Adjustable Weight (1Q50.20) -- gyro with a movable weight on its axis for precession.

Bicycle Wheel on Gimbals (1Q50.22) -- weighted bicycle wheel in two-way gimbals.

Bicycle Wheel Precession (1Q50.23) -- a bicycle wheel with handles which may be spun up with a string wrapped around the hub. It can then be suspended by a rope tied to one handle to show precession. Will also precess when stood on its end like a top.

Double Bicycle Wheel (1Q50.25) -- two bicycle wheels on a common axis. If they are rotating in the same direction they will precess, but if they are rotating in opposite directions their net angular momentum is zero and they simply fall over.

Motorized Gyroscope (1Q50.30) -- a motorized gyroscope with a heavy flywheel on gimbal bearings. Various weights may be hung from the end of the bearing arm to produce precession. The flywheel takes over a minute to come up to full speed, and if a weight is hung on the arm when the spin is still slow, precession will initially be rapid but will slow down as the flywheel speeds up.

Precession Rate and Angular Velocity -- use the motorized gyro and watch the rate of precession change as it slowly comes up to speed.

Nutation -- a variac is used to run the motorized gyro at a low speed (at around 30 Volts AC instead of 110) and various masses will cause noticeable nutation.

Gyroscopic Ship Stabilizer (1Q50.72) -- a motorized gyro is free to pivot when a ship model is rocked.

1Q60. Rotational Stability

Euler's Disk (Spinning Coin) (1Q60.25) -- an aluminum disk that acts as a non-harmonic oscillator. When spun on its edge, the disk exhibits periodic circular motion. As friction removes energy from the disk and it winds down, the frequency of oscillation increases with the decreasing amplitude. A glass sound board beneath the disk amplifies the sound of its motion so the class can hear the frequency of oscillation. This type of motion was first analyzed by Euler, hence the name.

Tippy Top (1Q60.30) -- a top that flips upside down.

Spinning Football (1Q60.35) -- spin a football on its side and it raises up on end. Note: Please practice first.
1R: Properties Of Matter

1R10. Hooke's Law

Hooke's Law (Mass on Spring) (1R10.10) -- weights are hung from a large spring mounted above the blackboard and the amount of stretch is marked on the board for a demonstration of Hooke's Law.

1R20. Tensile and Compressive Stress

Low Elastic Limit Spring (1R20.11) -- a copper coil stretched even a short distance won't return to its original length.

High Elastic Limit Spring -- a plastic slinky spring may be stretched a long way and will still return to its original length.

Young's Modulus (1R20.15) -- a long wire mounted in a vertical stand has a weight hanger on one end and a small platform partway down on which a pivoting mirror sits. Add weights to the weight hanger and the wire stretches, pivoting the mirror and deflecting a laser beam. The spot on the wall moves farther with each added weight.

Bending Beams (1R20.20) -- three flat bars of different lengths and thicknesses are mounted on the lecture desk so that they project over the edge. Weights are placed on the ends of the rods to compare the amount of bending in each case.

Elasticity of Air -- a long cardboard mailing tube has a cap fitted over one end. Pull up and release the cap suddenly and it will spring back.

1R30. Shear Stress

Stress and Strain (1R30.20) -- a rectangular block of foam rubber stretches to show various stresses and strains.

Torsion Rod (1R30.40) -- a limber metal rod is twisted by torque from hanging weights while a large scale shows the amount of twist. Remove the weights and the scale returns to zero.

1R40. Coefficient of Restitution

Coefficient of Restitution (1R40.10) -- spheres of different materials fall down a glass tube and bounce off a hard surface at the bottom. The square root of the ratio of rebound height to height of fall is the coefficient of restitution. Varies from around 0.95 (glass) to 0.00 (lead).

Happy and Sad Balls (1R40.30) -- two balls that look similar but have different elasticities are dropped on a table. One bounces, one doesn't.

1R50. Crystal Structure

Bravais Lattice Models -- unit cells of the 14 Bravais lattices.

Crystal Models (1R50.20) -- models of various crystals.

Lattice Energy Level Model -- soft foam "egg carton" material simulates energy levels in a regular atomic lattice.
2A: Surface Tension

2A10. Force of Surface Tension

Soap Film Pullup (2A10.10) -- a square wire frame with the bottom side free to slide is dipped in soap solution and pulled out; the surface tension of the soap film pulls the sliding wire up.

Floating Needle (2A10.20) -- Petri dish with a small amount of water is placed on overhead projector. A needle is gently lowered onto the water's surface with the help of a wire support, and the needle floats.

Surface Tension Disc (2A10.33) -- lift a floating disc off a water surface with a spring scale to show the force needed to overcome surface tension.

Camphor -- a piece of camphor placed in the water reduces the surface tension in the above demos.

Soap Bubbles -- small or large.

2A15. Minimal Surface

Minimum Energy Thread (Ring and Thread) (2A15.10) -- a loop of thread is tied across a rigid square frame, which is dipped in a soap solution. The thread will float limply in the soap film until the film inside the loop is punctured; the loop will then spring into a circle due to the surface tension of the soap film outside it, forming a surface of minimum energy.

Soap Film Minimal Surfaces (2A15.20) -- wire frames of various sizes and shapes are dipped into a soap solution, and form surfaces of minimum energy.

Soap Film Saddle -- a piece of flexible plastic with a circular hole cut out of the center is dipped into soap solution and emerges with a soap film filling the hole. Bend the plastic over, and the film distorts into a saddle shape to minimize surface area and energy.

2A20. Capillary Action

Capillary Tubes (2A20.10) -- glass tubes with different size bores all sit in a reservoir of colored water - the water rises to different heights in each tube, with an image of the tubes projected on a screen for easy visibility.

Capillary Action (2A20.20) -- a small capillary sits just above the surface of a container of colored water, which is raised by pushing a syringe. When the water touches the bottom of the tube it jumps up into the bore; an image of the tube is projected for easy visibility.

2A30. Surface Tension Propulsion

2B: Statics Of Fluids
2B20. Static Pressure

**Pressure vs. Depth (2B20.15)** -- an electronic pressure sensor is lowered into a tall column of water. As the sensor is lowered, the increasing pressure is displayed on a LED bar graph.

**Pressure vs. Depth in Water and Alcohol (2B20.16)** -- the electronic pressure sensor and LED bar graph display are used first in water and then in alcohol.

**Hydrostatic Paradox (2B20.34)** -- a truncated cone made of glass is open at both ends and fits against a flat glass plate. If the plate is held against the wide side of the cone and submerged in water, it will hold tight due to the pressure differential between the air inside and the water outside. With the plate against the small end of the cone, however, it will not stay put due to the smaller area of pressure differential.

**Pascal's Vases (2B20.42)** -- Tubes of various shapes rise from a common horizontal tube. When filled with water, the level is the same in each tube.

**Card on Inverted Glass (2B30.45)** -- Fill a glass with water, place a stiff card over opening and invert. Card remains in place due to atmospheric pressure below card.

**Hydraulic Press (2B20.60)** -- commercial hydraulic press with pressure indicator breaks boards and bends thick metal with the press of a finger.

**Compressibility of Water and Air (2B20.71)** -- A syringe filled with air is compressed when a large weight is placed on it, but a water filled syringe does not compress.

2B30. Atmospheric Pressure

**Crush a 55 Gallon Drum (2B30.20)** -- Boil water in a 55 gallon drum, seal, and then cool. This is by far, one of the most impressive demos that we have. Note: Our barrel supply is VERY limited so talk to us if you're interested in this demo.

**Crush a Can with a Vacuum Pump (2B30.25)** -- evacuate a one gallon metal can and it will collapse from the air pressure on the outside.

**Magdeburg Hemispheres (2B30.30)** -- two small hemispheres with handles are pressed together and evacuated; they cannot be separated by hand due to the unbalanced pressure on the outside.

**Suction Cup (2B30.36)** -- a large (4" diameter) suction cup of the type used to carry large panes of glass has a small hole in the top. If the suction cup is squeezed down onto a table and the hole covered with a finger, a student will not be able to pull the suction cup off the table as long as your finger covers the hole. Prove your superior strength as the student tries in vain to lift the suction cup, then remove your finger and the suction cup lifts right off.

**Stool and Rubber Sheet (2B30.50)** -- a square rubber sheet with an attached handle is set on top of a wooden stool or other heavy object. The weight of the sheet drives the air out from beneath it, and the air pressure on the outside holds the sheet and stool together. The stool can now be lifted by pulling up on the handle.

**Adhesion Plates (2B30.55)** -- two very flat glass plates will stick together without adhesives due to the unbalanced pressure on their outside surfaces.
Lift Weight with Vacuum -- an airtight cylinder fitted with a loaded piston is evacuated with a vacuum pump, raising the weight.

Vacuum Cannon (2B30.70) -- A long PVC pipe contains a ping-pong ball at one end. Both ends are sealed and the tube is then evacuated by a vacuum pump. When the seal is broken at the end with the ping-pong ball, atmospheric pressure accelerates the ping-pong ball and gives it enough kinetic energy to destroy empty aluminum cans. Rather than have a pressure reservoir that is over pressured, the emphasis of this demo is that normal atmospheric pressure can be used for impressive results.

2B35. Measuring Pressure

Mercury Barometer (2B35.10) -- a simple mercury barometer.

Barometer in Vacuum (2B35.15) -- a mercury barometer is totally enclosed in a glass tube. The tube is evacuated, and the mercury column height falls to zero.

Aneroid Barometer (2B35.40) -- has a glass back to show the mechanism.

2B40. Density and Buoyancy

Buoyant Force (2B40.14) -- two large scales show the weights of a container of water and of an aluminum cylinder. When the cylinder is lowered into the water, its weight as shown on the scale decreases; the weight reading of the water container simultaneously increases by the same amount.

Board and Weights Float (2B40.18) -- a board sinks equal amounts as equal weights are added.

Archimedes’ Principle (2B40.20) -- a large-face spring scale supports a plastic bottle and an aluminum cylinder on a string. The aluminum cylinder is lowered into a glass jar filled with colored water to the height of a spillover spout, so that any water displaced by the cylinder flows out into a beaker. The weight reduction of the cylinder is noted. Then the water that was displaced is poured into the plastic bottle tied to the scale - the weight reading increases to its original value, showing that the buoyant force is equal to the weight of water displaced. Can be used to find the density of the aluminum, and an irregular cylinder of mixed density (aluminum and lead) can be used to recreate Archimedes’ original experiment to determine the purity of a metal.

Archimedes’ Crown -- a "gold" crown can be weighed in air and in water to calculate the density of the metal and prove that it is not (alas!) made of gold.

Float a Battleship in a Bathtub (2B40.25) -- a large block of wood will float in a container that is only slightly larger with a small amount of water.

Boat and Weights (2B40.26) -- a toy boat floating in a large jar of water can be loaded down with weights and sinks lower in the water with each addition.

Helium Blimp -- a Goodyear-type blimp about one meter long can be adjusted for neutral buoyancy by adding weight to the gondola. Electric fans propel the blimp at the whim of the instructor and the hardwired remote control box. A big toy for big kids, but a lot of good physics too.

Cartesian Diver (2B40.30) -- large, easily visible Cartesian diver is controlled by pushing in a syringe attached to the tank. Increased pressure shrinks the air volume in the diver and plummets it to the bottom. Release the pressure and the diver returns to the top. A screw gizmo allows fine adjustment of pressure if desired, and the old-fashioned “push on the top” works as well.
Helium Balloon in Helium (2B40.43) -- a helium balloon is placed in a large upside-down glass jar, and it floats to the top. Helium is then squirted into the jar with a hose, and when the air has all been displaced the balloon sinks to the bottom. Pick the jar up and the balloon floats on the helium/air interface.

Helium Balloon in Liquid Nitrogen (2B40.44) -- a helium balloon is drenched with liquid nitrogen and shrinks to about half its original volume. Because the volume of air displaced by the balloon is now low, it will not fly. As it warms up and expands, the balloon takes off due to the increased buoyant force.

Weight of Air (2B40.45) -- an evacuated flask is hung on one arm of a scale, and the scale is brought to balance with sliding weights. Air is then admitted to the flask, and the extra weight of the air drives the balance down on that side. The actual weight of the air can be found by rebalancing the scale and subtracting the weight of the empty flask.

Water and Mercury in U-Tube (2B40.53) -- measure heights of liquid boundaries and use the data to calculate relative densities.

Density Ball (2B40.59) -- a metal sphere barely floats in cold water and sinks in hot water.

Hydrometer (2B40.60) -- two identical hydrometers are floated in two different liquids to demonstrate liquid density measurement, buoyancy.

Different Density Woods (2B40.61) -- float blocks of balsa, pine, and ironwood in water.

2B60. Siphons, Fountains, Pumps

Heron’s Fountain (2B60.10) -- A small “fountain” that shows it is possible to use air pressure to cause water to rise above its own level. Two plastic pop bottles are screwed together at their tops by a special adaptor that has two tubes passing through it, one going up into the upper bottle, the other going down into the lower bottle. Each tube also extends a short way into the other bottle, and each has small holes near the bottom. When the bottles are turned over, water flowing into the lower bottle raises the air pressure inside, the air then tries to flow up the upper tube into the upper bottle. But water is also flowing into the holes in the tube, and the flowing air pushes that water up the tube and out of the top, higher than the surface of the water in the upper bottle. Of course, only a small portion of the water is lifted in this way; the energy comes from the larger amount of water flowing downward.

Siphon (2B60.20) -- siphon water from one container to another.

2C: Dynamics Of Fluids

2C10. Flow Rate

Torricelli’s Tank (2C10.10) -- water fills a vertical glass tube with four outlet ports at different depths. Water shoots out the ports at a velocity that varies directly with depth.

Syringe and Water (2C10.26) -- a large syringe is used to show the change in velocity with changes in tube diameter. Fill syringe with water, then point into the air and press the plunger. Your thumb, and the water in the wide part of the syringe, are moving slowly, but the water emerging from the narrow tip has a high velocity.

2C20. Forces in Moving Fluids

Venturi Tubes (2C20.10) -- a horizontal metal pipe with a constriction in the center has four open-end manometers attached along its
length. Air flows at high speed through the pipe. Pressure decreases uniformly along the pipe, as shown by three of the manometers, but the manometer attached at the constriction shows a lower pressure than expected due to the increased air velocity (Bernoulli's Principle).

**Pitot Tube (2C20.25)** -- a pitot tube is connected to a water manometer and the air stream velocity is varied.

**Balls in Air Jet (2C20.30)** -- air blowing through a hand-held nozzle at high velocity supports large Styrofoam balls and holds them in place due to the greater pressure outside the air jet.

**Ball in a Funnel (2C20.35)** -- Air blowing out an upside down funnel will hold up a ping-pong ball.

**Bernoulli Hanging Plate (2C20.40)** -- a horizontal metal plate has a hole in the center out of which air flows downward at high velocity. A second plate pushed up against the first will cling to it due to the high velocity (low pressure) of the air flowing between them.

**Card and Spool (2C20.41)** -- A card with a small pin stuck through into the spool will be suspended when you blow into the spool.

**Suspended Parallel Cards (2C20.45)** -- air passing between two hanging cards pulls them together.

**Airplane Wing (2C20.50)** -- a cross-section of an airplane wing sits in an acrylic wind tunnel tube through which air is forced by a fan. Lift of the wing can be shown, and pressure readings can be taken at three points (top, front, and bottom of the airfoil) using a small open-end manometer.

**Curve Balls (2C20.60)** -- throw a curve ball using a styrofoam ball and a cardboard tube launcher. Dramatic curves are easy to throw, but practice helps.

**Flettner Rotor (2C20.80)** -- small wheeled cart has a motorized styrofoam cylinder mounted on top. When the cylinder rotates at high speed, air from an air track blower passing around the cylinder will make the cart move at right angles to the air stream.

**Tesla Turbine** -- demonstrates the boundary layer effect (adhesion between a moving fluid and a bounding surface). Compressed air is injected tangentially across a series of very smooth discs (hard drive platters) and drags across the surfaces. The platters can reach speeds of 10-15,000 rpm. This is related to Reynold's number, and laminar vs. turbulent flow (section 2C40).

