The Video Encyclopedia of Physics Demonstrations™
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CHAPTER 14

CONSERVATION OF ANGULAR MOMENTUM
Marbles are rolled down the inside of a large funnel with their initial velocities directed azimuthally near the top of the funnel, as shown in Figure 1.† As they roll, their angular speed increases, illustrating conservation of angular momentum.

† Sutton, *Demonstration Experiments in Physics*, Demonstration M-131, Elliptical Motion with Conservation of Angular Momentum.
We'll roll marbles down a chute into this large funnel to demonstrate conservation of angular momentum.

When they first enter the funnel, the marbles rotate slowly around the funnel. As the marbles approach the bottom of the funnel, their radius of rotation decreases. As the radius decreases, the rotational velocity increases, conserving angular momentum.

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**Equipment**

1. Large glass funnel.
2. Support system.
3. Steel ball bearings and/or marbles of various sizes and densities.
Train on a Circular Track

A wind-up train is allowed to start into motion from rest on a circular track, which in turn is mounted concentrically, as shown in Figure 1, on a bicycle wheel that is free to rotate in a horizontal plane.† When the train begins to move, the track rotates in the opposite direction, maintaining the initial zero angular momentum. As the engine spring unwinds and the engine slows down, the rotating track also slows down. Because of friction in the track bearings, the final angular momentum of the system is slightly greater than zero when the train stops, and the tracks continue to rotate slowly.

† Sutton, Demonstration Experiments in Physics, Demonstration M-123, Reaction Track. Freier and Anderson, A Demonstration Handbook for Physics, Demonstration Mt-4, Angular Momentum of a Train.
This circular train track rotates freely on a bicycle wheel bearing. After this wind-up train is released from rest, the train moves clockwise while the track moves counterclockwise. The angular momentum of the system, which was initially zero, is still zero.

When the train runs down, both train and track slow down and stop.

**Equipment**

1. Level circular model train track mounted on a bicycle wheel (with slight banking toward center).
2. Support system with bearings to minimize friction.
3. Model train locomotive.
4. Markers on rim of bicycle wheel to aid visibility of the rotational motion of the track and the relative position of the locomotive to a fixed position on the track.
The escape wheel in a pocket watch periodically changes its angular momentum as it oscillates, creating an oscillating torque on the watch itself.† This torque is too small to be observed under normal conditions. However, if the watch is balanced on a relatively frictionless small point, these vibrations may be seen using the setup shown in Figure 1. The laser beam bounces off a small mirror mounted on top of the watch, amplifying the tiny oscillations of the watch.

† Sutton, Demonstration Experiments in Physics, Demonstration M-173, Rotary Action and Reaction.
This pocketwatch has an escape wheel which rocks back and forth at regular intervals.

To conserve angular momentum, the watch must rotate slightly in the opposite direction as the wheel.

To show the motion, we've put a small piece of mirror on top of the watch, and set the watch on a low-friction base. When we bounce a laser beam off the mirror, the back-and-forth oscillations of the watch can be seen from the motion of the reflected beam.

**Equipment**

1. Wind-up pocket watch.
2. Plano-convex lens (hemispherical cross section).
4. Small piece of front slivered mirror.
5. Screen for reflected beam.
The demonstrator sits on a stool that rotates on a low-friction bearing, holding weights out at arm's length, as shown in Figure 1. Upon being started into rotation by an assistant, the demonstrator pulls the weights in, decreasing her moment of inertia. Because moving her arms inward or outward involves no external torque, the angular momentum of the system remains constant. Therefore the angular speed of the demonstrator increases when she pulls her arms in and decreases when she pushes her arms out.

† Sutton, Demonstration Experiments in Physics, Demonstration M-176, Pirouette. Freier and Anderson, A Demonstration Handbook for Physics, Demonstration Mt-2, Ballet Dancer with Dumbbells.
You’ve probably seen an ice skater perform a spin. We’ll use this rotating stool and a pair of hand-held weights to demonstrate the same effect.

After a person holding the weights out at arm’s length is spun, she rotates at a constant angular speed.

When she pulls the weights closer in, her angular speed increases. Moving the weights back out slows her down.

This animation shows the action from above.

