Rotational Motion and Equilibrium

Rigid Bodies, Translations, and Rotations

TERMS and PRINCIPALS

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1. **MC** In pure rotational motion of a rigid body, (a) all the particles of the body have the same angular velocity, (b) all the particles of the body have the same tangential velocity, (c) acceleration is always zero, (d) there are always two simultaneous axes of rotation.  
2. **MC** For an object with only rotational motion, all particles of the object have the same (a) instantaneous velocity, (b) average velocity, (c) distance from the axis of rotation, (d) instantaneous angular velocity.  
3. **MC** The condition for rolling without slipping is (a) \( a = r \omega^2 \), (b) \( v_{cm} = r \omega \), (c) \( F = ma \), (d) \( a = v^2/r \).  
4. **MC** A rolling object (a) has an axis of rotation through the axis of symmetry, (b) has a zero velocity at the point or line of contact, (c) will slip if \( s = r \theta \), (d) all of the preceding.  
5. **MC** For the tires on your skidding car, (a) \( v_{cm} = r \omega \), (b) \( v_{cm} > r \omega \), (c) \( v_{cm} < r \omega \), (d) none of the preceding.  
6. **CQ** Suppose someone in your physics class says that it is possible for a rigid body to have translational motion and rotational motion at the same time. Would you agree? If so, give an example.  
7. **CQ** For a rolling cylinder, what would happen if the tangential speed \( v \) were less than \( r \omega \)? Is it possible for \( v \) to be greater than \( r \omega \)? Explain.  
8. **CQ** If the top of your automobile tire is moving with a speed of \( v \), what is the reading of your speedometer? \( v/2 \)  
9. ● A wheel rolls uniformly on level ground without slipping. A piece of mud on the wheel flies off when it is at the 9 o’clock position (rear of wheel). Describe the subsequent motion of the mud.  
10. ● A rope goes over a circular pulley with a radius of 6.5 cm. If the pulley makes four revolutions without the rope slipping, what length of rope passes over the pulley? 1.6 m  
11. ● A wheel rolls five revolutions on a horizontal surface without slipping. If the center of the wheel moves 3.2 m, what is the radius of the wheel? 0.10 m
13. A ball with a radius of 15 cm rolls on a level surface, and the translational speed of the center of mass is 0.25 m/s. What is the angular speed about the center of mass if the ball rolls without slipping? 1.7 rad/s

15. A bocce ball with a diameter of 6.00 cm rolls without slipping on a level lawn. It has an initial angular speed of 2.35 rad/s and comes to rest after 2.50 m. Assuming constant deceleration, (a) determine the magnitude of its angular deceleration and (b) the magnitude of the maximum tangential acceleration of the ball’s surface (tell where that part is located). (a) 0.0331 rad/s² (b) 1.99×10⁻³ m/s²

**Torque, Equilibrium, and Stability**

17. MC It is possible to have a net torque when (a) all forces act through the axis of rotation, (b) \( \Sigma F = 0 \), (c) an object is in rotational equilibrium, (d) an object remains in unstable equilibrium. (b)

18. MC If an object in unstable equilibrium is allowed to displace slightly, (a) its potential energy will decrease, (b) the center of gravity is directly above the axis of rotation, (c) no gravitational work is done, (d) stable equilibrium will follow. (a)

19. MC Torque has the same units as (a) work, (b) force, (c) angular velocity, (d) angular acceleration. (a)

20. CQ When lifting an object with the use of the back rather than the legs, we often experience back pain. Why? back muscles have to exert greater torque

21. CQ A gymnast on the balance beam will squat when she feels she is losing her balance. Why? to lower center of gravity

23. CQ “Popping a wheelie” is a motorcycle stunt in which the front end of the cycle raises up off the ground on a fast start, and can remain there for some distance. Explain the physics involved in this stunt. frictional torque causes cycle to rotate upward, balanced by weight torque

24. CQ In the cases of both stable and unstable equilibrium, a small displacement of the center of gravity causes gravitational work to be done. However, there is another type of equilibrium in which the displacement of the center of mass involves no gravitational work. This is called neutral equilibrium, and the displaced center of gravity essentially moves in a straight line. Give an example of an object in neutral equilibrium. a cylinder or sphere on a level surface

25. In Fig. 8.4a, if the arm makes a 37° angle with the horizontal and a torque of 18 m·N is to be produced, what force must the biceps muscle supply? 5.6×10² N