### 2C30. Viscosity

**Bubbles in Oil (2C30.25)** -- three tubes containing oils with different viscosities each have an air bubble at the top of the tube. Turn over the rack holding the tubes, and the bubbles will drift up at three different terminal velocities.

**Viscous Drag (Terminal Velocity) (2C30.50)** -- small balls slightly more dense than water are dropped into a tall cylinder of water. Viscous drag slows the balls as they sink, giving them a low terminal velocity.

**Air Friction (2C30.65)** -- drop two identical pieces of paper simultaneously, with one flat and the other crumpled into a ball. The flat piece of paper has a higher drag and takes longer to reach the floor.

### 2C40. Turbulent and Streamline Flow

See also Section 4B20: Convection in 4 Thermodynamics.
Turbulence Sphere -- a glass sphere filled with rheoscopic fluid can be spun in a rotator to produce visible turbulent (and some not-so-turbulent) flow of the fluid.

2C50. Vorticies

Vortex Cannon (Smoke Rings) (2C50.15) -- use a large barrel to generate a smoke ring and blow out a candle with the vortex.

Tornado Tube (2C50.30) -- two liter pop bottles joined together at the necks by a small orifice and partially filled with water. Turn the pair over and give it a swirl and a tornado will form with air coming up through the center and water going down the periphery of the orifice.

2C60. Non-Newtonian Fluids

Density Balls in Beans (2C60.20) -- a ping pong ball will rise and a steel ball will sink in a large beaker of shaken beans.

3: Oscillations And Waves

3A: Oscillations

3A10. Pendula

See also Bowling Ball Pendulum (1M40.10).

Simple Pendula with Different Lengths and Masses (3A10.10) -- single bob on a string one meter long, or choose from the following for comparisons:

- Equal length with bobs of different mass (wood and lead)
- Equal length with different mass bobs of the same material
- Bobs of equal mass with pendulum lengths in a ratio of 1:4,

Weight on a Flexible Bar (Inverted Pendulum) (3A10.20) -- a vertical bar with a sliding weight is clamped at the bottom and free to oscillate at the top. The period of oscillation depends upon the position of the weight.

Metronome as a Pendulum (3A10.21) -- A metronome is used as an adjustable pendulum.

Torsion Pendulum (3A10.30) -- a heavy disc at the end of a limber vertical rod can be set into torsional oscillation. Mass can be added to the disc to show the effect on the period of oscillation.
Variable Angle (Variable $g$) Pendulum (3A10.40) -- A physical pendulum is mounted on a bearing so the angle of the plane of oscillation can be changed.

Conical Pendulum -- A ball on string suspended from a tall ring stand.

3A15. Physical Pendula

Physical Pendulum (3A15.20) -- Compare the period of a bar supported at the end with a simple pendulum that is $2/3$ the length of the bar.

Hoops and Arcs (3A15.40) -- a full circular hoop and portions of a hoop of the same diameter pivot from a hole at the center of the periphery of each. Though they vary greatly in size, each will swing on the pivot with the same frequency of oscillation.

Kater Pendulum (3A15.70) -- device used for a highly precise measurement of $g$. Analysis requires moments of inertia, for which we have no precise data.

3A20. Springs and Oscillators

Oscillating Mass on a Spring (3A20.10) -- a large mass is hung on a spring mounted in front of the blackboard, then pulled down and released to show simple harmonic motion.

Oscillating Glider on an Air Track (3A20.35) -- an air track glider of variable mass oscillates between two springs.

Water in U-tube (3A20.55) -- colored water oscillates between two legs of a glass U-tube. Motion can be frozen at any point by corking one leg of the tube.

Ball in Plastic Bowl (3A20.60) -- a rubber ball rolls in a large hemispherical plastic bowl.

See also Inertial Balance (1F10.11).

3A40. Simple Harmonic Motion

Circular vs. Simple Harmonic Motion (Spring) (3A40.10) -- the shadow of a pin moving uniformly around a circle in the vertical plane is superimposed over that of an oscillating spring and weight. The shadows of the pin and the weight are synchronized so that the shadows move in unison on the screen.

Circular vs. Simple Harmonic Motion (Pendulum) (3A40.20) -- the shadow of a pin moving uniformly around a circle in the horizontal plane is superimposed over that of a swinging pendulum. The shadows of the rotating pin and pendulum are synchronized so that the shadows move in unison on the screen.

Tuning Fork with Light (3A40.41) -- a large tuning fork with a low frequency has a small light bulb on one tine. The tuning fork is set into vertical oscillation and then moved horizontally in a dark room. The light bulb traces out a sine curve.

Lights on a Circle ($\Theta$ Device) -- lights on a large board are arranged in the shape of the Greek letter theta. Turn a crank slowly and pairs of bulbs light sequentially, one moving around the outer circle and the other moving back and forth across the horizontal crossbar; these two bulbs are aligned vertically to show the connection between circular motion and SHM.

Phase Shift (3A40.65) -- a vertical disc has two balls mounted at its edge which may be moved to different angular positions. As the
disc is rotated, the balls are shadow projected so that their circular motion appears as SHM. By moving the balls to different relative positions on the disc (in multiples of 45 degrees), their motion on the screen will be 90 degrees out of phase, 135 degrees out of phase, etc.

3A50. Damped Oscillators

**Water Damped Spring and Weight (3A50.10)** -- a weight on the end of a hand-held spring is set oscillating in a large jar of water and quickly damps out.

3A60. Driven Mechanical Resonance

**Tacoma Narrows Bridge Collapse (3A60.10)** -- A film showing the collapse of the original Tacoma Narrows Bridge due to resonance.

**Resonant Driven Pendula (3A60.31)** -- Three simple pendula of different lengths are hung from a horizontal bar with an attached driver pendulum. The driver pendulum is a stiff rod with an adjustable bob so that its frequency can be changed. The driver pendulum is set to the natural frequency of each pendulum in turn, and only that one pendulum oscillates.

**Bowling Ball Pendulum and Hammer (3A60.35)** -- a bowling ball hangs from the ceiling on a long cord. A rubber mallet is used to strike the ball and build up oscillations. If the striking frequency equals the natural frequency of the ball, the oscillations build up to large amplitudes, otherwise not.

**Driven Spring and Weight (3A60.43)** -- mass on spring is motor driven at an adjustable frequency; damping the motion in a cylinder of water shows a small shift in the resonant frequency of the oscillator.

**Driven Oscillator with Display (3A60.43)** -- a newer version of the above demo (Driven Spring and Weight). A spring with a weight on the bottom hangs from a driver made from an audio speaker. It is driven by a signal generator with a digital display, and exhibits a sharp resonance at approximately 0.9 Hz. The up-and-down motion of the driver is amplified by a simple lever mechanism for visibility so that the phase relationship of mass and driver can be studied below, at, and above the resonant frequency. A cylinder of water can be used to provide (a lot of) damping, or a piece of cardboard stuck to the bottom can be used for lighter damping.

**Reed Tachometer (3A60.50)** -- a set of metal reeds of descending natural frequencies is attached to a gyroscope. The gyroscope is slightly off-balance so that it vibrates as it spins, and as its rotational frequency passes through the frequencies of the reeds each reed vibrates in turn.

3A70. Coupled Oscillations

**Wilberforce Pendulum (3A70.10)** -- spring with weight which has a natural rotational frequency equal to its up-and-down frequency. Start the weight oscillating, and energy will transfer back and forth between the rotational and translational modes. Large bright dots on the weight improve visibility.

**Coupled Pendula (3A70.25)** -- Two identical massive bobs at the ends of two pendulum rods are coupled by a spring and set swinging. Alternately each one stops oscillating as its energy is transferred to the other, then begins swinging again as the energy is transferred back. Different springs change the amount of coupling and the time required for total energy transfer.

**Metronome Synchronization (Spontaneous Synchronization)** -- Five small metronomes on a lightweight plank are set to the same frequency and started oscillating out of phase. At first the plank sits on the table and the metronomes’ tick-tocks will be independent. The plank is then set on two empty soda cans (on their sides) to provide some light coupling between the metronomes. The
metronomes will phase lock with each other within a minute or two and the tick-tocks will all be in unison.

3A75. Normal Modes

2 or 3 Glider Air Track Resonance (3A75.10) -- either two or three gliders are hooked together with springs to form a coupled oscillator system. Different modes of oscillation may be set up easily by hand, or driven (more finicky) at the resonant frequencies of the modes by a push-pull driver of variable frequency.

Air Track Gliders with Spring Steel -- two gliders are attached with a long piece of spring steel. With the air track turned off, the gliders are brought close together (compressing the spring) and the gliders are tied with a loop of string. When the string is burned, the gliders oscillate about the midpoint of the spring steel. Can also be set in motion before burning the string.

3A80. Lissajous Figures

Lissajous Patterns (3A80.20) -- two audio oscillators, one connected to the vertical input of a large oscilloscope and the other to the horizontal input. A change of pattern is observed with a change in amplitude, frequency ratio, or phase.

3A95. Non-Linear Systems

Lockable Double Pendulum -- a (chaotic) double pendulum that has a locking bolt to turn it into a simple (non-chaotic) physical pendulum.

Periodic, Non-Harmonic Device (3A95.38) -- a pendulum bar with a massive bob at the end has a long limber wire projecting out of the top. The pendulum exhibits simple harmonic motion, but the wire is constrained by a loop encircling it and exhibits periodic but non-simple harmonic motion.

Pump Pendulum (3A95.70) -- a weight swings on the end of a string which passes over a pulley and is tied to a rod. If the string is tugged to lift the weight at the right frequency and phase the amplitude of the pendulum's swing increases gradually.

3B: Wave Motion

3B10. Transverse Pulses and Waves

Wave on a Rope (3B10.10) -- a long rope is attached to one wall, prof holds other end and shakes a wave along the rope to show a travelling transverse wave.

Tension Dependence of Wave Speed (3B10.15) -- waves plucked on a length of stretched rubber tubing shows a strong dependence on tubing tension.

Spring on Table (3B10.20) -- a long brass spring is stretched out on the lecture table and shaken at one end. Transverse waves of large amplitude and low velocity will propagate along the spring. The far end can be fixed or free.

Pulse on a Moving Chain (3B10.26) -- a loop of chain is hung loosely across two wheels at the same level, one free and one motor driven. Motor speed and chain tension can be adjusted so that a pulse wave produced by a sharp blow from a stick will propagate at the same speed as the chain motion and thus appear motionless. Practice to avoid knocking the chain off with too heavy a blow.

Transverse Waves (Bell Labs Wave Machine) (3B10.30) -- In these three machines, rods are arranged like ribs along a square wire "spine." A torsional wave can be sent down the spine by sharply displacing the tip of the first rod. As the wave propagates along the
spine, each rod is tipped in turn by the passage of the wave, and the displacement of the ends of the rods is visible to the class, appearing as a transverse wave (visibility can be increased by illuminating the fluorescent tips of the rods with UV). The spines are identical in each machine, but the lengths of the rods differ (46 cm in one, 23 cm in another, and lengths increasing regularly from 23 to 46 cm in the third), causing different propagation speeds. The 23 and 46 cm machines can be hooked directly together or through the "coupling" section, showing the advantages of coupling. The end rod of the machines can be free, fixed, or damped to show the effects on reflection from the end. Note: This is on the same setup as Longitudinal Waves (Hanging Slinky) (3B20.10).

3B20. Longitudinal Pulses and Waves

Longitudinal Waves (Hanging Slinky) (3B20.10) -- longitudinal waves propagate slowly on a large plastic slinky suspended horizontally on strings. The slinky is hand-driven and can be used to show single pulses or standing waves. Paper markers hang on the coils to increase visibility of compression and rarefaction. The far end can be free or fixed. Note: This is on the same setup as Transverse Waves (Bell Labs Wave Machine) (3B10.30).

Longitudinal Wave Model -- a model of travelling longitudinal waves. 21 vertical rods are attached to a horizontal shaft. Turning a crank turns the shaft, moving the vertical rods back and forth in place in such a way that a longitudinal "wave" passes along the rods, with a compression followed by a rarefaction for as long as you want to turn the crank. Reversing the cranking direction reverses the direction of the wave. In reality each rod moves back and forth sinusoidally in a groove on the shaft, with the motion of each rod progressively 30° ahead of its neighbor, creating the illusion of a wave.

3B22. Standing Waves

Standing Waves in Rubber Tubing (Varying Frequency) (3B22.10) -- a long piece of rubber tubing is stretched out horizontally and run over a pulley at one end, then tensioned with a hanging weight. At the other end a revolving beater bar strikes the tubing at a frequency which can be adjusted with a motor speed control. Transverse waves of any frequency can thus be sent along the tubing, and when the right frequencies are reached the tubing vibrates in various standing wave modes.

Three Strings (Varying Tension) (3B22.15) -- three strings of approximately the same length but under different tensions are driven at the same frequency. With the help of a stroboscope, the envelopes of the wave forms (fundamental, 1st and 2nd harmonics) can be observed in slow motion.

Standing Waves in Hanging Slinky (3B22.50) -- drive a hanging slinky by hand to produce standing longitudinal waves.

Standing Wave Model (3B22.90) -- a simple model that shows how standing waves form. A sine wave is drawn on a loop of acetate that moves between two rollers. The students see two sine waves, one moving to the left and one to the right at the same velocity. At some points (nodes) the amplitudes of the two waves will always be equal and opposite, so they cancel. At points in between (antinodes), the two waves will always be moving together, so they will reinforce at those points to create greater amplitudes. A grid can be inserted that marks the nodes and antinodes for easy viewing.

See also Vibrating Circular Wire (7A50.40).

3B25. Impedance and Dispersion

Impedance Matching (Bell Labs Wave Machine) (3B25.10) -- The long and short rods sections of the wave machine can either be connected abruptly (unmatched coupling) or with a section of gradually lengthening rods (matched coupling).

Wave Reflection (3B25.20) -- the Bell Labs Wave Machine described above can be used with the end fixed, damped, or free to show
the effect on the reflected wave.

**Spring Wave Reflection (3B25.25)** -- reflections from a long horizontal brass spring (3B10.20) with fixed and free ends.

**Acoustic Coupling (3B25.35)** -- a small speaker has a coupling horn which may be removed. With the horn on, the sound is much louder than with the horn off.

**Space Phone (Spring and Horn Toy) (3B25.55)** -- two plastic earpieces connected by a long light spring. If you put an ear to the earphone and twang the spring, a very spacey science-fiction sound is heard. There is some disagreement as to the cause, with some crediting dispersion of the wave in the spring, others saying that isn't possible. Your call. A microphone can be placed at the earphone for class enjoyment.

**3B27. Compound Waves**

**Wave Superposition (3B27.15)** -- Start positive pulses from each end of the Bell Labs Wave Machine.

**3B30. Wave Properties of Sound**

See also Light and Siren in Vacuum (6A02.10) in Section 6: Optics.

**Phonodeik** -- shows the y vs. t deflection of a scanning light beam which is reflected from a delicate mirror on the diaphragm of a mechanical microphone during oscillation. An "oscilloscope" from the pre-electronic era of candle flames, levers, and ingenuity. Note: This demonstration is currently missing.

**Sound in Helium (3B30.50)** -- helium can be blown through a variety of resonant music makers to demonstrate the higher notes that are created with a lower density gas. Choices include organ pipes, a jug or ocarina instrument, and (most popular) an inhaled lungful by the lecturer.

**3B33. Phase and Group Velocity**

**3B35. Reflection and Refraction (Sound)**

**Refraction of Water Waves (3B35.60)** -- Plane waves refract in a tank with deep and shallow sections.

**3B39. Transfer of Energy in Waves**

**3B40. Doppler Effect**

**Doppler Effect (3B40.10)** -- a siren at the end of a string emits sound as it is swung around and class hears the pitch rise and fall as the siren moves toward or away from them.

