PROBLEMS

Discussion Questions

Q10.1. When cylinder-head bolts in an automobile engine are tightened, the critical quantity is the torque applied to the bolts. Why is the torque more important than the actual force applied to the wrench handle?

Q10.2. Can a single force applied to a body change both its translational and rotational motion? Explain.

Q10.3. Suppose you could use wheels of any type in the design of a soapbox-derby racer (an unpowered, four-wheel vehicle that coast from rest down a hill). To conform to the rules on the total weight of the vehicle and rider, should you design with large massive wheels or small light wheels? Should you use solid wheels or wheels with most of the mass at the rim? Explain.

Q10.4. A four-wheel-drive car is accelerating forward from rest. Show the direction the car’s wheels turn and how this causes a friction force due to the pavement that accelerates the car forward.

Q10.5. Serious bicyclists say that if you reduce the weight of a bike, it is more effective if you do so in the wheels rather than in the frame. Why would reducing weight in the wheels make it easier on the bicyclist than reducing the same amount in the frame?

Q10.6. The harder you hit the brakes while driving forward, the more the front end of your car will move down (and the rear end move up). Why? What happens when cars accelerate forward?

Q10.7. Why do drag racers not use front-wheel drive only?

Q10.8. When you turn on an electric motor, it takes longer to come up to final speed if a grinding wheel is attached to the shaft. Why?

Q10.9. Experienced cooks can tell whether an egg is raw or hard-boiled by rolling it down a slope (taking care to catch it at the bottom). How is this possible? What are they looking for?

Q10.10. The work done by a force is the product of force and distance. The torque due to a force is the product of force and distance. Does this mean that torque and work are equivalent? Explain.

Q10.11. A valued client brings a treasured ball to your engineering firm, wanting to know whether the ball is solid or hollow. He has tried tapping on it, but that has given insufficient information. Design a simple, inexpensive experiment that you could perform quickly, without injuring the precious ball, to find out whether it is solid or hollow.

Q10.12. You make two versions of the same object out of the same material having uniform density. For one version, all the dimensions are exactly twice as great as for the other one. If the same torque acts on both versions, giving the smaller version angular acceleration \( \alpha \), what will be the angular acceleration of the larger version in terms of \( \alpha \)?

Q10.13. Two identical masses are attached to frictionless pulleys by very light strings wrapped around the rim of the pulley and are released from rest. Both pulleys have the same mass and same diameter, but one is solid and the other is a hoop. As the masses fall, in which case is the tension in the string greater, or is it the same in both cases? Justify your answer.

Q10.14. The force of gravity acts on the baton in Fig. 10.11, and forces produce torques that cause a body’s angular velocity to change. Why, then, is the angular velocity of the baton in the figure constant?

Q10.15. A certain solid uniform ball reaches a maximum height \( h_0 \) when it rolls up a hill without slipping. What maximum height (in terms of \( h_0 \)) will it reach if you (a) double its diameter, (b) double its mass, (c) double both its diameter and mass, (d) double its angular speed at the bottom of the hill?

Q10.16. A wheel is rolling without slipping on a horizontal surface. In an inertial frame of reference in which the surface is at rest, is there any point on the wheel that has a velocity that is purely vertical? Is there any point that has a horizontal velocity component opposite to the velocity of the center of mass? Explain. Do your answers change if the wheel is slipping as it rolls? Why or why not?

Q10.17. Part of the kinetic energy of a moving automobile is in the rotational motion of its wheels. When the brakes are applied hard on an icy street, the wheels “lock” and the car starts to slide. What becomes of the rotational kinetic energy?

Q10.18. A hoop, a uniform solid cylinder, a spherical shell, and a uniform solid sphere are released from rest at the top of an incline. What is the order in which they arrive at the bottom of the incline? Does it matter whether or not the masses and radii of the objects are all the same? Explain.

Q10.19. A ball is rolling along at speed \( v \) without slipping on a horizontal surface when it comes to a hill that rises at a constant angle above the horizontal. In which case will it go higher up the hill: if the hill has enough friction to prevent slipping or if the hill is perfectly smooth? Justify your answers in both cases in terms of energy conservation and in terms of Newton’s second law.

Q10.20. You are standing at the center of a large horizontal turntable in a carnival funhouse. The turntable is set rotating on frictionless bearings, and it rotates freely (that is, there is no motor driving the turntable). As you walk toward the edge of the turntable, what happens to the combined angular momentum of you and the turntable? What happens to the rotation speed of the turntable? Explain your answer.

Q10.21. Global Warming. As the earth’s climate continues to warm, ice near the poles will melt and be added to the oceans. What effect will this have on the length of the day? (Hint: Consult a map to see where the oceans lie.)

Q10.22. A point particle travels in a straight line at constant speed, and the closest distance it comes to the origin of coordinates is a distance \( l \). With respect to this origin, does the particle have nonzero angular momentum? As the particle moves along its straight-line path, does its angular momentum with respect to the origin change?

Q10.23. In Example 10.11 (Section 10.6) the angular speed \( \omega \) changes, and this must mean that there is nonzero angular acceleration. But there is no torque about the rotation axis if the forces the professor applies to the weights are directly, radially inward. Then, by Eq. (10.7), \( \alpha_z \) must be zero. Explain what is wrong with this reasoning that leads to this apparent contradiction.

Q10.24. In Example 10.11 (Section 10.6) the rotational kinetic energy of the professor and dumbbells increases. But since there are no external torques, no work is being done to change the rotational kinetic energy. Then, by Eq. (10.22), the kinetic energy must remain the same! Explain what is wrong with this reasoning that leads to this apparent contradiction. Where does the extra kinetic energy come from?

Q10.25. As discussed in Section 10.6, the angular momentum of a circus acrobat is conserved as she tumbles through the air. Is her linear momentum conserved? Why or why not?
Q10.26. If you stop a spinning raw egg for the shortest possible instant and then release it, the egg will start spinning again. If you do the same to a hard-boiled egg, it will remain stopped. Try it. Explain it.

Q10.27. A helicopter has a large main rotor that rotates in a horizontal plane and provides lift. There is also a small rotor on the tail that rotates in a vertical plane. What is the purpose of the tail rotor? (Hint: If there were no tail rotor, what would happen when the pilot changed the angular speed of the main rotor?) Some helicopters have no tail rotor, but instead have two large main rotors that rotate in a horizontal plane. Why is it important that the two main rotors rotate in opposite directions?

Q10.28. In a common design for a gyroscope, the flywheel and flywheel axis are enclosed in a light, spherical frame with the flywheel at the center of the frame. The gyroscope is then balanced on top of a pivot so that the flywheel is directly above the pivot. Does the gyroscope precess if it is released while the flywheel is spinning? Explain.

Q10.29. A gyroscope takes 3.8 s to precess 1.0 revolution about a vertical axis. Two minutes later, it takes only 1.9 s to precess 1.0 revolution. Has anyone touched the gyroscope? Explain.