26. The drain plug on a car’s engine has been tightened to a torque of 25 m·N. If a 0.15-m-long wrench is used to change the oil, what is the minimum force needed to loosen the plug? 1.7×10² N

27. In Exercise 26, due to limited work space, you must crawl under the car. The force thus cannot be applied perpendicularly to the length of the wrench. If the applied force makes a 30° angle with the length of the wrench, what is the force required to loosen the drain plug? 3.3×10² N

30. A uniform meter stick pivoted at its center (50 cm), has a 100-g mass suspended at the 25.0-cm position. (a) At what position should a 75.0-g mass be suspended to put the system in equilibrium? (b) What mass would have to be suspended at the 90.0-cm position for the system to be in equilibrium? (a) 83.3 cm (b) 62.5 g
35. A bowling ball (mass 7.00 kg and radius 17.0 cm) is released so fast that it skids without rotating down the alley (at least for a while). Assume the ball skids to your right and the coefficient of sliding friction between the ball and the lane surface is 0.400. (a) What is the direction of the torque exerted by the friction on the ball about the center of mass of the ball? (b) Determine the magnitude of this torque (again about the ball’s center of mass). (a) clockwise (b) 4.66 m·N

![Diagram of a bowling ball](image)

38. An artist wishes to construct a birds-and-bees mobile, as shown. If the mass of the bee on the lower left is 0.10 kg and each vertical support string has a length of 30 cm, what are the masses of the other birds and bees? (Neglect the masses of the bars and strings.) \( m_2 = 0.20 \text{ kg} \), \( m_3 = 0.50 \text{ kg} \), \( m_4 = 0.40 \text{ kg} \)

![Birds-and-bees mobile](image)

43. While standing on a long board resting on a scaffold, a 70-kg painter paints the side of a house, as shown in Fig. 8.40. If the mass of the board is 15 kg, how close to the end can the painter stand without tipping the board over? 1.2 m from left end of board

![Figure 8.40](image)

46. Suppose that the board in Fig. 8.40 were suspended from vertical ropes attached to each end instead of resting on scaffolding. If the painter stood 1.5 m from one end of the board, what would the tensions in the ropes be? (See Exercise 43 for additional data.) \( 2.6 \times 10^2 \text{ N} \); \( 5.7 \times 10^2 \text{ N} \)

47. In a circus act, a uniform board (length 3.00 m, mass 35.0 kg) is suspended from a rope at one end, and the other end rests on a concrete pillar. When a clown (mass 75.0 kg) steps out halfway onto the board, the board tilts so the rope end is 30° from the horizontal and the rope stays vertical. (a) In which situation will the rope tension be larger: (1) the board without the clown on it, (2) the board with the clown on it, or (3) you can’t tell from the data given? (b) Calculate the force exerted by the rope in both situations. (a) (b) 2.6 \times 10^2 \text{ N} < 5.7 \times 10^2 \text{ N}

Rotational Dynamics

49. The moment of inertia of a rigid body (a) depends on the axis of rotation, (b) cannot be zero, (c) depends on mass distribution, (d) all of the preceding. (d)
50. **MC** Which of the following best describes the physical quantity called torque: (a) rotational analogue of force, (b) energy due to rotation, (c) rate of change of linear momentum, or (d) force that is tangent to a circle? (a)

51. **MC** In general, the moment of inertia is greater when (a) more mass is farther from the axis of rotation, (b) more mass is closer to the axis of rotation, (c) it makes no difference. (a)

52. **MC** The moment of inertia about an axis parallel to the axis through the center of mass depends on (a) the mass of the rigid body, (b) the distance between the axes, (c) the moment of inertia about the axis through the center of mass, or (d) all of the preceding. (d)

53. **CQ** (a) Does the moment of inertia of a rigid body depend in any way on the center of mass of the body? Explain. (b) Can a moment of inertia have a negative value? If so, explain what this would mean. (a) yes (b) no; see ISM

54. **CQ** Why does the moment of inertia of a rigid body have different values for different axes of rotation? What does this mean physically? depends on how mass is distributed about an axis

55. **CQ** When a hard-boiled egg lying on a table is given a quick torque (spin), it will rise up and spin on one end like a top. A raw egg will not. Why the difference? hard-boiled egg is a rigid body

56. **CQ** Why does jerking a paper towel from a roll cause the paper to tear better than pulling it smoothly? Will the amount of paper on the roll affect the results? see ISM