**3B45. Shock Waves**

**3B50. Interference and Diffraction**

**Ripple Tank - Single Slit Diffraction (3B50.10)** -- diffraction from a plane wave passing through a single slit on the ripple tank.

**Ripple Tank - Double Source Interference (3B50.20)** -- two point sources in phase show interference.

**Ripple Tank - Double Slit Interference (3B50.25)** -- interference from a plane wave passing through two slits.

**Ripple Tank - Multiple Slits** -- plane waves pass through multiple slits.
Moiré Pattern (3B50.40) -- two patterns of concentric circles are laid atop one another on the overhead, and the separation between their centers changed by sliding one across the other. An interference pattern whose number of nodal lines depends on source separation appears on the screen.

Please see section 6: Optics for more interference and diffraction demonstrations using lasers or microwaves.

3B55. Interference and Diffraction of Sound

Two Speaker Interference (3B55.10) -- two small speakers driven in phase are attached to a long bar which can be rotated to sweep the minima and maxima points past the students (have them plug one ear). Frequency can be varied.

3B60. Beats

Beats from Tuning Forks (3B60.11) -- two matched tuning forks are used, one of which has an adjustable weight on one tine. By adjusting the weight the forks can be set to equal frequencies to show resonance, or set slightly apart to demonstrate beats.

Beats on Oscilloscope (3B60.20) -- the outputs of two audio oscillators are mixed and fed into an amplifier, then the amplifier output is fed into an oscilloscope and an audio speaker to produce visible and auditory indications of beats.

Beats (Two Speakers) -- two speakers powered by separate audio oscillators produce beats.

Also see Singing Glass Tubes (Beats) (3D30.70) and Organ Pipes (Beats).

3B70. Coupled Resonators

Coupled Tuning Forks (Sympathetic Vibrations) (3B70.10) -- Two matched tuning forks are mounted on resonance boxes. Hit one and the other vibrates too.

3C: Acoustics

3C10. The Ear

Model of the Ear (3C10.10) -- shows anatomical structure of the human hearing mechanism.

3C20. Pitch

Oscillator with Speaker and Oscilloscope (Range of Hearing) (3C20.10) -- run the frequency up and down, announcing the value as class gets a feel for the audio range and the relationship between frequency and pitch. Can also display on the scope subsonics and ultrasonics that cannot be heard.

Galton Whistle (3C20.15) -- this small ultrasonic whistle produces high intensity sounds at frequencies that are essentially inaudible to humans.

Siren Disk (3C20.30) -- a disk with four circular rows of holes uniformly spaced and another circular row of randomly spaced holes. The disk is rotated by a motor and a jet of air is directed at the holes. Puffs of air through the disk as a hole passes the air jet produce pressure variations, and thus sound. Different musical notes are heard from different circles of regularly-spaced holes but noise is heard from the circle of randomly-spaced holes.
Gear with Vibrating Card (3C20.40) -- similar to a card in the spokes of a bike wheel. Rotation of the gear can be varied to produce everything from a rapid clicking (under 20 Hz) to full-fledged sounds.

3C30. Intensity and Attenuation

Decibel Meter (3C30.22) -- a modern meter using a microphone and electronic amplification, with calibrated output in decibels. Try it with various sounds or have your class yell.

3C40. Architectural Acoustics

3C50. Wave Analysis and Synthesis

Fourier Synthesizer (3C50.10) -- a commercial Fourier synthesizer is connected to a speaker and an oscilloscope. The synthesizer can generate two fundamentals of 500 Hz and eight higher harmonics, each with amplitude and phase control. The synthesizer can produce either sine, square or triangular wave forms.

Audio Filter -- electronic filter can operate as a high or low pass filter with selectable frequency.

3C55. Music Perception and the Voice

Tuning Forks on Resonant Boxes (3C55.55) -- Two tuning fork and two resonant boxes. Shows that the box needs to be matched to the fork.

Microphone and Oscilloscope (3C55.70) -- Show the output of a microphone on the oscilloscope. Observe patterns of voices, speech, tuning forks, and musical instruments.

3D: Instruments

3D20. Resonance in Strings

Sonometer (3D20.10) -- the two ends of a stretched steel wire are hooked to an audio amplifier and a small horseshoe magnet is placed over the wire, so that transverse vibrations of the wire are transformed into currents along the wire. The currents are amplified and fed into an oscilloscope and/or speaker. Thus the waveform can be seen, and heard if desired. The wire is finger-plucked, and both tension and length are adjustable. Harmonics can be either ignored or intensified by changing placement of the magnet, and can also be damped out selectively with a small paintbrush.

3D22. Stringed Instruments

Guitar -- an acoustic guitar provides a good example of standing wave dependence upon string length and tension.

Piano -- a small upright piano is available in or from room A114 by arrangement.

Piano Key Action -- cutaway of actual key and hammer mechanism to show complicated nature of the system used to properly strike piano strings in order to excite a note and avoid damping.

3D30. Resonance Cavities

Vertical Resonance Tube (256/512 Hz) (3D30.10) -- a glass cylinder is filled with water to one of two preset levels and the tuning fork with a frequency equal to the resonant frequency for that level is held over the opening. It is noted that the sound is much louder than when the tube is filled to any other level.
Open and Closed Resonance Tube (256/512 Hz) (3D30.20) -- A metal tube is cut to length to resonate at 256 Hz when closed and 512 Hz when open.

The previous two demonstrations are most often used together.

Resonance Tube with Piston (3D30.15) -- a long glass tube with a moveable piston inside has a speaker at one end. Using a sound wave of known frequency, move the piston while listening for changes in sound intensity. Different points of maximum intensity will be found at regular spacing, which can be marked with stick-on dots on the side of the tube. The distance between the dots ($\frac{1}{2} \lambda$) and the known frequency can be used to calculate the speed of sound in air.

Helmholtz Resonators (3D30.40) -- classic spherical resonators can be made to resonate loudly by a tuning fork of the corresponding frequency.

Kundt's Tube (3D30.60) -- Air column resonance in a horizontal glass tube is shown by adding cork dust to the tube and driving the air column with a speaker inserted in one end of the tube. Accumulation of cork dust shows nodes (displayed on overhead projector). Tube length may be varied with a sliding stop at the far end.

Rijke Tube (3D30.70) -- a 6 cm diameter 62 cm long glass tube has a piece of wire mesh across the tube about 1/4 up from the bottom. The tube is held over a burner until the wire mesh glows red-hot, then removed and held vertically. A loud pure tone is produced as a result of a standing sound wave in the tube. Turn the tube horizontally and the tone stops, then starts again when the tube is held upright. The mesh is at the velocity antinode for the standing wave, and the moving air reinforces the standing wave by removing energy from the mesh at the frequency of oscillation.

Organ Pipes (Beats) -- 2 large (10 cm diameter, 140 cm and 122 cm long) metal pipes mounted vertically on lecture table will resonate at low frequencies when a source of “white noise” (Fisher burner) is placed at the bottom end. If both pipes are excited at once they produce beats.

Singing Glass Tubes (Beats) (3D30.70) -- two small glass Rijke tubes have electrically-heated wire grids and moveable tubes. Move a tube so that the grid is at the 1/4 point and the tube will "sing." Put it anywhere else, and no song. Since the tubes are slightly different lengths, running them both together produces beats.

3D32. Air Column Instruments

Slide Whistle (3D32.15) -- toy whistle has a slide arrangement to vary column length and thus pitch.

Open and Closed End Pipes (Various) (3D32.25) -- a variety of mouth blown organ pipes with different lengths and removable end pieces to show the effects of pipe length and the difference between open and closed end resonators.

Cardboard Tube -- a long cardboard mailing tube with a cap at one end produces a "thunk" sound at the resonant frequency of the tube when the cap is removed. Note: Another variation uses small metal tubes and stoppers.

Recorder -- a clarinet-like instrument used to discuss the effect of hole openings in effectively shortening the resonance length.

Ocarina -- a toy musical instrument (resonant cavity with finger holes).

3D40. Resonance in Plates, Bars, Solids
**Xylophone (3D40.10)** -- small xylophone covering two octaves, including sharps and flats.

**Xylophone Bars** -- produce xylophone sounds by striking centers of bars mounted on individual sounding boards.

**Wooden Xylophone** -- a set of tuned wood bars on a rope support cover one octave of frequency when struck.

**Rectangular Bar Oscillations (3D40.11)** -- a long hand-held metal bar has a rectangular cross-section. A high-pitch longitudinal oscillation frequency is excited by hammering the end. Two lower transverse frequencies are excited by striking one side or the other of the bar, with the wider side having the lower frequency.

**High Frequency Metal Bars (3D40.12)** -- three finger-held resonant metal bars are struck on the ends to produce frequencies of 5, 10, and 15,000 Hz.

**Singing Rods (3D40.21)** -- an aluminum rod (approximately 1.3 cm diameter by two meters long) is held at the center with one hand. The other hand strokes the rod between a rosined thumb and forefinger to induce longitudinal oscillations. The support point may be changed to produce harmonics of the fundamental tone, and two other rods of shorter lengths produce higher frequencies. Note: This demo requires some practice.

**Chladni Plates (3D40.31)** -- Classic demonstration of nodal patterns in vibrating metal plates as seen by heaping lines of white sand which build up at the nodes as the plates are excited by the driver section of a speaker. Many different patterns can be seen at different frequencies. Nodal patterns can also be varied by pressing a finger to the edge of the plates at various points.

**Drumhead (3D40.40)** -- a large rubber sheet stretched over a circular frame is driven by a speaker from below and develops standing waves at certain frequencies. Black grid lines on the sheet emphasize the displacement patterns (fundamental and 1st and 2nd overtones, which are not in harmonic multiples). Off-center placement of the speaker produces other patterns. Sheet tension can be adjusted to alter the fundamental frequency and overtones. Motion can be frozen using a strobe.

**Wine Glass Resonance (3D40.50)** -- Dip your finger in water and run it around the rim of a wine glass.

**Chinese Spouting Bowl (3D40.51)** -- A 15" diameter decorative bowl with handles is partially filled with water. Wet your hands and then rub the handles to create resonance. The standing wave will cause the water to jump up several inches or more. Note: Make sure your hands are clean first.

3D42. Percussion Instruments

3D46. Tuning Forks

**Tuning Forks (3D46.15)** -- various tuning forks for show and tell.

3D50. Electronic Instruments

3E: Sound Reproduction

3E20. Loudspeakers

**Cutaway Speaker (3E20.10)** -- a speaker that has been sliced to allow a side view of the cone motion when the speaker is speaking. Works best on the overhead projector.
**Simple Speaker** -- Daryl's favorite.

3E30. Microphones
3E40. Amplifiers
3E60. Recorders

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**4: Thermodynamics**

4A: Thermal Properties Of Matter
4B: Heat And The First Law
4C: Change Of State
4D: Kinetic Theory
4E: Gas Law
4F: Entropy And The Second Law

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**4A: Thermal Properties Of Matter**

4A10. Thermometry

*Show & Tell Thermometers (4A10.10) -- Choose from the following:*

- liquid (mercury or alcohol)
- bimetallic coil (large or small)
- liquid crystal (aquarium type) -- thermometer strip indicates temperatures from 66° F to 84° F by color changes

*Liquid Crystal Sheets (4A10.50) -- large sheets of temperature-sensitive liquid crystals change color with changing temperature.*

See also Galileo's Thermometer (Thermal Expansion of Air) (4E10.11).

4A20. Liquid Expansion

*Thermal Expansion of Water (4A20.10) -- a 1 liter flask filled with colored water has a long glass tube protruding up from the neck. A gas flame is placed under the flask and thermal expansion forces water up the tube.*

*Negative Expansion Coefficient of Water (4A20.30) -- a 2 liter flask of colored water with a glass tube inserted through the stopper is kept in a bath of ice water until the temperature of the water in the flask has fallen to 0° C. The water level in the vertical tube is noted, and the flask and tube are removed from the ice bath. As the temperature of the flask water rises above 0° C, the water level in the tube drops until the water has warmed to about 4° C, the temperature of maximum density, then begins to rise. Demonstrates why ice floats, and always forms at the top surface of the water.*

*Density of 4° C Water (4A20.35) -- a mixture of ice and water in a beaker is placed on a styrofoam insulation pad. After coming to equilibrium, a large display thermometer can be used to show that the water up around the ice is at 0° C, while the denser water at the bottom is at 4° C.*

4A30. Solid Expansion
Bimetallic Strip (4A30.10) -- two dissimilar metal strips bonded together and fastened to a handle. When heated, the strip bends because of the different expansion rates of the metals.

Bimetallic Coil -- same as the bimetallic strip in concept, but helical in form. The coil is heated and moves a large indicator arrow as it expands.

Thermostat Model (4A30.11) -- working model of a thermostat with a lamp heater and a bimetallic strip.

Ball and Ring (4A30.21) -- a metal ball and ring on handles are constructed so that the ball will just pass through the ring at room temperature. The ball is heated and will not pass through the ring. The ball and ring are both heated and the ball now passes through the heated ring.

Ball and Hole (4A30.22) -- a ball which is too large to pass through a hole in a square metal plate will pass easily through the hole after the plate has been heated in a flame. Many students expect the hole to shrink upon heating, but it actually expands along with the rest of the plate.

Heated Wire (4A30.60) -- a thin wire supported at both ends is electrically heated and the wire sags in the middle.

4A40. Properties of Materials at Low Temperatures

Elasticity at Low Temperatures (4A40.15) -- a lead spring is dipped in liquid nitrogen and hooked on a vertical stand. A weight is attached to the end of the spring and set into oscillation - the spring will oscillate when cold, but as it warms up its elastic limit is lowered and the weight sags onto the table.

Smash Stuff in Liquid Nitrogen (4A40.30) -- Cool flowers, racquetballs, fruit, etc. in liquid nitrogen. Please bring your own items (no watermelons).

4A50. Liquid Helium

4B: Heat And The First Law

4B10. Heat Capacity and Specific Heat

Calorimeter (4B10.26) -- Show & Tell version of a double-walled aluminum calorimeter with hole on top for thermometer, used for heat of fusion of water, etc.

Specific Heat (Quantitative) (4B10.28) -- three equal masses of metal shot (aluminum, steel, and lead) are placed in pop cans and heated in boiling water until they are all at 100° C. They are then each dumped into equal masses of water and stirred, then the final temperature of each is read with a large display thermometer. Reasonable (10%) figures for the heat capacities of the metals can be obtained from the data. The results will always be slightly on the low side due to heat losses during transfer, but are good to 10-15%.

Specific Heat (Rods and Wax) (4B10.30) -- cylinders of lead, brass, and aluminum are heated in boiling water, then lifted onto a block of paraffin. The plugs melt through the wax with speeds approximately proportional to their heat capacities.

Ruchardt’s Experiment for γ (4B10.70) -- A steel ball in a precision tube oscillates as gas escapes from a slightly over pressured flask. By measuring the oscillation frequency, you can determine the ratio γ = Cp/Cv. Note: Please talk to us in advance.
4B20. Convection

Convection D-Tube (4B20.10) -- a large glass tube in the shape of a “D” is filled with water and heated by a burner near one bottom corner. The resulting circulating convection current is shown by adding drops of dye to the water.

Convection Currents (Projection) (4B20.40) -- convection currents from a hot wire in a small water cell are projected onto a screen using a simple Schlieren optics system.

Convection with Overhead (4B20.45) -- a bunsen flame held between the overhead and screen clearly shows convection currents rising from the flame.

4B30. Conduction

Thermal Conductivity (4B30.12) -- five rods of different composition are attached to a steam chamber to provide equal temperatures at the bases of the rods. The rods are covered with wax, which melts and peels off as the rods heat up. Relative rates of heat conduction can be deduced from the rates at which the wax melts on each rod. The five materials in order of decreasing conductivity are: copper, aluminum, brass, steel, and glass.

4B40. Radiation

Leslie Cube (4B40.30) -- a brass cube filled with hot water has four different faces: one is plain brass, one painted white, one painted glossy black, and one painted flat black. A thermocouple connected to a projection galvanometer is positioned near the Leslie cube and the cube is rotated on its base so that each face passes in front of the thermocouple. A different rate of radiation is seen from each face.