---

**Equipment**

1. Tall stool securely mounted on the most stable, lowest friction, bearing supporting rotational system available.
2. Pair of dumbbells or sizable weights.
3. An assistant.
The demonstrator sits on a rotating stool with low-friction bearings, holding a long bar with weights on each end, as shown in Figure 1. When the bar is rotated, the system maintains its initial zero angular momentum, thus causing the demonstrator to rotate in the opposite sense.†

This man is sitting on a stool which is free to rotate. We'll give him a long bar with heavy weights on it. When the bar is rotating in one direction, he rotates in the opposite direction.

If we move the weights further out on the bar and repeat the demonstration, will he now rotate more, less, or the same amount as before?

He rotates more than before.

This animation shows the motion from above.

Equipment

1. Same rotational stool system as previous demonstration.
2. Long bar bearing two sizable weights that can be locked at the center of the bar or at its far end.
A spinning bicycle wheel is held by the demonstrator, who in turn sits on a rotating stool that is isolated by low-friction bearings, as shown in Figure 1. When the angle of the axis of rotation of the rotating bicycle wheel with respect to the vertical is changed, the vertical component of the wheel’s angular momentum is changed, inducing an equal and opposite change in the angular momentum of the demonstrator as a whole, illustrating conservation of vector angular momentum.

† Sutton, *Demonstration Experiments in Physics*, Demonstration M-178, Bicycle Wheel and Rotating Stand.
This person is sitting on a stool which is free to rotate.

A second person hands her a spinning bicycle wheel. If she tips the bicycle wheel to the side, the chair rotates.

When she tips the wheel the other way, the chair rotates in the opposite direction.

**Equipment**

1. Rotational stool (same as Demonstration 07-05).
2. Rim-loaded bicycle wheel with handles attached to its axle, including a starting disc and peg as described earlier.
3. An assistant.
A gyroscope, mounted in gimbal rings as shown in Figure 1 to isolate it from external torque, is moved about in space. It remains oriented in the same direction, exhibiting gyroscopic stability.†

† Sutton, *Demonstration Experiments in Physics*, Demonstrations M-170, Constancy of Axis; M-192, Gyrocompass; and M-192, Airplane Turn Indicator.
The gimbal mounts of this gyroscope allow it to turn freely in any direction.

When we spin the gyroscope at a high speed, the gyroscope will continue to point in any direction it is set, despite the motion of the frame around it.

This effect is used in commercial gyrocompasses to track the turning of airplanes and determine global position. As the airplane turns, the gyroscope maintains its orientation, and the amount of turn can be read from the amount the support frame turns around the gyroscope.

**Equipment**

1. Gimbals-mounted gyroscope with three degrees of freedom.
2. Securely mounted high rpm motor with attached start-up disc that is rubber coated.
3. Clamps.
A bicycle wheel rotating in the horizontal plane is braked by attaching it to a massive frame, as shown in Figure 1. When the frame is connected to the rotating wheel, the total moment of inertia increases substantially, leading to a dramatic decrease in the angular speed of the system. The angular momentum of the system remains constant.

Figure 1
This bicycle wheel rotates freely on a bearing support.

An outer metal frame also rotates freely on a separate bearing. A spring-loaded brake attached to the outer frame connects the two so that they rotate together.

We'll tie the brake back with a string so that we can spin the inner wheel. Then we'll burn the string.

When the burning string snaps, the brake clamps the frame to the wheel, and they spin with a rotational speed that is less than that of the wheel alone.

If we increase the mass of the outer frame and repeat the demonstration, the final speed is even smaller than before.

**Equipment**

1. Rim-loaded bicycle wheel mounted within a rectangular frame that carries a braking system “armed” with a retention string.
2. A stable gimbals/base system that supports number 1 with the least amount of friction.
3. Supply of strings.
5. Additional weights to load the outer reaches of the frame for higher moment of inertia.
A satellite derotator uses conservation of angular momentum to stop the rotation of a satellite in space. Shown in Figure 1 is a model of such a device. While the system is spinning, two massive discs are released, moving to a larger radius and carrying a large amount of angular momentum. With the appropriate choice of disc mass and final radius, all of the angular momentum of the system can be transferred to the discs, leaving the large rotator at rest.

Figure 1
This large metal disc is free to rotate on a bearing. A pair of smaller discs is attached to the outer edge; they can be released from the larger disc by pulling a trigger in the back. The large disc is spun by pulling on a cord wrapped around the axle. When the small discs are released they will fly out on cables attached to a separate bearing. Here’s what happens when they are released.