57. **CQ** Tight-rope walkers are continually in danger of falling (unstable equilibrium). Commonly, a performer carries a long pole while walking the tight rope, as shown in the chapter-opening photo. What is the purpose of the pole? (In walking along a narrow board or rail, you probably extend your arms for the same reason.) see ISM

58. ● A fixed 0.15-kg solid-disk pulley with a radius of 0.075 m is acted on by a net torque of 6.4 m·N. What is the angular acceleration of the pulley? 1.5×10^4 rad/s^2

59. ● What net torque is required to give a uniform 20-kg solid ball with a radius of 0.20 m an angular acceleration of 20 rad/s^2? 0.64 m·N

60. ●● A 2000-kg Ferris wheel accelerates from rest to an angular speed of 2.0 rad/s in 12 s. Approximate the Ferris wheel as a circular disk with a radius of 30 m. What is the net torque on the wheel? 1.5×10^9 m·N

61. ●●● A planetary space probe is in the shape of a cylinder. To protect it from heat on one side (from the Sun’s rays), operators on the Earth put it into a “barbecue mode,” that is, they set it rotating about its long axis. To do this, they fire four small rockets mounted tangentially as shown in ▼ Fig. 8.48 (the probe is shown coming toward you). The object is to get the probe to rotate completely once every 30 seconds, starting from no rotation at all. They wish to do this by firing all four rockets for a certain length of time. Each rocket can exert a thrust of 50.0 N. Assume the probe is a uniform solid cylinder with a radius of 2.50 m and a mass of 1000 kg and neglect the mass of each rocket engine. Determine the amount of time the rockets need to be fired. 1.31 s

**Rotational Work and Kinetic Energy**

74. **MC** From $W = \tau \theta$, the unit of rotational work is the (a) watt, (b) N·m, (c) kg·rad/s^2, (d) N·rad. (b)

75. **MC** A bowling ball rolls without slipping on a flat surface. The ball has (a) rotational kinetic energy, (b) translational kinetic energy, (c) both translational and rotational kinetic energy, (d) neither translational nor rotational kinetic energy. (c)

76. **MC** A rolling cylinder on a level surface has (a) rotational kinetic energy, (b) translational kinetic energy, (c) both translational and rotational kinetic energies. (c)
77. CQ Can you increase the rotational kinetic energy of a wheel without changing its translational kinetic energy? Explain. yes, see ISM

78. CQ In order to produce fuel-efficient vehicles, automobile manufacturers want to minimize rotational kinetic energy and maximize translational kinetic energy when a car is traveling. If you were the designer of wheels of a certain diameter, how would you design them? small total mass with more mass near the center

79. CQ What is required to produce a change in rotational kinetic energy? rotational work

80. • A constant retarding torque of 12 m·N stops a rolling wheel of diameter 0.80 m in a distance of 15 m. How much work is done by the torque? 4.5 × 10^2 J

81. • A person opens a door by applying a 15-N force perpendicular to it at a distance 0.90 m from the hinges. The door is pushed wide open (to 120°) in 2.0 s. (a) How much work was done? (b) What was the average power delivered? (a) 28 J (b) 14 W

82. • A constant torque of 10 m·N is applied to a 10-kg uniform disk of radius 0.20 m. What is the angular speed of the disk after it rotates 2.0 revolutions from rest? 35 rad/s

83. • A 2.5-kg pulley of radius 0.15 m is pivoted about an axis through its center. What constant torque is required for the pulley to reach an angular speed of 25 rad/s after rotating 3.0 revolutions, starting from rest? 0.47 m·N

85. •• A sphere with a radius of 15 cm rolls on a level surface with a constant angular speed of 10 rad/s. To what height on a 30° inclined plane will the sphere roll before coming to rest? (Neglect frictional losses.) 0.16 m

87. •• You wish to accelerate a small merry-go-round from rest to a rotational speed of one third of a revolution per second by pushing tangentially on it. Assume the merry-go-round is a disk with a mass of 250 kg and a radius of 1.50 m. Ignoring friction, how hard do you have to push tangentially to accomplish this in 5.00 s? (Use energy methods and assume a constant push on your part.) 78.5 N

91. •• An industrial flywheel with a moment of inertia of 4.25 × 10^2 kg·m^2 rotates with a speed of 7500 rpm. (a) How much work is required to bring the flywheel to rest? (b) If this work is done uniformly in 1.5 min, how much power is expended? (a) 1.31 × 10^7 J (b) 1.46 × 10^6 W