Radiation from Hot and Cold Bodies -- two parabolic reflectors are aligned facing each other on the lecture table, with a thermopile at the focal point of one of the reflectors and a heated sphere at the other. A projection galvanometer's deflection shows the transmission of heat by radiation. Replace the hot sphere with a sphere dipped in liquid nitrogen and the galvanometer will deflect in the opposite direction.

Two Can Radiation (4B40.40) -- Shiny and flat black cans filled with cool water warm up (15 minutes), or cool off when filled with boiling water (45 minutes).

Please see Section 6: Optics for more electromagnetic radiation demonstrations.

4B50. Heat Transfer Applications

Insulation (Dewar Flasks) (4B50.10) -- four dewar flasks (thermos bottles) are filled with boiling water and a thermometer and cork are placed in each mouth. Each flask has a different degree of insulation, and these are (from worst to best): unsilvered without vacuum between the walls, silvered without vacuum, unsilvered with vacuum, and silvered with vacuum. Water is left cooling until the end of the period, then temperature of each flask is read on a thermometer and relative rates of heat transfer are inferred from the different temperatures.

Water Balloon Heat Capacity (4B50.25) -- a lit match may be held directly beneath a water balloon without burning through the balloon, due to the high heat capacity of the water. In contrast, an air balloon explodes immediately on contact with the flame.

Leidenfrost Effect (4B50.30) -- Pour water into a hot pan, or pour liquid nitrogen on the floor.
4B60. Mechanical Equivalent of Heat

Drill and Dowel (4B60.55) -- a wooden dowel held in an electric drill chuck is ground against a large flat piece of wood. The friction between the two produces heat, smoke, etc.

Cork Popper (4B60.70) -- a motorized rotating hollow shaft holds a thimbleful of water and is sealed with a stopper. Wooden arms are squeezed together on either side of the rotating shaft, and the heat generated by friction boils the water and pops the cork.

4B70. Adiabatic Processes

Fire Syringe (4B70.10) -- A thick glass tube with a plunger has a small two match heads in the bottom. If the plunger is rapidly pushed in, the heat of compression ignites the match heads with a bright flare.

Cloud Flask (4B70.20) -- a flask containing a small amount of water has a large rubber bulb attached to the side. If the bulb is squeezed and released, a cloud will form in the flask, but only if a small amount of smoke is added first to act as condensation centers.

Temperature Change with Compression (4B70.31) -- a small plastic syringe contains a small thermocouple probe in the tip that connect to a large display thermometer. If the syringe is compressed rapidly, a temperature rise is seen on the thermometer. Pulling the plunger up rapidly lowers the temperature of the air inside.

4C: Change Of State

4C10. PVT Surfaces

PVT Surface Model - Carbon Dioxide (4C10.10) -- a three dimensional model showing various PVT states of carbon dioxide.

PVT Surface Model - Water (4C10.10) -- a three dimensional model showing various PVT states of water.

PVT Surface Model - Ideal Gas (4C10.10) -- a three dimensional model showing various PVT states of an ideal gas.

4C20. Phase Changes: Liquid-Solid

Regelation (4C20.30) -- a block of ice is supported at ends and a thin wire with weights attached is hung over the top. Pressure from the wire raises the melting temperature of the ice, and the wire will pass through the block without cutting it in two (the ice refreezes behind the wire) within 15 to 30 minutes. Ice skating and the making of snowballs are two examples of regelation at work.

Exothermic Reaction -- a small pouch contains a solution of water and a salt that dissolves endothermically (absorbs heat as it dissolves). When a small snapper inside the pouch is popped, the salt comes out of solution, releasing the heat it had absorbed while dissolving. The pouch can be recharged by placing it in boiling water until the salt dissolves. This is a commercial item used by campers for supplemental warmth. Please give plenty of notice for this demonstration.

4C30. Phase Changes: Liquid-Gas

Boil Water Under Reduced Pressure (4C30.10) -- a special long-necked spherical flask with a concave depression in its bottom is filled with water and boiled to drive out the air. The flask is then capped with a cork and thermometer (which shows the water is boiling at 100° C), turned upside down, and cooled by filling the hollow with ice. The resulting pressure reduction causes the water to boil at a reduced temperature (80-90° C or lower).
Liquid Nitrogen in a Balloon (4C30.35) -- a small amount of liquid nitrogen is poured into a balloon and allowed to evaporate and expand.

Hand Boiler -- convoluted glass tube contains a small amount of a volatile liquid. Heat from your hand will boil the liquid and the vapor pressure will force it to flow to the opposite end of the tube. Note: This is small and not very viewable for a large class.

4C31. Cooling by Evaporation

Cryophorus (4C31.10) -- A partially evacuated glass tube that contains some water in the bulb on one end. The other empty end is placed in liquid nitrogen and the change in pressure causes the water to boil and then freeze.

Freezing Water by Evaporation (Triple Point) (4C31.20) -- air pressure is lowered almost to vacuum over a small sample of water, which begins to boil. Evaporation in vacuum lowers temperature of the water until it reaches the triple point at .01 °C. Water then boils and freezes almost simultaneously - displayed on the overhead projector.

Drinking Bird (4C31.30) -- commercial novelty item. Dip the bird's beak into a beaker of water, then let it go. Evaporation of the water from the wet beak cools the beak, lowering the vapor pressure of the liquid inside and drawing it up into the head. That overbalances the bird and it tips into the water for a “drink.” In that position, the liquid inside flows back into the lower bulb, which rights the bird and starts the cycle over. Note: This is not very visible for a large class without using a camera and monitor.

4C32. Dew Point and Humidity

4C33. Vapor Pressure

4C40. Sublimation

Sublimation of CO2 (4C40.10) -- CO2 is solidified by dipping a balloonful in a container of liquid nitrogen. The balloon is cut open to show the solid CO2, which sublimes directly to the gaseous state.

4C45. Phase Changes: Solid-Solid

4C50. Critical Point

Critical Point of CO2 (4C50.10) -- liquid CO2 in a glass tube at high pressure is close enough to the critical point that warm air from a hair dryer will complete the transition. The tube is displayed with a video camera and the meniscus is seen, but when the tube is heated the meniscus slowly fades and disappears as the liquid CO2 goes through a gradual transition to a high-pressure gas. A turbulent mixture of liquid and gas with equal densities is seen above and below the meniscus point.

Critical Opalescence (4C50.20) -- a mixture of triethylamine and water in a tube is hand warmed and passes through the liquid/gas critical point. The liquid is clear at first, then clouds up as the critical point is reached; a sparkly meniscus forms at the phase interface.

4D: Kinetic Theory

4D10. Brownian Motion

Brownian Motion (4D10.10) -- a small chamber is filled with smoke and observed with a video camera and TV. See also Molecular Motion Demonstrator (4D30.20).

4D20. Mean Free Path
4D30. Kinetic Motion

**Molecular Motion Demonstrator (4D30.20)** -- a small variable speed motor shakes a four-sided frame mounted over a glass plate on the overhead projector. Various sized plastic and metal balls placed in the frame bounce randomly about, simulating molecular motion. Concepts which may be demonstrated include temperature, equipartition of energy, diffusion, and Brownian motion.

4D40. Molecular Dimensions

4D50. Diffusion and Osmosis

**Diffusion (4D50.20)** -- an upside-down porous clay bottle with tubing leading out of the bottom and into a test tube of water is placed under an inverted beaker. Natural gas or helium is introduced into the beaker, and the osmotic pressure between the two gases forces air out of the bottle and down the tubing, so that bubbles are seen coming from the end of the tubing. After the cup fills entirely with natural gas, a new equilibrium is reached and the bubbles stop.

**Bromine Diffusion (4D50.45)** -- Glass tubes containing bromine and bromine/air are cooled in liquid nitrogen and allowed to warm back up to show rates of diffusion. The bromine only tube will diffuse faster than the bromine/air mixture.

4E: Gas Law

4E10. Constant Pressure

**Galileo’s Thermometer (Thermal Expansion of Air) (4E10.11)** -- air expansion in a glass bulb causes liquid level in a vertical tube below the bulb to drop - qualitative only.

**Helium Balloon in Liquid Nitrogen (Charles’s Law / Volume vs. Temperature) (4E10.22)** -- a helium balloon is drenched with liquid nitrogen. As the helium shrinks in volume, the balloon loses buoyancy and comes to rest on the table. As the helium warms up, the balloon expands and begins to float again. Note: Constant pressure here is atmospheric pressure.

4E20. Constant Temperature

**Boyle’s Law (Pressure vs. Volume) (4E20.10)** -- A syringe is connected to a dial pressure gauge on the overhead projector. A decrease in volume of the syringe causes an inversely proportional increase in the pressure. An increase in the volume results in a decrease in the pressure.

4E30. Constant Volume

**Gay-Lussac’s Law (Pressure vs. Temperature) (4E30.10)** -- A hollow metal sphere is attached via tubing to a pressure gauge on the overhead projector. The sphere is immersed in water baths of various temperatures (boiling, room temperature, and ice water) and the corresponding pressure is noted. The data can be extrapolated to absolute zero if desired.

**Constant Volume Gas (Pressure Thermometer) (4E30.20)** -- constant volume is maintained by adjusting a water column, and pressure is read from the height of water in the other leg of the tube. Qualitative only, and only usable for small changes in pressure.

4F: Entropy And The Second Law

4F10. Entropy

**Mixing and Unmixing (4F10.10)** -- The area between two acrylic coaxial cylinders is filled with glycerin and red dye. When the inner
cylinder is rotated, the dye appears to be mixed but is distributed in a fine one armed spiral sheet. Reversing the direction of inner cylinder rotation will cause the original dye pattern to reappear. Note: Please talk to us about this first.

**Entropy Pennies** -- a tray is filled with pennies painted green on the tails and red on the heads. If the tray is shaken the pennies begin to flip at a rate dependent on the magnitude of the shaking. Eventually an equilibrium is reached, with approximately equal numbers of reds and greens. Further shaking will not, of course, return them to their original state. If only a few pennies are used, they will occasionally return to their original state, showing the dependence upon the number of particles in the system.

See also Gaussian Distribution (1A20.10).

**4F30. Heat Cycles**

**Heron’s Engine (or Hero’s Engine) (4F30.01)** -- working model of the first primitive steam engine. A glass globe containing a small amount of water is heated with a flame. The steam produced comes out through two arms and spins the globe.

**Stirling Engines (4F30.10)** -- Choose from the engines listed below.

- **Stirling Engine (Heavy Duty)** -- A heavy duty Stirling engine. This is the biggest engine, but perhaps the least instructive because of low visibility.

- **Stirling Engine (Transparent Pistons)** -- a new model Stirling engine has glass cylinders so the power and displacement pistons can be viewed (a video camera helps, and an animation of the process is available on The Video Encyclopedia of Physics Demonstrations).

- **Stirling Engine (Hot & Cold)** -- This one runs off any sort of a temperature differential, and doesn't need much of a $\Delta T$. It will run on a cup of hot water, or (in reverse) on a block of ice. As the temperature differential decreases with time, the engine slows down. Doesn't need a flame, so it's useful to show that hot and cold reservoirs are all it takes to produce work from heat.

- **Stirling Engine (Hand-Held)** -- our newest Stirling engine is so well machined and balanced that it can run off the heat from your hand. Quite impressive.

**Cutaway Steam Engine (4F30.31)** -- cutaway model of a steam engine shows the steam chamber, piston, valves, etc.

**5: Electricity And Magnetism**

5A: Electrostatics
5B: Electric Fields and Potential
5C: Capacitance
5D: Resistance
5E: Electromotive Force And Current
5F: DC Circuits
5G: Magnetic Materials
5H: Magnetic Fields And Forces
5I: Inductance
5K: Electromagnetic Induction
5A: Electrostatics

Note: Our Basic Electrostatics set contains the following: Rods and Cloth, Turntable, and the Electroscope.

5A10. Producing Static Charge

**Electrostatic Rods and Cloth (5A10.10)** -- Glass rods and silk (positive charge), clear acrylic rods and wool (positive charge), red acrylic rods and wool (negative charge), or rubber and fur (negative charge).

**Electrophorus (5A10.20)** -- An aluminum disc with an insulating handle is set atop a plastic plate which has been charged by rubbing with a cloth. A finger or grounded wire touched to the top of the plate removes the induced charge that is the same polarity as the charge on the plate, then the disc is lifted off the plate, leaving the disc charged to a high voltage. This may be repeated many times without re-charging the plastic.

5A20. Coulomb's Law

**Electrostatic Attraction and Repulsion (Charged Rods on Pivot) (5A20.10)** -- Charged rods (5A10.10) on a pivoting stand are free to rotate and show attraction or repulsion between charges. Note: See also Magnetic Attraction and Repulsion (5H20.10).

**Aluminized Ping-Pong Balls (Electrically Connected)** -- Two aluminized ping-pong balls hang from wires attached to a metal plate. Touch a charged rod to the plate and the balls separate.

**Aluminized Ping-Pong Balls (Electrically Insulated)** -- Two aluminized ping-pong balls hang from a plastic rod so that they may be given opposite charges to demonstrate attraction.

**Three Ping-Pong Balls** -- Three aluminized and electrically connected ping-pong balls hang from a common point on thin wires so that they just touch. The balls are now charged with a Wimshurst generator, causing them to fly apart by electrostatic repulsion. A camera is mounted above the ping-pong balls and shows that the direction of the repulsive force is outwards from the center of the three balls.

5A22. Electrostatic Meters

**Electroscope (5A22.10)** -- An electroscope with the pivoted detector shadow projected onto a translucent glass plate is used to show charge. One can charge the electroscope by direct conduction or by induction (bring a charged rod close to the plate of the electroscope, then touch the plate with your finger. This draws off the free charge. Remove your finger and the rod, and the electroscope is left with an unbalanced charge opposite that of the rod.

**Electrostatic Voltmeter (5A22.50)** -- A voltmeter which reads the potential near charged rods without affecting the charge.

5A30. Conductors and Insulators

**Conducting and Non-conducting “T” (Plastic and Aluminum Rods) (5A30.15)** -- A large "T" shaped terminal is attached to the electroscope. One arm is made of acrylic and the other arm is aluminum, but both have a metal ball on the end. Touch a charged rod
to the ball on each arm to show that only the aluminum arm conducts and charges the electroscope. This can also be done with wire and string.

5A40. Induced Charge

**Charge By Induction (Induction Spheres)** *(5A40.10)* -- Two metal spheres on insulated stands are touching each other. A charged rod is brought near one of them which induces the opposite charge on the other sphere. While the rod is held close to the first sphere, the other is moved away and touched to the electroscope.

**Wooden "Needle"** *(5A40.30)* -- A wood 1x2 is placed on a rotating stand, and will be attracted by either a positively or negatively charged rod due to induction and polarization of the charge within the wood.

**Metal Rod on Pivot** *(5A40.35)* -- A metal rod on a rotating stand will be attracted to a charged rod of either sign due to induced charge in the metal rod.

**Deflection of a Water Stream** *(5A40.40)* -- A charged rod deflects drops of water. Note: This is hard to see in a large class.

**Kelvin Water Dropper** *(5A40.70)* -- An unusual induction machine in which dripping water acts as the carrier for charge buildup in two metal cans. When a sufficiently high voltage is reached, the cans discharge through a small neon lamp. Note: This is hard to see in a large class.

5A50. Electrostatic Machines

**Wimshurst Machine** *(5A50.10)* -- A small hand-cranked generator produces sparks in the hundred-kilovolt range; in principle a continuously operating electrophorus (see 5A10.20).

**Van de Graaff Without Streamers** *(5A50.30)* -- A commercially made Van de Graaff machine; used for a number of demonstrations, including the classic stand-your-hair-on-end. Note: Talk to us in advance about how to do this hair-raising demo. Using paper streamers instead of hair works much better.