Q10.30. A gyroscope is precessing as in Fig. 10.32. What happens if you gently add some weight to the end of the flywheel axis farthest from the pivot?

Q10.31. A bullet emerges from a rifle spinning on its axis. Explain how this prevents the bullet from tumbling and keeps the streamlined end pointed forward.

Q10.32. A certain uniform turntable of diameter \( D_o \) has an angular momentum \( L_o \). If you want to redesign it so it retains the same mass but has twice as much angular momentum at the same angular velocity as before, what should be its diameter in terms of \( D_o \)?

Exercises

Section 10.1 Torque

10.1. Calculate the torque (magnitude and direction) about point \( O \) due to the force \( \vec{F} \) in each of the cases sketched in Fig. 10.37. In each case, the force \( \vec{F} \) and the rod both lie in the plane of the page, the rod has length 4.00 m, and the force has magnitude \( F = 10.0 \) N.

Figure 10.37 Exercise 10.1.

10.2. Calculate the net torque about point \( O \) for the two forces applied as in Fig. 10.38. The rod and both forces are in the plane of the page.

Figure 10.38 Exercise 10.2.

10.3. A square metal plate 0.180 m on each side is pivoted about an axis through point \( O \) at its center and perpendicular to the plate (Fig. 10.39). Calculate the net torque about this axis due to the three forces shown in the figure if the magnitudes of the forces are \( F_1 = 18.0 \) N, \( F_2 = 26.0 \) N, and \( F_3 = 14.0 \) N. The plate and all forces are in the plane of the page.

Figure 10.39 Exercise 10.3.

10.4. Three forces are applied to a wheel of radius 0.350 m, as shown in Fig. 10.40. One force is perpendicular to the rim, one is tangent to it, and the other one makes a 40.0° angle with the radius. What is the net torque on the wheel due to these three forces for an axis perpendicular to the wheel and passing through its center?

Figure 10.40 Exercise 10.4.

10.5. One force acting on a machine part is \( \vec{F} = ( -5.00 \) N)\( \hat{i} + (4.00 \) N)\( \hat{j} \). The vector from the origin to the point where the force is applied is \( \vec{r} = (-0.450 \) m)\( \hat{i} + (0.150 \) m)\( \hat{j} \). (a) In a sketch, show \( \vec{F}, \vec{r}, \) and the origin. (b) Use the right-hand rule to determine the direction of the torque. (c) Calculate the vector torque produced by this force. Verify that the direction of the torque is the same as you obtained in part (b).
A machinist is using a wrench to loosen a nut. The wrench is 25.0 cm long, and he exerts a 17.0-N force at the end of the handle at 37° with the handle (Fig. 10.41). (a) What torque does the machinist exert about the center of the nut? (b) What is the maximum torque he could exert with this force, and how should the force be oriented?

Figure 10.41 Exercise 10.6.

![Image of nut and wrench]

17.0 N

37°

25.0 cm

Figure 10.42 Exercise 10.8.

Spin axis

A flywheel of an engine has moment of inertia 2.50 kg·m² about its rotation axis. What constant torque is required to bring it up to an angular speed of 400 rev/min in 8.00 s, starting from rest?

A uniform, 8.40-kg, spherical shell 35.0 cm in diameter has four small 2.00-kg masses attached to its outer surface and equally spaced around it. This combination is spinning about an axis running through the center of the sphere and two of the small masses (Fig. 10.42). What friction torque is needed to reduce its angular speed from 75.0 rpm to 50.0 rpm in 30.0 s?

A machine part has the shape of a solid uniform sphere of mass 225 g and diameter 3.00 cm. It is spinning about a frictionless axle through its center, but at one point on its equator it is scraping against metal, resulting in a friction force of 0.0200 N at that point. (a) Find its angular acceleration. (b) How long will it take to decrease its rotational speed by 22.5 rad/s?

A cord is wrapped around the rim of a solid uniform wheel 0.250 m in radius and of mass 9.20 kg. A steady horizontal pull of 40.0 N to the right is exerted on the cord, pulling it off tangentially from the wheel. The wheel is mounted on frictionless bearings on a horizontal axle through its center. (a) Compute the angular acceleration of the wheel and the acceleration of the part of the cord that has already been pulled off the wheel. (b) Find the magnitude and direction of the force that the axle exerts on the wheel. (c) Which of the answers in parts (a) and (b) would change if the pull were upward instead of horizontal?

A solid, uniform cylinder with mass 8.25 kg and diameter 5.0 cm is spinning at 220 rpm on a thin, frictionless axle that passes along the cylinder axis. You design a simple friction brake to stop the cylinder by pressing the brake against the outer rim with a normal force. The coefficient of kinetic friction between the brake and rim is 0.333. What must the applied normal force be to bring the cylinder to rest after it has turned through 5.25 revolutions?

A stone is suspended from the free end of a wire that is wrapped around the outer rim of a pulley, similar to what is shown in Fig. 10.10. The pulley is a uniform disk with mass 10.0 kg and radius 50.5 cm and turns on frictionless bearings. You measure that the stone travels 12.6 m in the first 3.00 s starting from rest. Find (a) the mass of the stone and (b) the tension in the wire.

A grindstone in the shape of a solid disk with diameter 0.520 m, and a mass of 50.0 kg is rotating at 850 rev/min. You press an ax against the rim with a normal force of 160 N (Fig. 10.43), and the grindstone comes to rest in 7.50 s. Find the coefficient of friction between the ax and the grindstone. You can ignore friction in the bearings.

Figure 10.43 Exercise 10.13 and Problem 10.53.

![Image of grindstone and ax]

$m = 50.0 \text{ kg}$

$F = 160 \text{ N}$

10.14. A 15.0-kg bucket of water is suspended by a very light rope wrapped around a solid uniform cylinder 0.300 m in diameter with mass 12.0 kg. The cylinder pivots on a frictionless axle through its center. The bucket is released from rest at the top of a well and falls 10.0 m to the water. (a) What is the tension in the rope while the bucket is falling? (b) With what speed does the bucket strike the water? (c) What is the time of fall? (d) While the bucket is falling, what is the force exerted on the cylinder by the axle?

10.15. A 2.00-kg textbook rests on a frictionless, horizontal surface. A cord attached to the book passes over a pulley whose diameter is 0.150 m, to a hanging hook with mass 3.00 kg. The system is released from rest, and the books are observed to move 1.20 m in 0.800 s. (a) What is the tension in each part of the cord? (b) What is the moment of inertia of the pulley about its rotation axis?

10.16. A 12.0-kg box resting on a horizontal, frictionless surface is attached to a 5.00-kg weight by a thin, light wire that passes over a frictionless pulley (Fig. 10.44). The pulley has the shape of a uniform solid disk of mass 2.00 kg and diameter 0.500 m. After the system is released, find (a) the tension in the wire on both sides of the pulley, (b) the acceleration of the box, and (c) the horizontal and vertical components of the force that the axle exerts on the pulley.