92. •• A cylindrical hoop, a cylinder, and a sphere of equal radius and mass are released at the same time from the top of an inclined plane. Using the conservation of mechanical energy, show that the sphere always gets to the bottom of the incline first with the fastest speed and that the hoop always arrives last with the slowest speed. see ISM

94. ••• In a tumbling clothes dryer, the cylindrical drum (radius 50.0 cm and mass 35.0 kg) rotates once every second. (a) Determine its rotational kinetic energy about its central axis. (b) If it started from rest and reached that speed in 2.50 s, determine the average net torque on the dryer drum. (a) 173 J (b) 22.0 m·N

**Angular Momentum**

96. MC The units of angular momentum are (a) N·m, (b) kg·m/s^2, (c) kg·m^2/s, (d) J·m. (c)

97. MC The Earth’s orbital speed is greatest about (a) March 21, (b) June 21, (c) Sept. 21, (d) Dec. 21. (d)

98. MC The angular momentum may be increased by (a) decreasing the moment of inertia, (b) decreasing the angular velocity, (c) increasing the product of the angular momentum and moment of inertia, (d) none of these. (c)
99. **CQ** A child stands on the edge of a rotating playground merry-go-round (the hand-driven type). He then starts to walk toward the center of the merry-go-round. This results in a dangerous situation. Why? see ISM

100. **CQ** The release of vast amounts of carbon dioxide may result in an increase in the Earth’s average temperature through the so-called greenhouse effect and cause melting of the polar ice caps. If this occurred and the ocean level rose substantially, what effect would it have on the Earth’s rotation and on the length of the day? longer day; see ISM

101. **CQ** In the classroom demonstration illustrated in Fig. 8.50, a person on a rotating stool holds a rotating bicycle wheel by handles attached to the wheel. When the wheel is held horizontally, she rotates one way (clockwise as viewed from above). When the wheel is turned over, she rotates in the opposite direction. Explain why this occurs. [Hint: Consider angular-momentum vectors.] see ISM

102. **CQ** Cats usually land on their feet when they fall, even if held upside down when dropped (Fig. 8.51). While a cat is falling, there is no external torque and its center of mass falls as a particle. How can cats turn themselves over while falling? see ISM

103. **CQ** Two ice skaters that weigh the same skate towards each other with the same speed on parallel paths. As they pass each other, they link arms. (a) What is the velocity of their center of mass after they link arms? (b) What happens to their initial, linear kinetic energies? see ISM

104. • What is the angular momentum of a 2.0-g particle moving counterclockwise (as viewed from above) with an angular speed of $5\pi$ rad/s in a horizontal circle of radius 15 cm? (Give the magnitude and direction.) $7.1 \times 10^{-3}$ kg·m²/s toward you

105. • A 10-kg rotating disk of radius 0.25 m has an angular momentum of 0.45 kg·m²/s. What is the angular speed of the disk? 1.4 rad/s

106. **IE** ••• Circular disks are used in automobile clutches and transmissions. When a rotating disk couples to a stationary one through frictional force, the energy from the rotating disk can transfer to the stationary one. (a) Is the angular speed of the coupled disks (1) greater than, (2) less than, or (3) the same as the angular speed of the original rotating disk? Why? (b) If a disk rotating at 800 rpm couples to a stationary disk with three times the moment of inertia, what is the angular speed of the combination? (a) (2) less than (b) 200 rpm

107. •• A skater has a moment of inertia of 100 kg·m² when his arms are outstretched and a moment of inertia of 75 kg·m² when his arms are tucked in close to his chest. If he starts to spin at an angular speed of 2.0 rps (revolutions per second) with his arms outstretched, what will his angular speed be when they are tucked in? 2.7 rps

108. **IE** ••• An ice skater spinning with outstretched arms has an angular speed of 4.0 rad/s. She tucks in her arms, decreasing her moment of inertia by 7.5%. (a) What is the resulting angular speed? (b) By what factor does the skater’s kinetic energy change? (Neglect any frictional effects.) (c) Where does the extra kinetic energy come from? (a) 4.3 rad/s (b) $K = 1.1K_o$ (c) work done by skater

109. ••• While repairing his bicycle, a student has it upside down and has the front wheel spinning at 2.00 2.00 rev/s. Assume the wheel has a mass of 3.25 kg and all of the mass is located on the rim, which has a radius of 41.0 cm. To slow the wheel, he places his hand on the tire, thereby exerting a tangential force of friction on the wheel. It takes 3.50 s to come to rest. Use the change in angular momentum to determine the force he exerts on the wheel. Assume the frictional force of the axle is negligible. 4.78 N