See also Van de Graaff With Streamers *(5B10.15)*.

**Toepler-Holtz Machine** -- Large 200 - 300 kV discharges from this antique generator (c. 1895) are very impressive, but please give us a couple hours notice in order to pre-charge it beforehand. Specific demos include: Lightning Rod *(5B30.30)*, Point and Candle *(5B30.40)*, Pinwheel *(5B30.50)*. Caution: Crank slowly!

5B: Electric Fields and Potential

5B10. Electric Field

**Van de Graaff With Streamers** *(5B10.15)* -- A Van de Graaff generator with long paper streamers attached to the dome is used to show the radial shape of the electric field produced by the machine; one can also show the distortion of the field due to the introduction of a grounded metal rod. Note: This works much better than getting a students hair to stand up.

**Bouncing Ping-Pong Balls** *(5B10.30)* -- A variation of Franklin's Bells. Conductive ping-pong balls bounce up and down between two charged metal plates due to electrostatic forces on the balls. Also shows basic charge transfer. Note: This uses the same setup at the Millikan Oil Drop Analog.
Grass Seed Electric Field (5B10.40) -- Variously shaped electrodes are placed in a transparent basin filled with mineral oil and a small amount of grass seed. When a Wimshurst machine is connected to the electrodes and cranked, the shape of the resultant electric field is shown (on the overhead projector) by the orientation of the grass seed along the electric field lines.

5B20. Gauss' Law

Gaussian Surfaces (Show & Tell) -- Show and tell items of various geometries for point, line, and plane charge distributions.

Faraday Ice Pail (5B20.10) -- Shows that charge resides only on the outside of a conductor. A metal trash can is charged using a Wimshurst machine, then the charge distribution on the can is investigated using a metal ball on an insulating rod. The ball is inserted into the can, touched to the inside, then brought out and touched to the electroscope, which does not deflect. If the outside of the can is touched, however, the ball collects charge which can be transferred to the electroscope, causing deflection. On a dry day this can be repeated many times. Please practice this beforehand!

Faraday Cage (5B20.30) -- A large mesh grounded wire cage fits over the electroscope, shielding it from outside electrostatic effects. A high voltage source (a charged acrylic rod) brought near the cage will not deflect the electroscope.

Radio in a Faraday Cage (5B20.35) -- A small radio is placed in a copper wire mesh cage. Note: The lecture halls themselves sometimes act as large Faraday cages and block all radio transmissions.

5B30. Electrostatic Potential

Egg-Shaped Conductor (5B30.20) -- Show and tell item used to discuss charge density as a function of radius of curvature.

Van de Graaff and Wand (5B30.35) -- A grounded wand with a round bulb on one end and a sharp point on the other is brought near a charged Van de Graaff. The bulb end draws out impressive sparks, while the pointed end produces only corona discharge.

Note: The following three demonstrations are all done on the Toepler-Holtz machine. Please give us plenty of advance notice in order to charge it beforehand.

Lightning Rod (5B30.30) -- A model house with a conductor in the chimney is placed on the Toepler-Holtz machine. One electrode of the machine connects to the chimney, the other to a "cloud" suspended directly above the chimney. When the machine is cranked, impressive sparks between cloud and chimney simulate lightning bolts striking the house. A sharp-pointed lightning rod (which is electrically connected to the chimney) is then pushed up out of the top of the house, and the resulting corona discharge stops the "lightning" immediately.

Point and Candle (5B30.40) -- A burning candle brought near a sharp point attached to the Toepler-Holtz machine is nearly blown out due to the electrostatic repulsion on the ions in the flame and the coronal wind from the point. By comparison, holding the candle near the large ball electrode to which the point is attached produces a much smaller effect.

Pinwheel (5B30.50) -- A pinwheel with sharp points at the ends of the arms is mounted so as to spin horizontally on one of the electrodes of the Toepler-Holtz machine. When the machine is cranked, the corona discharge from the points causes the pinwheel to spin.

5C: Capacitance
5C10. Capacitors

Sample Capacitors (5C10.10) -- Show and tell capacitors of many types and sizes.

Parallel Plate Capacitor (Variable Separation) (5C10.20) -- Two parallel circular metal plates which form a capacitor are supported so that the distance between them can be varied. The plates are connected to an electrostatic voltmeter and charged. As the separation varies, the changing voltage between the plates is reflected in the reading on the voltmeter. See Parallel Plate Capacitor with Dielectrics (5C20.10).

Battery and Separable Capacitor (5C10.21) -- A parallel plate capacitor with its plates separated by a thin mica sheet is hooked to the electroscope and charged with a 90 V. battery. The plates are pulled apart, and the decrease in capacitance raises the voltage enough to deflect the electroscope, showing that battery electricity and static electricity are one and the same.

Tuning Capacitor (Variable Area) (5C10.35) -- Similar to the Parallel Plate Capacitor (5C10.20), but this is a large version of the tuning capacitor used in AM radios, in which the area (overlap) between the plates can be changed.

5C20. Dielectrics

Parallel Plate Capacitor with Dielectrics (5C20.10) -- Uses the same setup as the Parallel Plate Capacitor (5C10.20), but instead of varying the separation a large plastic or cardboard sheet is inserted between the plates while they are charged, and the changing voltage is noted.

Force on a Dielectric (5C20.20) -- A circular plastic disk on the end of a seesaw arm is balanced between and slightly above the plates of a large parallel plate capacitor. As the capacitor is charged, the force on the dielectric pulls it down between the plates.

Dissectable Leyden Jar (5C20.30) -- A Leyden jar with removable inner and outer conductors is charged with a Wimshurst machine, then discharged through an insulated metal rod - a large spark is observed. The Leyden jar is charged again, then disassembled by removing the inner and outer conductors. These can be touched together, grounded, etc., and no sparks are seen. However, if the Leyden jar is now reassembled and discharged with the metal rod, a discharge occurs which is almost as large as the first. Note: Please see us beforehand about technique.

5C30. Energy Stored in a Capacitor

Leyden Jars on the Toepler-Holtz (5C30.10) -- Basic demonstration of the ability of capacitors to store energy. The Toepler-Holtz machine is first run without the Leyden jars, and frequent but weak sparks are observed. The Leyden jars are then hooked to the electrodes of the machine, and the discharges become less frequent but much more powerful.

Exploding Capacitor (5C30.20) -- Three 1500 mF capacitors connected in parallel are charged to 400 volts. The capacitors look innocent enough after being charged, but lay a discharge strip across the terminals and the resulting BANG! will wake up that guy in the back row, and teach the students that capacitors are a potential danger (sorry).

Charge vs. Voltage (5C30.37) -- A small capacitor is charged at 1.5V, then discharged through a projection ballistic galvanometer, the amount of deflection of the galvanometer giving an indication of the charge the capacitor held. The same capacitor is then charged to 3V, and the deflection of the galvanometer upon discharge is approximately doubled.

Series and Parallel Capacitors (5C30.42) -- Two identical capacitors mounted on a vertical board which may be used singly or hooked together in series or parallel with copper strips are charged with a battery. After a combination has been charged (to 1.5 V) it can be
discharged through a projection ballistic galvanometer, and the amount of charge the combination held is reflected in the reading from the galvanometer.

5D: Resistance
5D10. Resistance Characteristics

Sample Resistors (5D10.10) -- Various types, values, and power ratings.

Rheostat -- A slide-wire or coil rheostat can be used to discuss the principles of a variable resistor.

Decade Box -- A commercial decade resistance box.

Resistance Wires (5D10.20) -- One board containing five wires of different lengths, areas, and materials. Each of the wires is hooked in turn across a battery and the current through the wire is shown on a large ammeter. The dependence of resistance on length, area, and composition of the wire can be shown. See also Ohm’s Law (5F10.10) and Series and Parallel Resistance (5F20.55).

5D20. Resistivity and Temperature

Coil in Liquid Nitrogen (5D20.10) -- A lamp in series with a resistance coil barely glows at room temperature, but when the coil is dipped in liquid nitrogen its resistance decreases and the bulb lights brightly.

Heated Wire (5D20.20) -- A resistance wire in series with a small lamp and an ammeter is heated by a gas flame. The resistance of the wire increases with rising temperature, causing the current to decrease and the lamp to dim.

5D30. Conduction in Solutions

Conductivity of Solutions (5D30.10) -- A probe consisting of two metal prongs with 110 V between them is dipped into various liquids, solutions, etc. If the liquid conducts, current flows and lights a bulb.

Glowing Pickle (5D30.30) -- Apply 110 VAC across a pickle and it lights at one end. Note: This demo will stink up the whole room.

5D40. Conduction in Gases

Jacob’s Ladder (5D40.10) -- A classic electrical display often seen in the background of mad-scientist B movies. Two long vertical electrodes are close together at the bottom, but separate gradually towards the top. 15,000 Volts from a transformer starts an arc at the bottom. Since the voltage is AC, the arc breaks as the voltage goes back to zero; and the ionized air that was heated during the arc rises while the arc is off. When the AC voltage again becomes high enough to strike an arc, it goes through the ionized air that has risen above the point of the previous arc. The process continues until the arc reaches the top of the electrodes, where it breaks off and reforms at the bottom to begin the cycle again.

Thermionic Emission (Edison Effect) (5D40.42) -- The current across a tube diode is measured as the applied voltage is increased, and it is found that no current will pass until the cathode has been heated by the cathode coil. Demonstrates the basic principle of the tube diode.

Neon Lamp (5D40.50) -- A neon lamp does not conduct below 80V, but passes current easily above that voltage, and will continue to carry current down to about 60 volts once the current has been started.
X-ray Ionization (5D40.80) -- Discharge a charged electroscope with X-rays.

X-ray Absorption -- interpose a lead sheet between the X-ray source and the electroscope and the electroscope discharges more slowly.

5E: Electromotive Force And Current
5E20. Electrolysis
Electrolysis of Water (5E20.10) -- DC passed through slightly acidic water produces hydrogen and oxygen at the electrodes. Matches are provided to ignite the Hydrogen.

5E30. Plating
Copper Electroplating (5E30.20) -- Copper and carbon electrodes in a glass container of copper sulfate are supplied with current from a DC power supply to copper plate the carbon electrode.

5E40. Cells and Batteries
Sample Batteries -- Various types and capacities.

Electroplate Battery -- Copper and carbon electrodes in copper sulfate will act as a battery (as shown on a voltmeter), but if the carbon is subsequently plated with copper, battery action ceases.

Human Battery (5E40.20) -- Cu and Zn electrodes attached to a galvanometer and touched to the tip of the instructor's tongue produce a current.

Simple Lead Storage Cell (5E40.60) -- Two lead plates in sulfuric acid may be charged with a battery eliminator, then discharged through a small bell. The longer the cell is charged, the longer the bell rings.

Internal Resistance of Batteries (5E40.75) -- Voltage from two sets of dry cells (old and new) are measured for an open circuit and a closed circuit with a load. Both sets show a voltage on an open circuit. For the fresh set of cells, voltage does not drop significantly when the load is added, but for the old set of cells with high internal resistance the voltage drops to practically zero.

Opposing EMF's -- Batteries are hooked together backwards to show the subtractive effect of opposing EMF's.

5E50. Thermoelectricity
Thermocouple (5E50.10) -- Current registers on a milliammeter when this large twisted wire thermocouple junction is heated in a flame.

Thermoelectric Magnet (5E50.30) -- Heat and cool opposite sides of a large thermocouple. Suspend a large weight from an electromagnet powered by the thermocouple current.

Thermoelectric Heat Pump (5E50.60) -- Mount aluminum blocks with digital thermometers on either side of a Peltier device. Run the current both ways.

5E60. Piezoelectricity
Piezoelectric Sparker (5E60.20) -- a piezo crystal sparker that can be used to charge an electroscope.

Piezoelectric Gas Lighter with Neon Lamp (5E60.21) -- The piezo element in a modified gas fire starter develops sufficient voltage to flash a neon lamp.

5F: DC Circuits
5F10. Ohm's Law

Ohm's Law (5F10.10) -- Uses the Resistance Wires (5D10.20) board described above, but in this demo the voltage is also varied, so that the dependence of current on voltage and resistance can be shown.

5F15. Power and Energy

Voltage and Current in House Lines (5F15.40) -- A bank of lamps and heaters are hooked up in parallel to 120 VAC. A switch on each allows them to be turned on and off independently. As each element is added to the circuit, the voltage and current flowing into the circuit are displayed on meters to allow calculation of power consumption. A fuse and/or circuit breaker may be added to the circuit to show the function of such safety devices, and the current may also be run in on an iron wire which will overheat and burn a paper rider if the breakers are bypassed and the “safe” current limits are exceeded. A good way to teach students not to stick pennies in fuse sockets!

Circuit Breaker -- A standard household magnetic breaker which will shut off current to a load if the current exceeds approximately 3 Amps.

I2R Losses (5F15.45) -- A nichrome wire, an iron wire, and a copper wire are hooked up in series with a Variac. A small paper rider is wrapped around each wire. As the voltage is increased, the wires begin to heat up in order of decreasing resistance. Although the current (and thus I2) is the same for all wires, the wire with the greatest R (nichrome) heats up first and burns its paper rider. Increasing the voltage (and current) further makes the iron wire burn the paper and makes the nichrome glow red-hot. The copper wire barely gets warm.

5F20. Circuit Analysis

Sum of IR Drops (Kirchoff's Voltage Law) (5F20.10) -- Three large variable resistors are hooked in series with a battery. The voltage drop across each resistor is measured with a voltmeter, and the sum of the IR drops is found to equal the battery voltage. The battery voltage may be varied.

Conservation of Current (Kirchoff's Current Law) (5F20.16) -- Current entering and leaving a circuit node can be read on three ammeters, and compared to show that current coming in is always equal to current going out of the node. Can also be used as a two-loop circuit to show the applications of Kirchoff's laws to analyze current flow in a slightly complex circuit.

Slide-Wire Potentiometer (5F20.30) -- Classic highly accurate voltage measuring device.

Wheatstone Bridges (5F20.40) -- Devices which measure resistance by balancing voltage drops over two different paths, one of which includes the resistor to be measured. Three types are available: (1) With Lamps - a demo item to show the principle but not make actual measurements, (2) With Slide-Wire - to make actual measurements, and (3) Commercial Bridge - a show-and-tell item.

Series and Parallel Light Bulbs (5F20.50) -- Two sets of three light bulbs, one hooked up in parallel and the other in series, will clearly
show the different current in the two circuits by the relative brightness of the bulbs.

Series and Parallel Resistance (5F20.55) -- Two identical resistance wires on a board are hooked across a battery, either singly, in series, or in parallel, and the resulting current for the different hookups is measured with an ammeter.

Resistor Cube -- Twelve identical resistors are soldered together to form the edges of a cube, whose resistance can be measured across an edge, a face, or across the entire cube from corner to corner.

5F30. RC Circuits

RC Charging Curve on Scope (5F30.20) -- An oscilloscope is hooked across a capacitor which is in series with a battery and resistor. When the switch is closed the capacitor begins to charge and the rising voltage is seen on the scope. Releasing the first switch and pressing another discharges the capacitor, with the resulting discharge curve shown on the scope. Circuit elements are laid out on a vertical board for easy viewing and analysis.

RC Circuit Analog -- A flat disc tied to the end of a spring is submerged in a large glass jar of water. Pull up suddenly on the end of the spring and the disc will rise in the water, quickly at first then more slowly as it approaches equilibrium, just as does the RC circuit described above. The spring is analogous to the capacitor in the RC circuit - pulling on it suddenly is the same as applying a sudden voltage - and the resistance of the water to the motion of the disc is the analogue of the electrical resistance in the circuit. The distance that the disc moves is the analogue of capacitor charge.

Relaxation Oscillator (5F30.60) -- A capacitor, resistor, and 90V battery are hooked in series, with a neon bulb in parallel with the capacitor. The capacitor charges to about 80V (the breakdown voltage of the neon bulb), then discharges through the bulb and begins the cycle again. The capacitor voltage curve can be displayed on an oscilloscope.

