1: Mechanics

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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.

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 skimmed 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.

### 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.

### 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 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.

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**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 bilaterally 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 bfilaments 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

Satellite 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.
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.