Figure 10.44 Exercise 10.16.

![Image of pulley and box]

10.17. A thin, uniform, 15.0-kg post, 1.75 m long, is held vertically using a cable and is attached to a 5.00-kg mass and a pivot at its bottom end (Fig. 10.45). The string attached to the 5.00-kg mass passes over a massless, frictionless pulley and pulls perpendicular to the post. Suddenly the cable breaks. (a) Find the angular acceleration of the post about the pivot just after the cable breaks. (b) Will the angular acceleration in part (a) remain constant as the post falls (before it hits the pulley)? Why? (c) What is the acceleration of the
5.00-kg mass the instant after the cable breaks? Does this acceleration remain constant? Why?

10.18. A thin, horizontal rod with length \( l \) and mass \( M \) pivots about a vertical axis at one end. A force with constant magnitude \( F \) is applied to the other end, causing the rod to rotate in a horizontal plane. The force is maintained perpendicular to the rod and to the axis of rotation. Calculate the magnitude of the angular acceleration of the rod.

Section 10.3 Rigid-Body Rotation About a Moving Axis

10.19. A 2.20-kg hoop 1.20 m in diameter is rolling to the right without slipping on a horizontal floor at a steady 3.00 rad/s. (a) How fast is its center moving? (b) What is the total kinetic energy of the hoop? (c) Find the velocity vector for each of the following points, as viewed by a person at rest on the ground: (i) the highest point on the hoop; (ii) the lowest point on the hoop; (iii) a point on the right side of the hoop, midway between the top and the bottom. (d) Find the velocity vector for each of the points in part (c), except as viewed by someone moving along with the same velocity as the hoop.

10.20. A string is wrapped several times around the rim of a small hoop with radius 8.00 cm and mass 0.180 kg. The free end of the string is held in place and the hoop is released from rest. After the hoop has descended 75.0 cm, calculate (a) the angular speed of the rotating hoop and (b) the speed of its center.

10.21. What fraction of the total kinetic energy is rotational for the following objects rolling without slipping on a horizontal surface? (a) a uniform solid cylinder; (b) a uniform sphere; (c) a thin-walled, hollow sphere; (d) a hollow cylinder with outer radius \( R \) and inner radius \( R/2 \).

10.22. A hollow, spherical shell with mass 2.00 kg rolls without slipping down a 38.0° slope. (a) Find the acceleration, the friction force, and the minimum coefficient of friction needed to prevent slipping. (b) How would your answers to part (a) change if the mass were doubled to 4.00 kg?

10.23. A solid ball is released from rest and slides down a hillside that slopes downward at 65.0° from the horizontal. (a) What minimum value must the coefficient of static friction between the hill and ball surfaces have for no slipping to occur? (b) Would the coefficient of friction calculated in part (a) be sufficient to prevent a hollow ball (such as a soccer ball) from slipping? Justify your answer. (c) In part (a), why did we use the coefficient of static friction and not the coefficient of kinetic friction?

10.24. A uniform marble rolls down a symmetric bowl, starting from rest at the top of the left side. The top of each side is a distance \( h \) above the bottom of the bowl. The left half of the bowl is rough enough to cause the marble to roll without slipping, but the right half has no friction because it is coated with oil. (a) How far up the smooth side will the marble go, measured vertically from the bottom? (b) How high would the marble go if both sides were as rough as the left side? (c) How do you account for the fact that the marble goes higher with friction on the right side than without friction?

10.25. A 392-N wheel comes off a moving truck and rolls without slipping along a highway. At the bottom of a hill it is rotating at 25.0 rad/s. The radius of the wheel is 0.600 m, and its moment of inertia about its rotation axis is 0.800MR^2. Friction does work on the wheel as it rolls up the hill to a stop, a height \( h \) above the bottom of the hill; this work has absolute value 3500 J. Calculate \( h \).

10.26. A Ball Rolling Uphill. A bowling ball rolls without slipping up a ramp that slopes upward at an angle \( \beta \) to the horizontal (see Example 10.7 in Section 10.3). Treat the ball as a uniform, solid sphere, ignoring the finger holes. (a) Draw the free-body diagram for the ball. Explain why the friction force must be directed uphill. (b) What is the acceleration of the center of mass of the ball? (c) What minimum coefficient of static friction is needed to prevent slipping?

Section 10.4 Work and Power in Rotational Motion

10.27. A playground merry-go-round has radius 2.40 m and moment of inertia 2100 kg·m^2 about a vertical axle through its center, and it turns with negligible friction. (a) A child applies an 18.0-N force tangentially to the edge of the merry-go-round for 15.0 s. If the merry-go-round is initially at rest, what is its angular speed after this 15.0-s interval? (b) How much work did the child do on the merry-go-round? (c) What is the average power supplied by the child?

10.28. The engine delivers 175 hp to an aircraft propeller at 2400 rev/min. (a) How much torque does the aircraft engine provide? (b) How much work does the engine do in one revolution of the propeller?

10.29. A 1.50-kg grinding wheel is in the form of a solid cylinder of radius 0.100 m. (a) What constant torque will bring it from rest to an angular speed of 1200 rev/min in 2.5 s? (b) Through what angle has it turned during that time? (c) Use Eq. (10.21) to calculate the work done by the torque. (d) What is the grinding wheel's kinetic energy when it is rotating at 1200 rev/min? Compare your answer to the result in part (c).

10.30. An electric motor consumes 9.00 kW of electrical energy in 1.00 min. If one-third of this energy goes into heat and other forms of internal energy of the motor, with the rest going to the motor output, how much torque will this engine develop if you run it at 2500 rpm?

10.31. The carbide tips of the cutting teeth of a circular saw are 8.6 cm from the axis of rotation. (a) The no-load speed of the saw, when it is not cutting anything, is 4800 rev/min. Why is its no-load power output negligible? (b) While the saw is cutting lumber, its angular speed slows to 2400 rev/min and the power output is 1.9 hp. What is the tangential force that the wood exerts on the carbide tips?

10.32. An airplane propeller is 2.08 m in length (from tip to tip) and has a mass of 117 kg. When the airplane's engine is first started, it applies a constant torque of 1950 N·m to the propeller, which starts from rest. (a) What is the angular acceleration of the propeller? Model the propeller as a slender rod and see Table 9.2. (b) What is the propeller's angular speed after making 5.00 revolutions? (c) How much work is done by the engine during the first 5.00 revolutions? (d) What is the average power output of the engine during the first 5.00 revolutions? (e) What is the instantaneous power output of the motor at the instant that the propeller has turned through 5.00 revolutions?