Emergency Flasher -- A commercial emergency flasher uses a 9V battery to flash a neon lamp at approximately 2 Hz. (Battery voltage is stepped up internally to provide the 600 volts needed to flash the tube).

Strobe Light -- A commercial strobe light with variable frequency flash.

5F40. Instruments

Galvanometer as Ammeter and Voltmeter (5F40.20) -- A galvanometer is used with shunt and series resistors.

5G: Magnetic Materials

5G10. Magnets

Lodestone (5G10.16) -- A rock formed of magnetite, a naturally-occurring magnetic mineral. Color-coded with North and South poles.

Broken Magnets (5G10.20) -- A broken bar magnet held together by its magnetism acts as a single magnet when whole. It can be pulled apart into two or more pieces and their fields traced with compasses and/or iron filings to show that each piece is also a complete magnet.

5G20. Magnetic Domains and Magnetization

Barkhausen Effect (5G20.10) -- A soft iron core is surrounded by a pickup coil. Bringing a permanent magnet near causes domains in the iron to flip, which is picked up by the coil and amplified into a crackling, rushing noise.
Magnetic Domain Model (5G20.30) -- A plastic plate holds small bar magnets on bearings which simulate domains - they line up with one another, flip in the presence of an external field, etc. Use on the overhead projector.

Permalloy Bar in Earth's Field (5G20.55) -- A permalloy rod (iron and nickel) is not itself magnetic but has a high magnetic permeability. If the rod is aligned with a pre-existing magnetic field such as the Earth's or a magnet's, it becomes magnetic enough to pick up small pieces of iron.

Huesler Alloy -- An alloy of manganese, aluminum, and copper is attracted to a magnet even though none of its constituent metals is magnetic by itself.

Electromagnet with 1.5 Volt Battery (5G20.70) -- A small electromagnet powered by a 1.5V battery that can hold several kilograms.

Big Electromagnet (5G20.72) -- A huge coil carries up to 25A; very strong field will attract nails, etc. that are thrown near. Nail on a string allows the shape of the field to be probed, and the removable iron core concentrates the magnetic flux. Note: See also Lamp in Parallel with a Solenoid (5J20.20).

5G30. Paramagnetism and Diamagnetism

Paramagnetism and Diamagnetism (5G30.15) -- Test tubes filled with manganese chloride, copper sulfate and bismuth are balanced at opposite ends of hanging bars which are free to rotate. Bring a powerful horseshoe magnet near the manganese chloride (paramagnetic) and it will be pulled slowly into the magnet. The copper sulfate (also paramagnetic) will be less strongly attracted to the magnet. Bismuth (diamagnetic) will be slightly repelled.

5G40. Hysteresis

Hysteresis Waste Heat (5G40.50) -- A thimbleful of water sits atop the secondary coil of a transformer. Waste heat from eddy currents and magnetic hysteresis boils the water.

5G45. Magnetostriiction and Magnetores

5G50. Temperature and Magnetism

Heated Canadian Nickel (5G50.15) -- Nickel (Curie temp: 358 °C) is magnetic at room temperature and non-magnetic when heated with a gas torch. A Canadian nickel hangs from a wire and is initially suspended by a strong magnet. After heating, the nickel falls away from the magnet.

Dysprosium with Liquid Nitrogen (5G50.25) -- Dysprosium (Curie temp: -188 °C) becomes magnetic when cooled with liquid nitrogen. A piece of dysprosium hangs freely at room temperature. After cooling it is attracted to a strong magnet, but falls away as it warms up.

The above two demonstrations work nicely together.

Curie Temperature Wheel (5G50.20) -- A rotating wheel (made of 70% iron and 30% nickel) passes through the poles of a magnet, and has a Curie point slightly above room temperature. A spot on the wheel directly above the magnet is heated with focused light and loses its magnetic properties. The spot directly below the magnet is then drawn upwards and the wheel begins to revolve. By the time the first hotspot makes a complete circle, it has cooled enough that the spinning is continuous.

Meissner Effect (Superconductor Levitation) (5G50.50) -- A LN2 cooled ceramic superconductor (Yttrium Barium Copper Oxide,
YBa2Cu3O7) will levitate a small rare-earth magnet due to induced eddy currents in the superconductor.

5H: Magnetic Fields And Forces

5H10. Magnetic Fields

**Compass (5H10.11)** -- Large arrow compass to demonstrate Earth's field, field around magnets, solenoids.

**Dip Needle (5H10.15)** -- The compass above may be oriented vertically along a North-South line to serve as a large dip needle to show the angle of declination of the Earth's field.

**Oersted's Needle (5H10.20)** -- A compass is brought near a wire carrying a large current. Or a compass is set near the wire with the DC power supply turned off. When the power supply is turned on, the compass will reorient itself to be perpendicular to the current.

**Magnetic Fields Around Magnets on Overhead Projector (5H10.30)** -- Iron filings on a plastic shield are placed on the overhead projector and used to show the shape of the field around bar and horseshoe magnets. Small transparent compasses are also available to show the sense of the field.

**Magnetic Shielding (5H10.61)** -- Various metals, etc. are inserted between an electromagnet and some nails the magnet is holding up. Materials that are magnetic (iron) absorb the magnetic flux, allowing the nails to fall - nonmagnetic materials don't. A double thickness of iron causes more nails to fall. Warning: We're not sure how reliable this demo is.

5H15. Fields and Currents

**Magnetic Fields Around Conductors on Overhead Projector (5H15.10)** -- Bare wires in various configurations on transparent boards carry a large current; board is placed on overhead and sprinkled with iron filings to show shape of the field. Small transparent compasses can be used to show the sense of the field.

5H20. Forces on Magnets

**Magnetic Attraction and Repulsion (Bar Magnets on Pivot) (5H20.10)** -- Bar magnets on a pivoting stand show attraction and repulsion. Note: See also Electrostatic Attraction and Repulsion (5A20.10).

**Levitron (5H20.22)** -- A spinning magnetic top that levitates stably (sort of) above a large permanent magnet. It takes some adjustment to get it working right, so please give us lots of notice and be prepared to practice beforehand.

5H25. Magnet/Electromagnet Interaction

**Hanging Solenoid and Bar Magnet (5H25.10)** -- Free-hanging solenoid interacts with a pivoting bar magnet only when the current is on. The interaction is weak at first, but is much stronger with the iron core in place.

5H30. Force on Moving Charges

**Electrostatic Deflection of an Electron Beam (Oscilloscope)** -- An external DC power supply is connected to either the vertical or horizontal plates of the open oscilloscope. Changing the applied voltage changes the deflection of the electron beam.

**Magnetic Deflection of an Electron Beam (Open Oscilloscope) (5H30.10)** -- An electron beam is deflected by the field from a bar magnet.
**Magnetic Deflection of an Electron Beam (Crooke's Tube) (5H30.15)** -- An electron beam is deflected by the field from a bar magnet.

**Fine Beam Tube (5H30.20)** -- An electron beam in an evacuated glass sphere is bent into a circle by the magnetic field from a pair of large Helmholtz coils. The beam is faintly visible in a dark room because of collisions with a tiny amount of helium in the tube.

**Thomson's E/M Experiment** -- An electron beam in an open oscilloscope is vertically deflected by an electric field, then by a transverse magnetic field which balances the electric field and reduces the deflection to zero. Ratio of electron charge to mass could then be calculated from the values for deflection and field intensities, but the demo is usually only done qualitatively.

**Ion Motor (Force on Ions) (5H30.55)** -- Cork particles floating in a solution of copper sulfate in a circular container will rotate when current is passed through the solution in the presence of a magnetic field. Reverse either the current or the magnets to reverse the direction of the solution and cork. Remove the magnets and the solution and cork will slowly come to rest.

**5H40. Force on Current in Wires**

**Pinch Wires (5H40.20)** -- Parallel hanging wires are either attracted or repelled by one another, depending on the direction of currents in the wires. Three different configurations.

**Jumping Wire (5H40.30)** -- A single thick wire passes between the poles of a powerful horseshoe magnet. When a heavy duty DC power supply is turned on, the wire jumps out of the field.

**Barlow's Wheel (Video Only!) (5H40.50)** -- A flat disk of aluminum on bearings whose bottom half passes between the poles of a powerful magnet. A large DC current runs from the center to the bottom point of the disk, and the force on the electrons flowing through the magnetic field causes the disk to rotate. Note: This demo is no longer in service, due to concerns over the exposed mercury involved in its operation. It is however, available on our laser disk collection.

**Ampere's Frame (Video Only!) (5H40.70)** -- A square frame of aluminum rod, free to rotate, through which a large DC current flows. A magnet brought near one side of the frame causes rotation (in a direction predicted by the right hand rule). Note: This demo is no longer in service, due to concerns over the exposed mercury involved in its operation. It is however, available on our laser disk collection.

**5H50. Torques on Coils**

**D'Arsonval Meter (Model Galvanometer) (5H50.10)** -- A large open model of an galvanometer. A large coil on spring-mounted bearings twists in the magnetic field of a magnet when current flows in the coil.

**5J: Inductance**

**5J10. Self Inductance**

**Inductors (Show and Tell) (5J10.10)** -- Various commercial and homemade coils.

**5J20. LR Circuits**

**LR Circuit (5J20.10)** -- A large inductor in series with a resistor, a battery and a switch. When the switch is closed the current rises slowly from zero to a steady-state value as shown by the voltage across the resistor.
Lamp in Parallel with a Solenoid (5J20.20) -- A large DC current introduced suddenly to this large inductor cannot pass through the coil at first, so an incandescent lamp in parallel with the coil lights brightly. After the current becomes steady, the coil draws more current and bulb dims. When the current is switched off suddenly, the induced voltage in the coil (back EMF) again lights the lamp. A separate neon lamp in parallel with the coil shows that the direction of the second voltage surge is the opposite of the first.

5J30. RLC Circuits - DC

Damped LRC Oscillation (5J30.11) -- The capacitor in an LRC circuit is fully charged with a battery, then the battery is removed, a switch is closed and the circuit is allowed to oscillate down to equilibrium. Voltage across the capacitor is displayed on the scope as the oscillations die away.

5K: Electromagnetic Induction

5K10. Induced Currents and Forces

Wire and Magnet (5K10.15) -- A single loop of wire is passed between poles of a large horseshoe magnet, causing current to flow (shown on a galvanometer). The faster the wire is moved, or the greater the number of loops, the larger the current.

Coil Pendulum in Magnet (5K10.18) -- A pendulum with a large coil for a bob swings between the poles of a large horseshoe magnet. A small light bulb wired to the coil flashes when the coil swings through the magnetic field.

Simple Coil and Bar Magnet (5K10.20) -- A coil is connected to a galvanometer. A bar magnet is passed through the coil and the galvanometer measures the current.

10/20/40 Turn Coils with Magnet (5K10.21) -- Coils of 10, 20, and 40 turns wired in series on a common stand, through which a permanent magnet is moved to produce small currents as shown on a galvanometer.

Mutual Induction (5K10.30) -- Two coils slide on a track so that the distance between them can be varied. Current is pulsed into one coil with a switch, which induces current in the second coil. Meters show the currents in both coils, and show that there must be a changing current in the first coil to induce current in the second. Intensity of induced current changes with separation, and various metal cores can be inserted to determine their effect on the magnetic flux.

Earth Coil (5K10.60) -- A hand-held coil is moved in the Earth's magnetic field and produces a current (must be shown with projection galvanometer).

5K20. Eddy Currents

Eddy Current Pendulum (5K20.10) -- A flat plate of aluminum on the end of a pendulum swings between the poles of a magnet. Eddy currents in the plate damp out the swing. Both a plate and a ring are available, split and unsplit. The split limits the size of the eddy currents and greatly decreases the damping in both plate and ring.

Eddy Current Brake (5K20.22) -- A motorized spinning aluminum disk can be slowed down by slipping the poles of a magnet over the edge.

Eddy Current Free Fall (5K20.25) -- A magnet and a piece of brass slide down either a length of aluminum channel or copper pipe. The copper pipe has a much stronger effect but is less visible than the aluminum channel.
Thompson’s Flying Ring (Jumping Rings) (5K20.30)  -- AC in a large solenoid creates eddy currents in an aluminum ring and the ring goes flying; a split ring does not. Also includes rings made of iron and copper. This uses the same setup as Vertical Primary Coil and Secondary Coils with Lamps (5K30.30).

Arago’s Disk (5K20.42)  -- An aluminum disk spins beneath a magnet on bearings, causing the magnet to rotate due to eddy currents in the plate. The magnet may be restrained by a rubber band to make a model of a speedometer linkage.

Spinning Can  -- A large horseshoe magnet is spun over an aluminum can sitting on a pivot. The can spins in the same direction as the magnet due to eddy currents from the rotating magnetic field.

5K30. Transformers

Ferromagnetism (Rowland Ring)  -- Show and tell simple transformer.

Transformers (5K30.20)  -- Two coils sit on a common iron core. AC is fed into one coil, and the magnitude of the voltage in the second coil is shown by the brightness of a lamp. Turn ratios can be 1:1, 2:1, or 1:2.

Transformer Laminations  -- A transformer core that has been pulled apart to show the individual laminations.

Vertical Primary Coil and Secondary Coils with Lamps (5K30.30)  -- A tall primary coil that carries AC has an iron core which extends out of the top. Two secondary coils with different numbers of turns can be placed on top to light a small or large light bulb. Same setup as Thompson’s Flying Ring (Jumping Rings) (5K20.30).

Transformers and Power Lines  -- A step-up transformer with a turn ratio of 250 to 1000 converts 110 Volts from the wall (indicated by a 60 Watt bulb) into over 400 Volts. This is transmitted 30 feet across the width of the room (with a couple high resistance rheostats simulating hundreds of miles of power line) to an identical step-down transformer and a second 60 Watt bulb. Start with both transformers disconnected to show the huge power loss over the long distance (the second bulb will be dim). Then connect both transformers and the second bulb will be nearly as bright as the first.

5K40. Motors and Generators

DC Motor (5K40.10)  -- A large open coil powered by DC current through a split-ring commutator spins between the poles of a set of permanent magnets. See also AC and DC Generator (5K40.40).

Faraday Disk Dynamo (5K40.15)  -- An aluminum disk spinning between magnet poles produces a current between the center and the edge of the disc as shown on a large galvanometer.

AC and DC Generator (5K40.40)  -- A large model generator with a coil spinning between permanent magnets. Can produce DC (split-ring commutator) or AC (solid ring) current. Good visibility. Can also be run as a DC Motor (5K40.10).

Army Surplus Generator (5K40.80)  -- A hand-cranked generator will provide up to 60 watts of output power for an incandescent light bulb. Use the Hand Crank Generator with Lamp if you’re interested in showing/feeling the back EMF.

Hand Crank Generator with Lamp  -- A small crank generator lights lamp - easier to turn with the bulb out of the socket.

Genecon Generators  -- Two small hand cranked generators can be connected to each other (spin one and the other will spin as well), or to a small light bulb.
Falling Weight Generator (SK40.85) -- A weight on a string wrapped around the shaft of a generator falls more slowly when there is an electrical load on the generator.

5L: AC Circuits

5L10. Impedance

5L20. RLC Circuits - AC

Driven LRC Circuit (SL20.18) -- A LRC circuit is driven by a 60 Hz input, and the resulting voltage and current across any component can be displayed on an oscilloscope. I and V are tested by means of a probe that plugs into a highly-visible schematic board which shows the electrical location of the probe. All components can be varied to determine the effect on resonance as shown by the voltage on the screen. Phase shifts between I and V may be shown for each component.

5L30. Filters and Rectifiers

Rectifier Circuit (SL30.10) -- A diode rectifier circuit mounted on a vertical board can be probed at different points with an oscilloscope to see the effect of diode rectification on an AC voltage. Filtering elements at the output end of the circuit may be switched in and out to demonstrate the smoothing of ripples in the DC output.

5M: Semiconductors And Tubes

5M10. Semiconductors

Hall Effect Probe (SM10.10) -- Shows the voltage developed at right angles to a current in a conductor in a magnetic field; as used in Gaussmeters.