The large disc stops and the small discs revolve at high speed.

Let’s watch that in slow motion.

What will happen if we add extra mass to the smaller discs and repeat the demonstration?

Now the large disc spins backwards.

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**Equipment**

1. Satellite derotator (built as described in the above script).
2. Two small clamps.
3. Several larger clamps to securely hold the support system down.
4. Start-up cord and handle.
CHAPTER 15

PRECESSION
A bicycle wheel spinning on a long axle is supported at one end of the axle by a rope, as shown in Figure 1. The external torque caused by the force of gravity on the wheel causes it to precess.† When it is supported by a rope at the other end of the axis, it precesses in the opposite sense.

When we spin this bicycle wheel by pulling on a string wrapped around the axle, we give the wheel angular momentum. If we release one of the handles on the wheel and hold it only by the rope on this handle, there will be an unbalanced torque on the wheel due to its weight. How will the wheel react?

The bike wheel precesses.

If we suspend the bike wheel from the other handle, the wheel precesses in the opposite direction.

**Equipment**

1. Rim-loaded bicycle wheel with handles mounted on its axle, each with a different color rope attached (this bicycle wheel has the start-up disc/peg as described earlier).
2. Start-up spring.
A small gyroscope is balanced by a weight whose radius can be adjusted, as shown in Figure 1. When the spinning gyroscope is balanced no precession occurs. If the weight is repositioned along the arm, unbalancing the system, the gyroscope will precess. The direction of precession depends on whether the weight is closer to or farther away from the pivot than the balance point.

A gyroscope is mounted on a pivot and counterweighted so that it is balanced when the weight is in the right position.

If we spin the gyro counterclockwise as seen from the pivot, its angular momentum vector points in toward the pivot.

If the weight is now moved outward from the balance position, the gyro precesses counterclockwise.

If we move the weight in closer than the balance position, the direction of precession reverses.

---

**Equipment**

1. Gyroscope with long adjustable counterbalance arm/support system.
2. Same start-up motor/disc as described previously.
A bicycle wheel is mounted so that it rotates freely on a set of gimbals, as shown in Figure 1. Weights are positioned at various points along the extended axle, and the resulting precession observed.
This bicycle wheel with a weighted rim is mounted in a pair of bearings so it is free to move in two directions. A pair of weights on the axle of the wheel can be adjusted so that the axle is either balanced or tips to one side.

We'll spin the wheel by hand with the weights initially balanced. What will happen if we move one of the weights outward so that the wheel is no longer balanced?

The wheel precesses.

If we move the weight further out, the precession rate increases.

If we move the other weight out to rebalance the wheel, the precession stops.

Pushing the first weight back to its original position makes the wheel precess in the opposite direction.

---

**Equipment**

1. Bicycle wheel with loaded rim mounted within a large, custom-built pair of gimbals with good bearings to minimize frictional losses; all supported above a stable base.
2. Wheel fitted with an identical pair of extension rods off each end of the axle, with each carrying one of a pair of identical weights and locking thumb screws.
Two identical bicycle wheels are mounted coaxially onto a rigid axle that is supported at one end, as shown in Figure 1. When both of the bicycle wheels rotate with the same angular speed in the same direction their angular momenta add together, and when released they precess as a unit around the fixed point. On the other hand, if they rotate in opposite directions their angular momenta cancel, and the system will not precess. The wheels will fall downward on their axle.

This pair of bicycle wheels is mounted on a common axle that is free to swing on a bearing.

When we spin both wheels in the same direction and then release them, the wheels precess horizontally instead of falling down.

If we now spin the two wheels in opposite directions at equal speeds, will they still precess?

They fall straight down. The two wheels spinning with equal but opposite angular velocities act as if they are not spinning at all.

**Equipment**

1. Two bicycle wheels with collinear axle supported from a single end that is free to pivot.
2. Large bearing support system with heavy stable base.
3. Several large clamps.
4. Rim marker on each wheel.
Motorized Gyroscope

A motorized gyroscope, shown in Figure 1, is used to illustrate the principles of vector angular momentum and torque.† The spinning gyroscope remains in a constant orientation until an external net force is exerted on the gyroscope. The relation between the direction of the force and the resulting precession is investigated on the video.