10.33. (a) Compute the torque developed by an industrial motor whose output is 150 kW at an angular speed of 4000 rev/min. (b) A drum with negligible mass, 0.400 m in diameter, is attached to the motor shaft, and the power output of the motor is used to raise a weight hanging from a rope wrapped around the drum. How heavy a weight can the motor lift at constant speed? (c) At what constant speed will the weight rise?
Section 10.5 Angular Momentum

10.34. A woman with mass 50 kg is standing on the rim of a large disk that is rotating at 0.50 rev/s about an axis through its center. The disk has mass 110 kg and radius 4.0 m. Calculate the magnitude of the total angular momentum of the woman-plus-disk system. (Assume that you can treat the woman as a point.)

10.35. A 2.00-kg rock has a horizontal velocity of magnitude 12.0 m/s when it is at point P in Fig. 10.47. (a) At this instant, what are the magnitude and direction of its angular momentum relative to point O? (b) If the only force acting on the rock is its weight, what is the rate of change (magnitude and direction) of its angular momentum at this instant?

10.36. (a) Calculate the magnitude of the angular momentum of the earth in a circular orbit around the sun. Is it reasonable to model it as a particle? (b) Calculate the magnitude of the angular momentum of the earth due to its rotation around an axis through the north and south poles, modeling it as a uniform sphere. Consult Appendix E and the astronomical data in Appendix F.

10.37. Find the magnitude of the angular momentum of the second hand on a clock about an axis through the center of the clock face. The clock hand has a length of 15.0 cm and a mass of 6.00 g. Take the second hand to be a slender rod rotating with constant angular velocity about one end.

10.38. A hollow, thin-walled sphere of mass 12.0 kg and diameter 48.0 cm is rotating about an axis through its center. The angle (in radians) through which it turns as a function of time (in seconds) is given by \( \theta(t) = At^2 + Bt^3 \), where A has numerical value 1.50 and B has numerical value 1.10. (a) What are the units of the constants A and B? (b) At the time 3.00 s, find (i) the angular momentum of the sphere and (ii) the net torque on the sphere.

Section 10.6 Conservation of Angular Momentum

10.39. Under some circumstances, a star can collapse into an extremely dense object made mostly of neutrons and called a neutron star. The density of a neutron star is roughly \( 10^{14} \) times as great as that of ordinary solid matter. Suppose we represent the star as a uniform, solid, rigid sphere, both before and after the collapse. The star’s initial radius was \( 7.0 \times 10^6 \) km (comparable to our sun); its final radius is 16 km. If the original star rotated once in 30 days, find the angular speed of the neutron star.

10.40. A small block on a frictionless, horizontal surface has a mass of 0.0250 kg. It is attached to a massless cord passing through a hole in the surface (Fig. 10.48). The block is originally revolving at a distance of 0.300 m from the hole with an angular speed of 1.75 rad/s. The cord is then pulled from below, shortening the radius of the circle in which the block revolves to 0.150 m. Model the block as a particle. (a) Is angular momentum of the block conserved? Why or why not? (b) What is the new angular speed? (c) Find the change in kinetic energy of the block. (d) How much work was done in pulling the cord?

10.41. The Spinning Figure Skater. The outstretched hands and arms of a figure skater preparing for a spin can be considered a slender rod pivoting about an axis through its center (Fig. 10.49). When the skater’s hands and arms are brought in and wrapped around his body to execute the spin, the hands and arms can be considered a thin-walled, hollow cylinder. His hands and arms have a combined mass 8.0 kg. When outstretched, they span 1.8 m; when wrapped, they form a cylinder of radius 25 cm. The moment of inertia about the rotation axis of the remainder of his body is constant and equal to 0.40 kg · m². If his original angular speed is 0.40 rev/s, what is his final angular speed?

10.42. A diver comes off a board with arms straight up and legs straight down, giving her a moment of inertia about her rotation axis of 18 kg · m². She then tucks into a small ball, decreasing this moment of inertia to 3.6 kg · m². While tucked, she makes two complete revolutions in 1.0 s. If she hadn’t tucked at all, how many revolutions would she have made in the 1.5 s from board to water?

10.43. A large wooden turntable in the shape of a flat uniform disk has a radius of 2.00 m and a total mass of 120 kg. The turntable is initially rotating at 3.00 rad/s about a vertical axis through its center. Suddenly, a 70.0-kg parachutist makes a soft landing on the turntable at a point near the outer edge. (a) Find the angular speed of the turntable after the parachutist lands. (Assume that you can treat the parachutist as a particle.) (b) Compute the kinetic energy of the system before and after the parachutist lands. Why are these kinetic energies not equal?

10.44. A solid wood door 1.00 m wide and 2.00 m high is hinged along one side and has a total mass of 40.0 kg. Initially open and at rest, the door is struck at its center by a handful of sticky mud with mass 0.500 kg, traveling perpendicular to the door at 12.0 m/s just before impact. Find the final angular speed of the door. Does the mud make a significant contribution to the moment of inertia?

10.45. A small 10.0-g bug stands at one end of a thin uniform bar that is initially at rest on a smooth horizontal table. The other end of the bar pivots about a nail driven into the table and can rotate freely, without friction. The bar has mass 50.0 g and is 100 cm in length. The bug jumps off in the horizontal direction, perpendicular to the bar, with a speed of 20.0 cm/s relative to the table. (a) What is the angular speed of the bar just after the frisky insect leaps? (b) What is the total kinetic energy of the system just after the bug leaps? (c) Where does this energy come from?

10.46. Asteroid Collision! Suppose that an asteroid traveling straight toward the center of the earth were to collide with our planet at the equator and bury itself just below the surface. What
would have to be the mass of this asteroid, in terms of the earth’s mass $M$, for the day to become 25.0% longer than it presently is as a result of the collision? Assume that the asteroid is very small compared to the earth and that the earth is uniform throughout.

**10.47.** A thin, uniform metal bar, 2.00 m long and weighing 90.0 N, is hanging vertically from the ceiling by a frictionless pivot. Suddenly it is struck 1.50 m below the ceiling by a small 3.00-kg ball, initially traveling horizontally at 10.0 m/s. The ball rebounds in the opposite direction with a speed of 6.00 m/s.

(a) Find the angular speed of the bar just after the collision.

(b) During the collision, why is the angular momentum conserved but not the linear momentum?

**Section 10.7 Gyroscopes and Precession**

**10.48.** Draw a top view of the gyroscope shown in Fig. 10.32. (a) Draw labeled arrows on your sketch for $\vec{\omega}$, $\vec{I}$, and $\vec{\tau}$. Draw $d\vec{L}$ produced by $\vec{\tau}$. Draw $\vec{I}$ and $d\vec{L}$. Determine the sense of the precession by examining the directions of $\vec{I}$ and $\vec{L} + d\vec{L}$.

(b) Reverse the direction of the spin angular velocity of the rotor and repeat all the steps in part (a).

(c) Move the pivot to the other end of the shaft, with the same direction of spin angular velocity as in part (b), and repeat all the steps.

(d) Keeping the pivot as in part (c), reverse the spin angular velocity of the rotor and repeat all the steps.