Solar Cells -- A small bank of solar cells hooked to a milliammeter produce current, increasing with brighter light.

Electroluminescent Panel -- A solid state panel glows with a pale green light when energized by the proper voltage.

5M20. Tubes

Tube-Style Radio Circuit -- An old style radio circuit laid out schematically shows the function of various parts of the circuit.

Large Radio Tubes -- 30cm tall amplifier tubes may be shown with a modern transistor to show advancement of the technology.

See also Thermionic Emission (Edison Effect) (SD40.42).

5N: Electromagnetic Radiation

5N10. Transmission Lines and Antennas

Radio and Charging Rod -- A plastic rod is charged by rubbing it vigorously with a wool cloth. The small discharges between the rod and the cloth give off electromagnetic noise that can be picked up on an AM radio.

Cenco 3-meter Transmitter (SN10.60) -- A small tube-style dipole transmitter sends radio waves to a pickup antenna, lighting a small bulb in the center of the antenna. Moving the antenna away from the transmitter dims the bulb, and rotating the antenna at right
angles extinguishes the bulb, showing the polarized nature of the radio waves.

**EM Spear (5N10.80)** -- A large rolling model of an electromagnetic wave shows the relation between electric and magnetic field vectors.

**5N20. Tesla Coil**

**Induction Coil (5N20.10)** -- A standard induction coil with mechanical "make and break" oscillator produces approximately 100,000 V.

**Tesla Coil (5N20.50)** -- Tesla air-core resonant transformer produces 1/2 million volts at 350 kHz.

**Hertzian Waves** -- A spark transmitter has two large resonant circuits (jar capacitor and resistance) tuned to the same frequency - transmitter circuit is powered by a spark coil, receiver picks up electromagnetic waves emitted and lights a neon bulb. Receiver can be detuned to show decreased efficiency.

**5N30. Electromagnetic Spectrum**

**White Light Spectrum (5N30.10)** -- Project white light through a high dispersion prism.

**Ultraviolet Spectrum (5N30.15)** -- White light from a carbon arc lamp falls on a screen of half white paper and half fluorescent paper.

**Microwave Transmitter and Receiver Set (Brett's Microwave Apparatus) (5N30.30)** -- A microwave emitter and receiver are mounted on a vertical circular board. The emitter is stationary, while the receiver is free to rotate with the board. A bar-graph display mounted on the board shows the intensity of the microwave signal picked up by the receiver as it is moved around. Note: Please specify which of the following effects you would like to show:

- Straight Line Propagation
- Reflection from Flat Surfaces (See 6A10.18)
- Refraction
- Single Slit Diffraction (See 6C10.50)
- Double Slit Interference (See 6D10.20)
- Multiple Slit Interference
- Waveguide
- Interferometer (See 6D40.20)
- Polarization (See 6H10.20)
- Bragg Diffraction (See 7A60.50)
- Total Internal Reflection
- Barrier Penetration (Tunneling) (See 7A50.20)

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6: Optics

6A: Geometrical Optics
6B: Photometry
6C: Diffraction
6D: Interference
6F: Color
6H: Polarization
6J: The Eye
6Q: Modern Optics
6A: Geometrical Optics

Various Light Sources -- a collection of show and tell light sources from candles and carbon arcs to noble-gas discharge tubes, LEDs, and lasers.

6A01. Speed of Light

6A02. Straight Line Propagation

Light and Siren in Vacuum (6A02.10) -- a small electronic siren and a LED are mounted inside a bell jar. The air is then evacuated from the jar, and although the LED can still be seen, no sound can be heard from the siren. Also listed as 3B30.30.

Straight Line Propagation (6A02.15) -- cast shadows of a hand, etc. from a carbon arc lamp without a lens, and/or show laser beam through chalk dust cloud.

6A10. Reflection from Flat Surfaces

Angle of Incidence and Reflection (6A10.11) -- a beam of white light falls on a mirror mounted on a large rotating protractor. Various angles of incidence and reflection can be compared to show that \( I = R \).

Microwave Reflection (6A10.18) -- Reflect a microwave beam off a metal plate into a receiver.

Diffuse and Specular Reflection (6A10.20) -- reflect white light or a laser off a rough surface to show diffuse reflection. Compare with a mirror, metal surface, etc.

Corner Reflector (6A10.30) -- three plane mirrors joined to form the corner of a cube. This has retroreflecting properties, and is similar to the reflectors left on the moon for laser distance determinations and the reflectors in those brightly reflecting roadway lane dividers.

Parity Reversal (6A10.37) -- two ball-and-stick figures (Cartesian coordinate systems) of opposite “handedness” are used with a plane mirror to show parity reversal of reflected images.

Image Reversal (DIXIE/SOUTH) -- DIXIE has mirror symmetry along the horizontal axis and appears unchanged in the mirror, but SOUTH looks quite different. Also CHECK/THIS.

Image Perversion (TIME/EMIT) -- the word “TIME” is printed on a clear sheet of acrylic which is backed with an opaque sheet of cardboard. When you turn it around to face the mirror, the students will see that the word is reversed left-to-right (“EMIT” with a backwards E). Many students think that the mirror has reversed the word left-to-right. Pull the cardboard off and they will see that the image has the same left-to-right orientations the original - you reversed it left-to-right when you turned it around.

Hinged Mirrors (Multiple Rejections) (6A10.40) -- two plane mirrors are joined with a hinge and can be adjusted to various angles. A small flashlight bulb mounted between the mirrors is the object, and the number and positions of its images are noted as the angle between the mirrors changes.

Parallel Mirrors (“Barbershop Mirror” Effect) (6A10.45) -- two plane mirrors are placed parallel to and facing one another. An object is placed between them and multiple images are seen in the view past the edges of the front mirror.
**Beer Sign** -- a commercial sign using the "Barbershop Mirror" effect. Beer logo is placed between two mirrors, the front mirror being partially transparent. Some of the light bouncing between the mirrors escapes through the front mirror, and multiple images of the logo are seen.

**Location of Image (Candle in a Glass of Water) (6A10.60)** -- a vertical glass window pane stands between two objects - a candle in front and a beaker of water in the rear at the position of the candle's image in the glass. The image of the candle appears to be burning under water. The entire stand can be rotated to show that the position of the candle's image relative to the glass does not change with different viewing angles.

6A20. Reflection from Curved Surfaces

**Concave and Convex Mirrors On Optics Board (6A20.10)** -- uses the optics board to trace incident and reflected rays from concave and convex mirrors. See also Lenses On Optics Board (6A60.20).

Large Concave Mirror (6A20.31):
- **Strawberry** -- real image of plastic strawberries placed in front of the mirror.
- **Candle Burning at Both Ends** -- a burning candle placed slightly above the center of curvature of the mirror has a real image of the flame at its bottom - it appears to be burning on both ends.
- **One Candle Searchlight** -- burning candle placed at the focus of the mirror throws a roughly parallel beam to the far wall.

6A40. Refractive Index

**Broken glass in Oil (6A40.30)** -- Broken glass fragments will disappear in mineral oil because they have near identical indices of refraction. Tip the container to see the effect.

**Mirage with a Laser (6A40.47)** -- A laser beam almost grazing a hot surface will show deflection.

6A42. Refraction from Flat Surfaces

**Refraction and Reflection from a Plastic Block (6A42.12)** -- a large rectangular acrylic block on the optics board (see above) will refract and partially reflect incident beams. Can be rotated to various angles to vary the angle of incidence/refraction.

**Small Refraction Tank (6A42.43)** -- A lamp is positioned in an opaque tank so the filament cannot be seen. Add water until the light from the filament is refracted and seen over the edge of the tank.

**Refraction from Water Tank (6A42.45)** -- A stick appears bent or broken when inserted into water at an angle.

**Acrylic and Lead Glass Refraction (6A42.47)** -- Hold a stick behind a block of acrylic (n=1.4) and lead glass (n=2). At each interface (air to acrylic and acrylic to lead glass), the image of the stick is shifted when viewed off the normal to the surface of the blocks.

**Apparent Depth** -- the lead glass and acrylic blocks mentioned above, when viewed from an angle, demonstrate the apparent depth effect. The edge which is viewed directly shows the true depth of the blocks; the edge viewed through the blocks appears shorter, or closer to the surface.

6A44. Total Internal Reflection
Critical Angle and Total Internal Reflection (6A44.20) -- a parallel beam of light traveling underwater is reflected up to the water/air interface by a small mirror. The mirror may be rotated to change the angle of incidence. Fluorescein in the water and a thread screen above the water allow the incident, refracted, and reflected beams to be seen clearly. As the angle of incidence reaches the critical angle, the refracted beam is seen to skim just over the surface of the water. Increase the angle slightly from that, and the refracted beam disappears while the reflected beam jumps in intensity (total internal reflection).

Light Pipes and Fiber Optics (6A44.40) -- Transmit white light or a laser beam through straight and curved Lucite rods, or various optical fibers.

6A46. Rainbow

Rainbow on Optics Board (6A46.30) -- using a single beam of white light and large acrylic disc on the optics board.

Note: The following two rainbow demonstrations are only viewable individually or in small groups.

Artificial Rainbow (Water Flask) -- a round flask filled with water simulates a raindrop, casting a small rainbow on the screen when illuminated with a carbon arc.

Rainbow (Glass Beads) -- a point source of light situated above a black velvet board covered with tiny glass beads creates a rainbow.

6A60. Thin Lens

Lenses On Optics Board (6A60.20) -- concave and convex lenses on the optics board show the basic properties of lenses, ray tracing, etc. See also Concave and Convex Mirrors On Optics Board (6A20.10).

Image Formation (6A60.30) -- light from a backlit "object" is focused by a convex lens onto a translucent screen. Image reversal and magnification can be shown.

Conjugate Focal Positions -- the above arrangement is used to show that there are two lens positions which will form an image on the screen.

Magnification (6A60.35) -- a backlit black-and-white grid and a large (12 in.) lens are used to demonstrate magnification by convex lenses. Also good for showing spherical and chromatic aberrations. Note: See also Fresnel Lens Magnification (6A65.70).

6A61. Pinhole

Pinhole Camera Effect (6A61.20) -- large but workable pinhole camera projects the image of a lamp filament onto a translucent screen.

6A65. Thick Lens

Chromatic Aberration (6A65.21) -- shows different points of focus for red and blue light through a large plano-convex lens. Can also show colored halo around focused white light.

Achromatic Pair -- shows correction of chromatic aberration using a correcting lens.

Spherical Aberration (6A65.40) -- shows different points of focus for different areas of a large plano-convex lens. First the outer half of the lens is blocked off, and an image is brought to focus using the lens. Then the inner half is blocked off, and the image is seen to
be out of focus. The image can now be brought back to focus by moving the lens. The image formed by the outer half of the lens is seen to be fuzzier than that formed by the inner half.

**Fillable Air Lenses (6A65.52)** -- air-filled lenses held under water in a parallel beam of light show "reverse" refraction in going from a higher to a lower index of refraction. Concave lens focuses beam, etc. Removing your finger from the top of the handle tube allows the lens to fill with water, so that the medium of the lens is the same as the surroundings and the parallel beam of light passes through without effect. Remove the water-filled lens thus formed from the optics tank and insert it in the thread screen to show that its focusing properties are now the opposite of the original air-filled lens.

**Glass Lenses in Air and Water** -- a lens is inserted in the thread screen to show the focal length, then is dipped into the optics tank to show a much longer focal length in water due to the greater refractive index of the medium. Can also be done with the optics tank half-full to show both focii simultaneously.

**Cylindrical Lens** -- shows properties of a cylindrical lens.

**Fresnel Lens Magnification (6A65.70)** -- Magnification (6A60.35) using a large plastic Fresnel lens.

### 6A70. Optical Instruments

**Microscope Model (6A70.10)** -- A working model of a simple microscope. Note: This works quite well with the Telescope Models (6A70.20).

**Projection Microscope** -- a self-contained projection microscope magnifies the grids from two fine wire mesh screens.

**Microscope Chart** -- an overhead transparency chart showing the components of a microscope.

**Telescope Models (6A70.20)** -- Choose any or all of the three types listed below. We use an eye chart for the object, and small video cameras for class viewing.

- **Galilean (Non-inverting) Telescope** -- uses a converging objective lens and a diverging eyepiece lens to produce a non-inverted image.

- **Keplerian (Inverting) Telescope** -- uses two converging lenses to produce an inverted image (but with a wider field of view and greater magnification).

- **Newtonian (Reflecting) Telescope** -- a simple off-axis Newtonian reflector gives an upright (but mirrored left-right) image.

**Zoom Lens** -- a slide projector so equipped.

### 6B: Photometry

#### 6B10. Luminosity

**Inverse Square Law (6B10.20)** -- Double or triple the distance between a point light source and a photometer.

**Light Meters** -- electronic photometers, one with digital and one with analog output.
6B30. Radiation Pressure
6B40. Blackbodies

**Bichsel Boxes (6B40.20)** -- two 3x5 index card boxes each with a small hole in the lid; one is painted black inside and the other white. Hold the boxes up to the students with the holes facing them and they appear almost identical. Open the lids and the difference is obvious. Useful in discussing blackbody cavity radiation.

**Blackbody Radiator (6B40.26)** -- a small metal cube has a narrow hole drilled in the side. As viewed with a video camera, the hole appears darker than the surrounding metal. If the cube is heated with a blowtorch to a high enough temperature, the hole will glow brighter than the surrounding metal.

**Infrared in the Spectrum (6B40.41)** -- light from a hot carbon arc is spread into a spectrum, then various portions of the spectrum are scanned with a thermopile. It is shown that the greatest amount of energy is in the infrared portion of the spectrum where no visible light exists, then tapers off into the visible and disappears in the ultraviolet. Note: This is done on the same setup as Ultraviolet in the Spectrum (7B13.40).

**Radiation Spectrum of a Hot Object (6B40.55)** -- light from a slide projector powered by a variac is spread into a spectrum. With the variac at a low setting the projector bulb is red-hot and the spectrum consists of red light only. Turn the variac up slowly, and as the temperature of the bulb increases the spectrum comes to include orange, yellow, green, and (at white heat) blue light.

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**6C: Diffraction**

Please see section 3B50. Interference and Diffraction for ripple tank demonstrations.

**6C10. Diffraction Through One Slit**

**Laser and Single Slit (6C10.10)** -- a laser beam passes through a slide with four single slits of known widths.

**Laser and Single Slit (Cornell Slide) (6C10.12)** -- The Cornell slide has several single slits of various widths as well as a gradually widening slit.

**Laser and Adjustable Single Slit (6C10.15)** -- a variable-width single slit shows diffraction of a laser beam.

**Microwave Single Slit Diffraction (6C10.50)** -- single slit diffraction of microwaves.

**6C20. Diffraction Around Objects**

**Arago's (or Poisson's) Bright Spot (6C20.10)** -- Light from a laser is diffracted by a small ball bearing and is viewed using a camera and TV. This is on the same table as Point and Eye of a Needle (6C20.22).

**Hair or Thin Wire (6C20.20)** -- projected diffraction pattern from a thin wire in a laser beam.

**Point and Eye of a Needle (6C20.22)** -- Light from a laser is diffracted by the point or eye of a needle and is viewed using a camera and TV. This is on the same table as Arago's (or Poisson's) Bright Spot (6C20.10).

**Knife Edge Diffraction (6C20.15)** -- a projected edge diffraction pattern using a razor blade, laser, and lens.
Aperture Diffraction (Airy Disk) (6C20.30) -- projected circular diffraction pattern from passing a laser beam through a small aperture.

Diffraction from a Feather (6C20.62) -- a laser beam passing through the closely-spaced hairs of a feather will spread into a diffraction pattern on the screen.

6D: Interference

Please see section 3B50. Interference and Diffraction for ripple tank demonstrations.

6D10. Interference From Two Sources

Laser and Double Slits (6D10.10) -- A laser passes through a slide with four double slit combinations (two different slit widths and two spacings).