† Freier and Anderson, A Demonstration Handbook for Physics, Demonstration Mu-10, MITAC Gyroscope.
This motorized gyroscope will be used to show precession of a spinning object.

This heavy steel disc is rotated by a motor until it is spinning at about 1200 revolutions per minute.

When a force is exerted on the end of the axle shaft, the shaft and disc move to the right instead of down.

When we push the shaft up, it moves to the left.

What will happen if we try to push the shaft to the right?

The shaft moves up.

If we push the shaft to the left, it moves down.

If we hang this weight on the end of the shaft to provide a constant force, the disc precesses to the right at this speed. If we turn off the motor and let the disc slow down, will the rate of precession increase or decrease?

The rate of precession increases as the disc slows.

---

**Equipment**

1. Motorized gyroscope.
2. Length of rod.
3. Weight with string loop.
CHAPTER 16

ROTATIONAL PHENOMENA
A rotating system such as that shown in Figure 1 may possess both static and dynamic balance; this demonstration illustrates the difference. If the system possesses static balance it will remain balanced in any orientation. If it also possesses dynamic balance it will rotate smoothly, as does the system in Figure 1. On the other hand, when the bar is rotated, as shown in Figure 2, it possesses static balance but not dynamic balance. When it is rotated it begins to vibrate violently. This is why the tires on your car must be balanced dynamically.

Figure 1

Figure 2
We'll use this device to demonstrate two different types of balance.

This bar is free to rotate around an axis supported by springs. The bar is statically balanced and will rest stably in any position.

The bar is also dynamically balanced, so that, if we rotate the bar, the axis stays stationary.

If we tilt the bar with respect to its axis of rotation, it is still statically balanced.

But the bar is no longer dynamically balanced, and will shake its support axis when spun.

**Equipment**

1. Linear analog of a wheel and axle, where the axle is supported from its ends, from above, and from below by four identical springs, all within a vertical rectangular framework. The “wheel” can be locked in either a vertical position or a slightly off-vertical position by a pin and locking thumb screw.
2. Clamps to hold framework firmly vertical.
A spinning football exhibits dynamical stability when it is spun. If it is spun about its smaller axis, it will rise up and spin about its longer axis.†

We'll use this football to show the unusual behavior some objects exhibit while spinning on a surface.

When the football is spun on a table along its shortest axis, it climbs up to spin along the long axis even though it must raise its center of gravity to do so.

**Equipment**

1. Rubber football.
2. Smooth surface.
A tippy top is an asymmetric top with a partial sphere on one end and a stem on the other end, as shown in Figure 1. When it is spun with its heavy end down, it rises up so that the heavier end is on top, as shown in the figure, apparently defying the law of gravitation.

This is a toy known as a Tippy Top, which performs a strange maneuver when it is spun. When the top is at rest on the table, it sits with the heaviest half down to keep its center of gravity low.

When the top is spun on the table, the heavier half gradually rises. The top prefers to spin in this orientation even though it must raise its center of mass to do so.

**Equipment**

1. Toy Tippy Top.
2. Smooth surface.
A gyroscopic ship stabilizer can be used to stabilize a sailing ship against some of the tipping motions that can be annoying to the passengers. If the gyroscope is attached properly to the ship, as shown in Figure 1, a sideward rolling motion of the ship can be converted into motion of the gyroscope, rapidly damping out the rocking of the ship.† Friction in the bearing the gyroscope pivots on is critical, and must be adjusted carefully. Too little friction and the gyroscope merely pivots with no loss of energy. Too much friction (no freedom to pivot) and the ship would “precess.”

† Sutton, Demonstration Experiments in Physics, Demonstration M-194, Ship Stabilizer.
A ship is often subjected to large waves which rock it from side to side. We'll use this model, which also rocks freely from side to side, to show how ships can be stabilized using a heavy gyroscope.

When the gyroscope in the center of the ship model is not spinning, the model rocks freely when pushed by hand.

When we start the gyroscope spinning and repeat the action, the rocking quickly dies out.

**Equipment**

Ship analog carrying a motorized gyro disc, which as a system is free to rotate about a vertical axis whenever the ship experiences "a wave."
This demonstration illustrates that objects tend to spin in the orientation that gives them maximum moment of inertia about the spin axis.† A ring and a long rod, illustrated in Figure 1, are shown in the video.