**10.49.** The rotor (flywheel) of a toy gyroscope has mass 0.140 kg. Its moment of inertia about its axis is $1.20 \times 10^{-4}$ kg·m². The mass of the frame is 0.0250 kg. The gyroscope is supported on a single pivot (Fig. 10.50) with its center of mass a horizontal distance of 4.00 cm from the pivot. The gyroscope is precessing in a horizontal plane at the rate of one revolution in 2.20 s.

(a) Find the upward force exerted by the pivot.

(b) Find the angular speed with which the rotor is spinning about its axis, expressed in rev/min.

(c) Copy the diagram and draw vectors to show the angular momentum of the rotor and the torque acting on it.

**Figure 10.50** Exercise 10.49.

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**10.50.** A gyroscope on the Moon. A certain gyroscope precesses at a rate of 0.50 rad/s when used on earth. If it were taken to a lunar base, where the acceleration due to gravity is 0.165 g, what would be its precession rate?

**10.51.** A gyroscope is precessing about a vertical axis. Describe what happens to the precession angular speed if the following changes in the variables are made, with all other variables remaining the same: (a) the angular speed of the spinning flywheel is doubled; (b) the total weight is doubled; (c) the moment of inertia about the axis of the spinning flywheel is doubled; (d) the distance from the pivot to the center of gravity is doubled.

(e) What happens if all four of the variables in parts (a) through (d) are doubled?

**10.52.** The earth precesses once every 26,000 years and spins on its axis once a day. Estimate the magnitude of the torque that causes the precession of the earth. You may need some data from Appendix F. Make the estimate by assuming (i) the earth is a uniform sphere and (ii) the precession of the earth is like that of the gyroscope shown in Fig. 10.34. In this model, the precession axis and rotation axis are perpendicular. Actually, the angle between these two axes for the earth is only $23\frac{1}{2}$°; this affects the calculated torque by about a factor of 2.

**Problems**

**10.53.** A 500-kg grindstone is a solid disk 0.520 m in diameter. You press an ax down on the rim with a normal force of 160 N (Fig. 10.43). The coefficient of kinetic friction between the blade and the stone is 0.60, and there is a constant friction torque of $6.50\, N\cdot m$ between the axle of the stone and its bearings.

(a) How much force must be applied tangentially at the end of a crank handle 0.500 m long to bring the stone from rest to 120 rev/min in 9.00 s? (b) After the grindstone attains an angular speed of 120 rev/min, what tangential force at the end of the handle is needed to maintain a constant angular speed of 120 rev/min?

(c) How much time does it take the grindstone to come from 120 rev/min to rest if it is acted on by the axle friction alone?

**10.54.** An experimental bicycle wheel is placed on a test stand so that it is free to turn on its axle. If a constant net torque of 5.00 N·m is applied to the tire for 2.00 s, the angular speed of the tire increases from 0 to 100 rev/min. The external torque is then removed, and the wheel is brought to rest by friction in its bearings in 125 s. Compute (a) the moment of inertia of the wheel about the rotation axis; (b) the friction torque; (c) the total number of revolutions made by the wheel in the 125-s time interval.

**10.55. Speedometer.** Your car’s speedometer converts the angular speed of the wheels to the linear speed of the car, assuming standard-size tires and no slipping on the pavement. (a) If your car’s standard tires are 24 inches in diameter, at what rate (in rpm) are your wheels rotating when you are driving at a freeway speed of 60 mi/h? (b) Suppose you put oversize, 30-inch-diameter tires on your car. How fast are you really going when your speedometer reads 60 mi/h? (c) If you now put on undersize, 20-inch-diameter tires, what will the speedometer read when you are actually traveling at 50 mi/h?

**10.56.** A uniform hollow disk has two pieces of thin light wire wrapped around its outer rim and is supported from the ceiling (Fig. 10.51). Suddenly one of the wires breaks, and the remaining wire does not slip as the disk rolls down. Use energy conservation to find the speed of the center of this disk after it has fallen a distance of 1.20 m.

**Figure 10.51** Problem 10.56.
10.57. A thin, uniform 3.80-kg bar, 80.0 cm long, has very small 2.50-kg balls glued on at either end (Fig. 10.52). It is supported horizontally by a thin, horizontal, frictionless axle passing through its center and perpendicular to the bar. Suddenly the right-hand ball becomes detached and falls off, but the other ball remains glued to the bar. (a) Find the angular acceleration of the bar just after the ball falls off. (b) Will the angular acceleration remain constant as the bar continues to swing? If not, will it increase or decrease? (c) Find the angular velocity of the bar just as it swings through its vertical position.

10.58. While exploring a castle, Exena the Exterminator is spotted by a dragon who chases her down a hallway. Exena runs into a room and attempts to swing the heavy door shut before the dragon gets her. The door is initially perpendicular to the wall, so it must be turned through 90° to close. The door is 3.00 m tall and 1.25 m wide, and it weighs 750 N. You can ignore the friction at the hinges. If Exena applies a force of 220 N at the edge of the door and perpendicular to it, how much time does it take her to close the door?

10.59. A thin rod of length \( l \) lies on the \(+x\)-axis with its left end at the origin. A string pulls on the rod with a force \( \vec{F} \) directed toward a point \( P \) a distance \( h \) above the rod. Where along the rod should you attach the string to get the greatest torque about the origin if point \( P \) is (a) above the right end of the rod? (b) Above the left end of the rod? (c) Above the center of the rod?

10.60. Balancing Act. Attached to one end of a long, thin, uniform rod of length \( L \) and mass \( M \) is a small blob of clay of the same mass \( M \). (a) Locate the position of the center of mass of the system of rod and clay. Note this position on a drawing of the rod. (b) You carefully balance the rod on a frictionless tabletop so that it is standing vertically, with the end without the clay touching the table. If the rod is now tipped so that it is a small angle \( \theta \) away from the vertical, determine its angular acceleration at this instant. Assume that the end without the clay remains in contact with the tabletop. (Hint: See Table 9.2.) (c) You again balance the rod on the frictionless tabletop so that it is standing vertically, but now the end of the rod with the clay is touching the table. If the rod is again tipped so that it is a small angle \( \theta \) away from the vertical, determine its angular acceleration at this instant. Assume that the end with the clay remains in contact with the tabletop. How does this compare to the angular acceleration in part (b)? (d) A pool cue is a tapered wooden rod that is thick at one end and thin at the other. You can easily balance a pool cue vertically on one finger if the thin end is in contact with your finger; this is quite a bit harder to do if the thick end is in contact with your finger. Explain why there is a difference.

10.61. You connect a light string to a point on the edge of a uniform vertical disk with radius \( R \) and mass \( M \). The disk is free to rotate without friction about a stationary horizontal axis through its center. Initially, the disk is at rest with the string connection at the highest point on the disk. You pull the string with a constant horizontal force \( \vec{F} \) until the wheel has made exactly one-quarter revolution about a horizontal axis through its center, and then you let go. (a) Use Eq. (10.20) to find the work done by the string. (b) Use Eq. (6.14) to find the work done by the string. Do you obtain the same result as in part (a)? (c) Find the final angular speed of the disk. (d) Find the maximum tangential acceleration of a point on the disk. (e) Find the maximum radial (centripetal) acceleration of a point on the disk.