Laser and Double Slits (Cornell Slide) (6D10.11) -- The Cornell slide has various double slits as well as a gradually widening double slit.

Microwave Double Slit Interference (6D10.20) -- three double slit spacings for the microwave apparatus.

6D15. Interference of Polarized Light

6D20. Gratings

Laser and Multiple Slits (6D20.10) -- A laser passes through a slide with 2, 3, 4, and 5 slits.

Laser and Multiple Slit Interference (Cornell Slide) (6D20.10) -- The Cornell slide has five sets of multiple slits.

Transmission Gratings with White Light and Lasers (6D20.20) -- White light and two lasers (one red, one green) are passed through four diffraction gratings of various line densities. The white light produces a continuous spectrum and the two lasers produce different diffraction patterns.

Two Dimensional Gratings (6D20.35) -- very fine wire mesh slides (100 to 3,000 lines per inch) and a laser produce two dimensional patterns.

Crossed Gratings and a Laser (6D20.50) -- a pair of 1D gratings at right angles diffracts laser light into a two dimensional pattern.

Point Source and Wire Mesh (6D20.55) -- a point source of white light is viewed through small pieces of wire mesh handed out to the students. The weave of the mesh is fine enough to diffract the light.

Reflection Gratings -- concave reflection gratings can simultaneously disperse and focus white light.

6D30. Thin Films

Newton's Rings (6D30.10) -- white light projection of interference patterns from a thin layer of air between two layers of glass; one flat and the other curved but nearly flat. A concentric circular interference pattern is obtained which can be varied by squeezing the plates of glass.
Soap Film Interference (6D30.20) -- white light is reflected off a thin soap film onto a screen. Dazzling multicolor interference patterns are formed, with rough bands of different colors indicating the varying thickness of the film. Eventually a dark area forms at the top (where the film is less than a quarter wavelength thick), spreads down throughout the pattern, and the film pops.

Glass Plates in Sodium Light (6D30.30) -- two large flat glass plates are stacked and illuminated by a sodium lamp. The yellow and black interference fringes are easily visible to the entire class.

Pohl's Mica Sheet (6D30.40) -- violet light from a mercury arc is reflected from a thin sheet of mica onto a screen to produce a circular interference pattern from the interference of reflections from the front and back surfaces of the mica.

Interference Filters (Dichroic Filters) (6D30.60) -- thin film layers of various thicknesses on glass are inserted in the thread screen to demonstrate their effect upon a beam of white light. Both reflected and transmitted colors can be seen simultaneously, and the reflected color is seen to be different than the transmitted color. Changing the angle of incidence changes the colors.

6D40. Interferometers

Michelson Interferometer - Laser (6D40.10) -- The Michelson Interferometer and laser.

Michelson Interferometer - Microwaves (6D40.20) -- Interference maxima and minima from microwaves are detected as one of the "mirrors" is moved.

Fabry-Perot Interferometer (6D40.35) -- a workable interferometer but with poor mirrors (low finesse).

6F: Color

6F10. Synthesis and Analysis of Color

Additive Color Mixing Box (6F10.10) -- a box containing red, blue, and green light sources with individual brightness controls shows aspects of additive color mixing, primary and secondary colors, etc.

Color Filters (6F10.20) -- various color filters used with white light.

Subtractive Color Mixing -- colored filters are stacked on the overhead to show subtractive color mixing.

Newton's Color Disk (6F10.25) -- a disk sectioned into primary colors "smears" into white light when rotated.

Spinning Black and White Disks -- illusion of color on a spinning black and white disk due to the eye's different reaction speeds to different colors.

Recombined Spectrum (6F10.30) -- a continuous spectrum from a prism is recombined into white light with a second prism.

Colored Objects in Spectrum (6F10.75) -- objects colored with fairly pure hues are moved through a white light spectrum to show reflectivity and apparent color in different colors of light.

Polaroid-Land Effect -- Two black and white slides of the same image are projected so that they overlap on the front screen. Specific red and green filters are placed in front of each slide projector. This causes the black and white image to appear in full color.
6F30. Dispersion
6F40. Scattering

**Artificial Sunset (6F40.10)** -- A beam of white light is scattered when passing through a water tank that also contains a hypo solution (Sodium Thiosulfate) and acid.

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6H: Polarization

6H10. Dichroic Polarization

**Polaroid Sheets (6H10.10)** -- 12" x 12" sheets of Polaroid material for use on the overhead projector.

**Polarization of Microwaves (6H10.20)** -- polarized microwaves pass through a metal grating; the orientation of the grating (vertical or horizontal) greatly affects the intensity of the transmitted beam.

**Slotted Boxes (6H10.30)** -- a rope passes through slots in wooden boxes which can be horizontal or vertical. Wiggle the rope and the first box "polarizes" the wave. The wave will either stop at the second box or pass through, depending on whether the slot is crossed or parallel to the first.

**Vector Models** -- dowel rod models for plane and circular polarization.

6H20. Polarization by Reflection

**Polarization by Reflection (Brewster’s Angle) (6H20.10)** -- a beam of white light reflects off a glass plate and appears on the wall. Interpose a Polaroid sheet and rotate it to show that the reflected beam is polarized. Do the same with the beam shining straight onto the wall to show that the unreflected beam is not polarized. The angle of incidence can be changed to show that there is an optimum angle of reflection for maximum polarization of the beam.

**Polarization by Double Reflection (6H20.20)** -- a parallel beam light source mounted on the edge of a rotation stand strikes a glass plate mounted at the center of the stand and is reflected up along the axis of rotation. The beam then strikes a second glass plate and is reflected onto a translucent screen. The spot of light will be either bright or dim depending on the relative angle between the two glass plates as the stand is rotated through a full turn or more. Polarization state of the transmitted beams may also be checked, using a polaroid sheet.

6H30. Circular Polarization

**Three Polaroid Sheets (6H30.10)** -- Two polaroid sheets (6H10.10) are placed on the overhead projector with their axes of polarization perpendicular to each other (no light passes through). A third polarizer is then placed in between the original two sheets and rotated so that light will pass through.

**Sugar Tube (6H30.40)** -- light passes through a flask of sugar solution (corn syrup) sitting between two Polaroid sheets on the overhead. Adding more syrup increases the path length, changing the transmitted color due to increased optical rotation.

6H35. Birefringence

**Polarization by Double Refraction (6H35.15)** -- a small beam of light passes through a calcite crystal, is doubly refracted, and is projected on a screen as two dots. Rotating a Polaroid analyzer atop the crystal makes the dots appear and disappear in alternation, showing that the beams are polarized perpendicular to one another. Rotating the crystal makes one dot revolve around the other.
Quarter Wave Plate (6H35.40) -- A birefringent plate produces ordinary and extraordinary waves of equal amplitudes, but 90° out of phase. Linearly polarized light will be changed into circularly polarized light. Can be used with a linear polaroid sheet and a mirror.

Polarization by Stress in Plastic (6H35.50) -- transparent acrylic shapes are held between two crossed Polaroid sheets and squeezed. The top polarizer can be rotated or removed.

6H50. Polarization by Scattering

Polarization by Scattering (6H50.10) -- White light passes through a Polaroid analyzer, then is scattered by passage through a tank of water with a little milk added. The polarized light is scattered preferentially in the direction of its polarization, and by rotating the analyzer the direction of most intense scattered light can be varied. A mirror atop the tank allows simultaneous viewing of top and front views for comparison of vertically and horizontally scattered light.

6J: The Eye

6J10. The Eye

Human Eye Model (6J10.10) -- A take-apart model of the human eye.

Resolving Power of the Eye (6J10.80) -- A black screen with four double slit patterns is placed in front of a bright sodium lamp. The double slit patterns vary in separation and the class is asked in which pattern can they resolve both slits.

6J11. Physiology

Eye Defects Transparency -- overhead transparency shows the optical causes of various eye defects.

Color Blindness (6J11.70) -- color blindness slides are projected to test the class.

6Q: Modern Optics

6Q10. Holography

Holograms (6Q10.10) -- A variety of holograms are available using lasers or white light. A video camera allows for whole-class viewing if desired. Note Please give us at least two days notice!

6Q20. Physical Optics

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7: Modern Physics

7A: Quantum Effects
7B: Atomic Physics
7D: Nuclear Physics
7E: Elementary Particles
7F: Relativity
7A: Quantum Effects

7A10. Photoelectric Effect

**Photoelectric Effect with Electroscope (7A10.10)** -- bright white light from an arc lamp strikes a metal plate mounted atop a negatively charged electroscope. The electroscope discharges quickly if the plate is zinc, less quickly for aluminum or copper. Will not discharge if a plate of glass is held between the light and the zinc (cuts out UV), or if the electroscope is positively charged.

**Photomultiplier Tube** -- show and tell.

7A15. Millikan Oil Drop

**Millikan Oil Drop (7A15.10)** -- recreation of the classic experiment used to find the charge of the electron.

**Millikan Oil Drop Analog** -- Two parallel metal plates are connected to a Wimshurst machine with a pith ball connected to the bottom plate. As the machine is cranked, the electric field increases and eventually the force on the pith ball will overcome the force of gravity and it will levitate between the plates. Note: This uses the same setup as the Bouncing Ping-Pong Balls (5B10.30) but without the ping-pong balls.

7A20. Compton Effect

7A50. Wave Mechanics

**Microwave Barrier Penetration (7A50.20)** -- microwaves are beamed into a large plastic prism, and are totally internally reflected off to the side (the detector shows no microwaves penetrating straight through). When another prism is slid up against the first to make a square, the microwaves suddenly penetrate straight through both prisms even though there is still a tiny air gap between the two.

**Vibrating Circular Wire (7A50.40)** -- A 10” diameter loop of thin wire is attached to a speaker driver and driven at specific frequencies that set up standing waves in the loop. Useful for talking about de Broglie waves.

See also Standing Waves in Rubber Tubing (Varying Frequency) (3B22.10).

7A55. Particle/Wave Duality

7A60. X-ray and Electron Diffraction

**Electron Diffraction (7A60.10)** -- electrons emitted from a hot filament are diffracted through a thin layer of polycrystalline graphitised carbon (which acts like a diffraction grating) and hit a fluorescent screen. The diffraction pattern consists of a central bright spot of undeflected electrons and two concentric rings. The diameters of the rings can be changed by altering the accelerating voltage of the electrons (increasing the momentum decreases the de Broglie wavelength).

**Bragg Diffraction of Microwaves (7A60.50)** -- microwaves are beamed into a model "atomic lattice" consisting of regularly-spaced metallic cylinders. Interference fringes are observed as the detector is rotated around the lattice.

**Sample X-ray Tubes (7A60.95)** -- various commercial tubes.

7A70. Condensed Matter

See section 1R50. Crystal Structure.
7B: Atomic Physics

7B10. Spectra

Bohr Atom (Hydrogen Spectrum) -- the spectrum from a Hydrogen spectra tube is seen by the class using pass-out transmission gratings. This is similar to the following demo (Line Spectra) but with only Hydrogen and no other gases.

Line Spectra (7B10.10) -- Hydrogen, Neon, Mercury, and Helium emission tubes are examined with transmission gratings which are handed out to the students. The sources are arranged in a vertical stack and operate simultaneously, so that all four spectra are seen at once. A white light atop the stack may be turned on separately to compare a continuous spectrum with the four quantized emission spectra.

7B11. Absorption

Absorption by Sodium Vapor (7B11.25) -- a salt-soaked stainless steel screen is held in a flame in front of two backlit screens; one lit by white light and the other by sodium light. In front of the white light screen, the flame is transparent and faintly yellow. In front of the yellow sodium light screen, the flame appears black.

Absorption Spectrum of Neophan Glass -- a piece of neophan glass inserted into a continuous spectrum demonstrates broad absorption lines in the yellow and green areas of the spectrum (used to cut out sodium emission glare from hot glass).

7B13. Resonance Radiation

Triboluminescence (7B13.05) -- Crush wintergreen lifesavers and they give off faint flashes of light.

Ultraviolet in the Spectrum (7B13.40) -- light from a Carbon arc lamp is spread into a continuous spectrum, and a fluorescent sheet placed beyond the violet end of the spectrum fluoresces where no visible light exists. Note: This is done on the same setup as Infrared in the Spectrum (6B40.41).

Fluorescence (7B13.50) -- various fluorescent materials are available for viewing under ultraviolet light, including natural minerals, man-made objects, liquids, and paints.

Luminescence (7B13.55) -- a luminescent rubber ball, skeleton etc. which may be charged up by normal (or UV) light for a glow-in-the-dark effect.

Chemiluminescence -- one of those chemical light sticks. Break the vial inside and as the two chemicals mix they emit a green glow.

7B20. Fine Splitting

7B30. Ionization Potential

Frank-Hertz Experiment (7B30.20) -- classic experiment demonstrating quantized energy levels of bound electrons. A voltage/current curve for a discharge through Mercury vapor is displayed on the oscilloscope and seen to contain repetitive peaks and valleys.

Discharge Tube and Vacuum Pump (7B35.10) -- electric current runs through a long glass tube as it is being evacuated. The glow from the current goes from nothing at atmospheric pressure to a maximum at low pressure and finally back to nothing when the tube is fully evacuated. At the proper pressure level, a structured discharge is seen.
Note: The simple Crooke's Tube is in Section 5: Electricity and Magnetism.

**Crooke's Tube with Maltese Cross (7B35.40)** -- electrons fly through a discharge tube and cause a phosphor screen at the end of the tube to glow. Raise a metal cross into the path of the electrons and a cross-shaped shadow appears on the screen, showing that electrons travel in straight lines.

**Crooke's Tube with Paddle Wheel (7B35.50)** -- a small paddlewheel is free to roll along the axis of a Crooke's Tube. When current is flowing through the tube, electrons strike the paddles and transfer momentum to the wheel, rolling it along the tube. Reverse the current and the wheel rolls the other way.

**Plasma Tube (7B35.75)** -- an evacuated tube containing a metal conductor is energized by a Tesla coil and forms long flickering streamers of current which are attracted to fingers touching the outside of the tube.

7B50. Atomic Models

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7D: Nuclear Physics

7D10. Radioactivity

**Geiger Counter (7D10.10)** -- commercial Geiger counter detects beta and gamma rays. Both artificial and natural radioactive sources are available. Probe and source can be put in a special frame which allows the distance between them to be varied to determine the effect on count rates. Absorbers of different materials fit in slots in the frame to demonstrate their effect on intensity.

**Half-Life (7D10.20)** -- a computer-based Geiger counter is used to demonstrate the half-life of a short-lived isotope. A chemical extraction process is used to isolate an isotope of protactinium with a half-life of about 100 seconds (the isotope is a daughter product of a much longer-lived isotope). The Geiger counter measures the count rate of the beta decay for the protactinium and displays it in graph form as count rate vs. time. The rapid decay of the isotope can easily be seen and a rough calculation of the half-life can be done. Note: The software is currently non-functional. We're working on it.

7D20. Nuclear Reactions

7D30. Particle Detectors

**Cloud Chamber (7D30.50)** -- an automatically cycling Wilson cloud chamber shows the tracks of alpha particles from a Radium source.

7D40. NMR

**Nuclear Magnetic Resonance** -- nuclei of atoms in an intense magnetic field absorb radio-frequency energy at their resonant frequency; shows as a "blip" on the voltage in a small pickup coil. Note: We need at least one day's notice.

7D50. Models of the Nucleus

**Rutherford Scattering Model (7D50.10)** -- an analogue of Rutherford's classic alpha scattering experiment has rolling ball bearings which strike a "nucleus" and scatter at various angles.

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7E: Elementary Particles
7E10. Miscellaneous

7F: Relativity

7F10. Special Relativity

Streib’s Relativity Machine (7F10.10) -- a device which simulates length and time contraction at relativistic speeds.

Length Contraction Board (7F10.32) -- show and tell item with boards of different lengths to display the Lorentz contraction at 0, .9c, .99c, .999c, etc.

7F20. General Relativity

Source URL: https://phys.washington.edu/complete-demonstration-list