This metal rod hangs from a hand drill, which begins to rotate slowly.

At first the rod rotates about its long axis, but as the speed increases the rod rises up to spin about an axis perpendicular to its length.

This hoop exhibits a similar behavior when it is spun. At first it spins about an axis along the diameter of the hoop, but at higher speeds it rises up and rotates about an axis at right angles to the hoop.

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**Equipment**

1. Variable speed electric hand drill.
2. Steel cable with solid rod securely clamped to one end, and a chuck fitting securely clamped to the other end.
3. Another steel cable with metal hoop in place of the rod, as described above.
A rectangular shaped object with all three dimensions different is spun and thrown into the air simultaneously, as shown in Figure 1. If it is rotating about the axis with either the greatest or the least moment of inertia, it will spin in a stable manner. If it is spun about the intermediate moment of inertia axis, it will wobble in an unstable manner while it is spinning.

Figure 1

This wooden board has three axes of rotation.

About this axis, the board has the greatest moment of inertia. When the board is spun around that axis and thrown into the air, it rotates smoothly.

About this axis, the board has the smallest moment of inertia.

When the board is spun around that axis and thrown into the air, it again rotates smoothly.

About this axis, the board has an intermediate moment of inertia. When the board is spun around that axis and thrown, it is unstable.

---

**Equipment**

Rectangular piece of dimensional lumber (we used 1 x 8).
Demo 07-21  Sections of a Cone

A cone is dissected by cutting it along various orientations. When the cut is perpendicular to the axis, the conic section is a circle. When the cut is parallel to the side of the cone, the section is a parabola. When the cut is parallel to the axis of the cone, the section is a hyperbola. When the angle at which the cone is cut is between that of the circle and that of the parabola, the resulting conic section is an ellipse. These can be seen in Figure 1.

Figure 1
This cone is sliced across various cross sections to show the curves that result.

One cross section has been cut perpendicular to the axis of the cone, and is circular in shape.

One cross section has been cut at a small angle to the axis, and is elliptical in shape.

One cross section has been cut parallel to one side of the cone, and shows a parabolic shape.

One cross section has been cut parallel to the axis of the cone, and shows a hyperbolic shape.

---

**Equipment**

Commercially available wooden cone with all of the desired conical cross sections.
An ellipse can be drawn as follows: a length of string is looped around two fixed points and a pen, as shown in Figure 1. As the pen is moved, keeping the string taut, it traces out an ellipse, as seen.† If the distance between the two fixed points or the length of the string are changed, a new ellipse is formed with a different eccentricity.

We'll show how an ellipse can be drawn using this board and two steel dowels.

A loop of string is put around the dowels, and a marking pen is held taut against the string.

The pen is run around the dowels, and traces out an ellipse.

Here is the same process repeated using the same string, but with the two dowels separated by a smaller distance.

**Equipment**

1. Large paper-covered board with two pegs with two pairs of possible positions on the major axis.
2. Loop of string of appropriate size.
3. Pen.
A Cavendish balance is used to determine the value of the universal constant of gravitation G.† Using the actual apparatus, shown in Figure 1, and animation as shown in Figure 2, to illustrate the motion of the balance, the manner in which the apparatus functions is illustrated on the video.

This device, known as a Cavendish balance, can be used to measure the universal gravitational constant. Inside the balance, two small lead spheres are attached to the end of a light bar suspended from a very fine wire. Two large lead spheres outside the balance can be rotated to either of two positions.

This animation shows the balance from above.

When the small spheres are in equilibrium, the gravitational forces between the large and small balls are balanced by the torsional force from the suspension wire. When the large spheres are moved to the opposite positions, the forces act in the same direction. The small spheres accelerate, turning an attached mirror and deflecting a laser beam. They oscillate back and forth, eventually reaching a new equilibrium position where the forces are once again balanced. The angle between the two equilibrium positions can be used to calculate the gravitational force between the spheres and thus the gravitational constant.

We’ll reverse the large spheres and watch a speeded-up animation of the laser spot, with a clock in the corner of the screen to keep track of the actual elapsed time.

After 1\frac{1}{2} hours, the spot has settled into a new equilibrium position 43 centimeters away from the first.

**Equipment**

1. Commercially available Cavendish balance.
2. Laser.
3. Clock.