10.62. The mechanism shown in Fig. 10.53 is used to raise a crate of supplies from a ship's hold. The crate has total mass 50 kg. A rope is wrapped around a wooden cylinder that turns on a metal axle. The cylinder has radius 0.25 m and moment of inertia \( I = 2.9 \text{ kg} \cdot \text{m}^2 \) about the axle. The crate is suspended from the free end of the rope. One end of the axle pivots on frictionless bearings; a crank handle is attached to the other end. When the crank is turned, the end of the handle rotates about the axle in a vertical circle of radius 0.12 m, the cylinder turns, and the crate is raised. What magnitude of the force \( \vec{F} \) applied tangentially to the rotating crank is required to raise the crate with an acceleration of 0.80 m/s²? (You can ignore the mass of the rope as well as the moments of inertia of the axle and the crank.)

10.63. A large 16.0-kg roll of paper with radius \( R = 18.0 \text{ cm} \) rests against the wall and is held in place by a bracket attached to a rod through the center of the roll (Fig. 10.54). The rod turns without friction in the bracket, and the moment of inertia of the paper and rod about the axis is \( 0.260 \text{ kg} \cdot \text{m}^2 \). The other end of the bracket is attached by a frictionless hinge to the wall such that the bracket makes an angle of 30.0° with the wall. The weight of the bracket is negligible. The coefficient of kinetic friction between the paper and the wall is \( \mu_k = 0.25 \). A constant vertical force \( F = 40.0 \text{ N} \) is applied to the paper, and the paper unrolls. (a) What is the magnitude of the force that the rod exerts on the paper as it unrolls? (b) What is the magnitude of the angular acceleration of the roll?

10.64. A block with mass \( m = 5.00 \text{ kg} \) slides down a surface inclined 36.9° to the horizontal (Fig. 10.55). The coefficient of kinetic friction is 0.25. A string attached to the block is wrapped around a flywheel on a fixed axis at \( O \). The flywheel has mass 25.0 kg and moment of inertia 0.500 \text{ kg} \cdot \text{m}^2 \) with respect to the axis of rotation. The string pulls without slipping at a perpendicular distance of 0.200 m from that axis. (a) What is the acceleration of the block down the plane? (b) What is the tension in the string?

10.65. Two metal disks, one with radius \( R_1 = 2.50 \text{ cm} \) and mass \( M_1 = 0.80 \text{ kg} \) and the other with radius \( R_2 = 5.00 \text{ cm} \) and mass \( M_2 = 1.60 \text{ kg} \), are welded together and mounted on a frictionless axis through their common center, as in Problem 9.89. (a) A light string is wrapped around the edge of the smaller disk, and a 1.50 kg block is suspended from the free end of the string. What is the magnitude of the downward acceleration of the block after it is
released? (b) Repeat the calculation of part (a), this time with the string wrapped around the edge of the larger disk. In which case is the acceleration of the block greater? Does your answer make sense?

10.66. A lawn roller in the form of a thin-walled, hollow cylinder with mass $M$ is pulled horizontally with a constant horizontal force $F$ applied by a handle attached to the axle. If it rolls without slipping, find the acceleration and the friction force.

10.67. Two weights are connected by a very light flexible cord that passes over a 50.0-N frictionless pulley of radius 0.300 m. The pulley is a solid uniform disk and is supported by a hook connected to the ceiling (Fig. 10.56). What force does the ceiling exert on the hook?

10.68. A solid disk is rolling without slipping on a level surface at a constant speed of 2.50 m/s. (a) If the disk rolls up a 30.0° ramp, how far along the ramp will it move before it stops? (b) Explain why your answer in part (a) does not depend on either the mass or the radius of the disk.

10.69. The Yo-yo. A yo-yo is made from two uniform disks, each with mass $m$ and radius $R$, connected by a light axle of radius $b$. A light, thin string is wound several times around the axle and then held stationary while the yo-yo is released from rest, dropping as the string unwinds. Find the linear acceleration and angular acceleration of the yo-yo and the tension in the string.

10.70. A thin-walled, hollow spherical shell of mass $m$ and radius $r$ starts from rest and rolls without slipping down the track shown in Fig. 10.57. Points $A$ and $B$ are on a circular part of the track having radius $R$. The diameter of the shell is very small compared to $R$, and rolling friction is negligible. (a) What is the minimum height $h_0$ for which this shell will make a complete loop-the-loop on the circular part of the track? (b) How hard does the track push on the shell at point $B$, which is at the same level as the center of the circle? (c) Suppose that the track had no friction and the shell was released from the same height $h_0$ you found in part (a). Would it make a complete loop-the-loop? How do you know? (d) In part (c), how hard does the track push on the shell at point $A$, the top of the circle? How hard did it push on the shell in part (a)?

10.71. Figure 10.58 shows three identical yo-yos initially at rest on a horizontal surface. For each yo-yo, the string is pulled in the direction shown. In each case, there is sufficient friction for the yo-yo to roll without slipping. Draw the free-body diagram for each yo-yo. In what direction will each yo-yo rotate? (Try it!) Explain your answers.

10.72. As shown in Fig. 10.46, a string is wrapped several times around the rim of a small hoop with radius 0.0800 m and mass 0.180 kg. The free end of the string is pulled upward in just the right way so that the hoop does not move vertically as the string unwinds. (a) Find the tension in the string as the string unwinds. (b) Find the angular acceleration of the hoop as the string unwinds. (c) Find the upward acceleration of the hand that pulls on the free end of the string. (d) How would your answers be different if the hoop were replaced by a solid disk of the same mass and radius?

10.73. Starting from rest, a constant force $F = 100$ N is applied to the free end of a 50-m cable wrapped around the outer rim of a uniform solid cylinder, similar to the situation shown in Fig. 10.9(a). The cylinder has mass 4.00 kg and diameter 30.0 cm and is free to turn about a fixed, frictionless axle through its center. (a) How long does it take to unwrap all the cable, and how fast is the cable moving just as the last bit comes off? (b) Now suppose that the cylinder is replaced by a uniform hoop, with all other quantities remaining unchanged. In this case, would the answers in part (a) be larger or smaller? Explain.

10.74. A uniform marble rolls without slipping down the path shown in Fig. 10.59, starting from rest. (a) Find the minimum height $h$ required for the marble not to fall into the pit. (b) The moment of inertia of the marble depends on its radius. Explain why the answer to part (a) does not depend on the radius of the marble. (c) Solve part (a) for a block that slides without friction instead of the rolling marble. How does the minimum $h$ in this case compare to the answer in part (a)?

10.75. Rolling Stones. A solid, uniform, spherical boulder starts from rest and rolls down a 50.0-m-high hill, as shown in Fig. 10.60. The top half of the hill is rough enough to cause the boulder to roll without slipping, but the lower half is covered with ice and there is no friction. What is the translational speed of the boulder when it reaches the bottom of the hill?

10.76. A solid, uniform ball rolls without slipping up a hill, as shown in Fig. 10.61. At the top of the hill, it is moving horizontally, and then it goes over the vertical cliff. (a) How far from the foot of the cliff does the ball land, and how fast is it
moving just before it lands? (b) Notice that when the balls lands, it has a greater translational speed than when it was at the bottom of the hill. Does this mean that the ball somehow gained energy? Explain!

10.71. A 42.0-cm-diameter wheel, consisting of a rim and six spokes, is constructed from a thin, rigid plastic material having a linear mass density of 25.0 g/cm. This wheel is released from rest at the top of a hill 58.0 m high. (a) How fast is it rolling when it reaches the bottom of the hill? (b) How would your answer change if the linear mass density and the diameter of the wheel were each doubled?

10.78. A high-wheel antique bicycle has a large front wheel with the foot-powered crank mounted on its axle and a small rear wheel turning independently of the front wheel; there is no chain connecting the wheels. The radius of the front wheel is 65.5 cm, and the radius of the rear wheel is 22.0 cm. Your modern bike has a wheel diameter of 66.0 cm (26 inches) and front and rear sprockets with radii of 11.0 cm and 5.5 cm, respectively. The rear sprocket is rigidly attached to the axle of the rear wheel. You ride your modern bike and turn the front sprocket at 1.00 rev/s. The wheels of both bikes roll along the ground without slipping. (a) What is your linear speed when you ride your modern bike? (b) At what rate must you turn the crank of the antique bike in order to travel at the same speed as in part (a)? (c) What then is the angular speed (in rev/s) of the small rear wheel of the antique bike?

10.79. In a lab experiment you let a uniform ball roll down a curved track. The ball starts from rest and rolls without slipping. While on the track, the ball descends a vertical distance \( h \). The lower end of the track is horizontal and extends over the edge of the lab table; the ball leaves the track traveling horizontally. While free falling after leaving the track, the ball moves a horizontal distance \( x \) and a vertical distance \( y \). (a) Calculate \( x \) in terms of \( h \) and \( y \), ignoring the work done by friction. (b) Would the answer to part (a) be any different on the moon? (c) Although you do the experiment very carefully, your measured value of \( x \) is consistently a bit smaller than the value calculated in part (a). Why? (d) What would \( x \) be for the same \( h \) and \( y \) as in part (a) if you let a silver dollar roll down the track? You can ignore the work done by friction.

10.80. In a spring gun, a spring of force constant 400 N/m is compressed 0.15 m. When fired, 80.0\% of the elastic potential energy stored in the spring is eventually converted into the kinetic energy of a 0.0590-kg uniform ball that is rolling without slipping at the base of a ramp. The ball continues to roll without slipping up the ramp with 90.0\% of the kinetic energy at the bottom converted into an increase in gravitational potential energy at the instant it stops. (a) What is the speed of the ball's center of mass at the base of the ramp? (b) At this position, what is the speed of a point at the top of the ball? (c) At this position, what is the speed of a point at the bottom of the ball? (d) What maximum vertical height up the ramp does the ball move?

10.81. If a wheel rolls along a horizontal surface at constant speed, the coordinates of a certain point on the rim of the wheel are \( x(t) = R(2\pi T t) + \sin(2\pi T t) \) and \( y(t) = R(1 - \cos(2\pi T t)) \), where \( R \) and \( T \) are constants. (a) Sketch the trajectory of the point from \( t = 0 \) to \( t = 2T \). A curve with this shape is called a cycloid. (b) What are the meanings of the constants \( R \) and \( T \)? (c) Find the \( x \)- and \( y \)-components of the velocity and of the acceleration of the point at any time \( t \). (d) Find the times at which the point is instantaneously at rest. What are the \( x \)- and \( y \)-components of the acceleration at these times? (e) Find the magnitude of the acceleration of the point. Does it depend on time? Compare to the magnitude of the acceleration of a particle in uniform circular motion, \( a_{uu} = 4\pi^2 R/T^2 \). Explain your result for the magnitude of the acceleration of the point on the rolling wheel, using the idea that rolling is a combination of rotational and translational motion.

10.82. A child rolls a 0.600-kg basketball up a long ramp. The basketball can be considered a thin-walled, hollow sphere. When the child releases the basketball at the bottom of the ramp, it has a speed of 8.0 m/s. When the ball returns to her after rolling up the ramp and then rolling back down, it has a speed of 4.0 m/s. Assume the work done by friction on the basketball is the same when the ball moves up or down the ramp and that the basketball rolls without slipping. Find the maximum vertical height increase of the ball as it rolls up the ramp.

10.83. A uniform, solid cylinder with mass \( M \) and radius \( 2R \) rests on a horizontal tabletop. A string is attached by a yoke to a frictionless axle through the center of the cylinder so that the cylinder can rotate about the axle. The string runs over a disk-shaped pulley with mass \( M \) and radius \( R \) that is mounted on a frictionless axle through its center. A block of mass \( M \) is suspended from the free end of the string (Fig. 10.62). The string doesn’t slip over the pulley surface, and the cylinder rolls without slipping on the tabletop. Find the magnitude of the acceleration of the block after the system is released from rest.

**Figure 10.62** Problem 10.83.

10.84. A uniform drawbridge 8.00 m long is attached to the roadway by a frictionless hinge at one end, and it can be raised by a cable attached to the other end. The bridge is at rest, suspended at 60.0° above the horizontal, when the cable suddenly breaks. (a) Find the angular acceleration of the drawbridge just after the cable breaks. (Gravity behaves as though it all acts at the center of mass.) (b) Could you use the equation \( \omega = \omega_0 + \dot{\omega}t \) to calculate the angular speed of the drawbridge at a later time? Explain why. (c) What is the angular speed of the drawbridge as it becomes horizontal?

10.85. A 5.00-kg ball is dropped from a height of 12.0 m above one end of a uniform bar that pivots at its center. The bar has mass 8.00 kg and is 4.00 m in length. At the other end of the bar sits another 5.00-kg ball, unattached to the bar. The dropped ball sticks to the bar after the collision. How high will the other ball go after the collision?

10.86. A uniform, 0.0300-kg rod of length 0.400 m rotates in a horizontal plane about a fixed axis through its center and perpendicular to the rod. Two small rings, each with mass 0.0200 kg, are mounted so that they can slide along the rod. They are initially held by catches at positions 0.0500 m on each side of the center of the rod, and the system is rotating at 30.0 rev/min. With no other changes in the system, the catches are released, and the rings slide outward along the rod and fly off at the ends. (a) What is the angular speed of the system at the instant when the rings reach the ends of the rod? (b) What is the angular speed of the rod after the rings leave it?
10.87. A uniform rod of length $L$ rests on a frictionless horizontal surface. The rod pivots about a fixed frictionless axis at one end. The rod is initially at rest. A bullet traveling parallel to the horizontal surface and perpendicular to the rod with speed $v$ strikes the rod at its center and becomes embedded in it. The mass of the bullet is one-fourth the mass of the rod. (a) What is the final angular speed of the rod? (b) What is the ratio of the kinetic energy of the system after the collision to the kinetic energy of the bullet before the collision?

10.88. The solid wood door of a gymnasium is 1.00 m wide and 2.00 m high, has total mass 35.0 kg, and is hinged along one side. The door is open and at rest when a stray basketball hits the center of the door head-on, applying an average force of 1500 N to the door for 8.00 ms. Find the angular speed of the door after the impact. [Hint: Integrating Eq. (10.29) yields $\Delta x_\tau = \int (\tau_x) dt = (\tau_x) t = \omega \Delta t$. The quantity $\int (\tau_x) dt$ is called the angular impulse.]

10.89. A target in a shooting gallery consists of a vertical square wooden board, 0.250 m on a side and with mass 0.750 kg, that pivots on a horizontal axis along its top edge. The board is struck face-on at its center by a bullet with mass 1.90 g that is traveling at 360 m/s and that remains embedded in the board. (a) What is the angular speed of the board just after the bullet's impact? (b) What is the maximum height above the equilibrium position does the center of the board reach before starting to swing down again? (c) What minimum bullet speed would be required for the board to swing all the way over after impact?

10.90. Neutron Star Glitches. Occasionally, a rotating neutron star (see Exercise 10.39) undergoes a sudden and unexpected speedup called a glitch. One explanation is that a glitch occurs when the crust of the neutron star settles slightly, decreasing the moment of inertia about the rotation axis. A neutron star with angular speed $\omega_0 = 70.4$ rad/s underwent such a glitch in October 1975 that increased its angular speed to $\omega = \omega_0 + \Delta \omega$ where $\Delta \omega = 2.01 \times 10^{-6}$ rad/s. If the radius of the neutron star before the glitch was $11.0$ km, by how much did its radius decrease in the starquake? Assume that the neutron star is a uniform sphere.

10.91. A 500.0-g bird is flying horizontally at 2.25 m/s, not paying much attention, when it suddenly flies into a stationary vertical bar, hitting it 25.0 cm below the top (Fig. 10.63). The bar is uniform, 0.750 m long, has a mass of 1.50 kg, and is hinged at its base. The collision stuns the bird so that it just drops to the ground afterward (but soon recovers to fly happily away). What is the angular velocity of the bar (a) just after it is hit by the bird, and (b) just as it reaches the ground?

10.92. A small block with mass 0.250 kg is attached to a string passing through a hole in a frictionless, horizontal surface (see Fig. 10.48). The block is originally revolving in a circle with a radius of 0.800 m about the hole with a tangential speed of 4.00 m/s. The string is then pulled slowly from below, shortening the radius of the circle in which the block revolves. The breaking strength of the string is 30.0 N. What is the radius of the circle when the string breaks?

10.93. A horizontal plywood disk with mass 7.00 kg and diameter 1.00 m pivots on frictionless bearings about a vertical axis through its center. You attach a circular model-railroad track of negligible mass and average diameter 0.95 m to the disk. A 1.20-kg, battery-driven model train rests on the tracks. To demonstrate conservation of angular momentum, you switch on the train's engine. The train moves counterclockwise, soon attaining a constant speed of 0.600 m/s relative to the tracks. Find the magnitude and direction of the angular velocity of the disk relative to the earth.

10.94. A stiff uniform wire of mass $M_0$ and length $L_0$ is cut, bent, and the parts soldered together so that it forms a circular wheel having four identical spokes coming out from the center. None of the wire is wasted, and you can neglect the mass of the solder. (a) What is the moment of inertia of this wheel about an axis through its center perpendicular to the plane of the wheel? (b) If the wheel is given an initial spin with angular velocity $\omega_0$ and stops uniformly in time $T$, what is the frictional torque at its axle?

10.95. In a physics laboratory you do the following ballistic pendulum experiment: You shoot a ball of mass $m$ horizontally from a spring gun with a speed $v$. The ball is immediately caught a distance $r$ below a frictionless pivot by a pivoted catcher assembly of mass $M$. The moment of inertia of this assembly about its rotation axis through the pivot is $I$. The distance $r$ is much greater than the radius of the ball. (a) Use conservation of angular momentum to show that the angular speed of the ball and catcher just after the ball is caught is $\omega = \frac{m v r}{(m r^2 + 1)}$. (b) After the ball is caught, the center of mass of the ball-catcher assembly system swings up with a maximum height $h$. Use conservation of energy to show that $\omega = \sqrt{2(M + m) g h / (m r^2 + 1)}$. (c) Your lab partner says that linear momentum is conserved in the collision and derives the expression $m v = (m + M) v' V$, where $V$ is the speed of the ball immediately after the collision. She then uses conservation of energy to derive that $V = \sqrt{2g h}$, so that $m v = (m + M) \sqrt{2g h}$. Use the results of parts (a) and (b) to show that this equation is satisfied only for the special case where $r$ is given by $I = M r^2$.

10.96. A 55-kg runner runs around the edge of a horizontal turntable mounted on a vertical, frictionless axis through its center. The runner's velocity relative to the earth has magnitude 2.8 m/s. The turntable is rotating in the opposite direction with an angular velocity of magnitude 0.20 rad/s relative to the earth. The radius of the turntable is 3.0 m, and its moment of inertia about the axis of rotation is 80 kg · m². Find the final angular velocity of the system if the runner comes to rest relative to the turntable. (You can model the runner as a particle.)

10.97. Recession of the Moon. Careful measurements of the earth–moon separation indicate that our satellite is presently moving away from us at approximately 3.0 cm per year. Neglect any angular momentum that the moon might be transferred from the earth to the moon. Calculate the rate of change (in rad/s per year) of the moon's angular velocity around the earth (consult Appendix E and the astronomical data in Appendix F). Is its angular velocity increasing or decreasing? [Hint: $H = \text{constant},$ then $d\theta/dt = 0$.

10.98. Center of Percussion. A baseball bat rests on a frictionless, horizontal surface. The bat has a length of 0.900 m, a mass of 0.800 kg, and its center of mass is 0.600 m from the handle end of the bat (Fig. 10.64). The moment of inertia of the bat about its center of mass is 0.0530 kg · m². The bat is struck by a baseball traveling perpendicular to the bat. The impact applies an impulse $I = \int F \, dt$ at a point a distance $x$ from the handle end of the bat. What must $x$ be so that the handle end of the bat remains at rest as the bat begins to move? [Hint: Consider the motion of the center of mass and the rotation about the center of mass. Find $x$ so that these two motions combine to give $\theta = 0$ for the end of the bat just after the collision. Also, note that integration of Eq. (10.29) gives...