Rotational Kinematics and Dynamics Problems

The problems in this section can be solved by applying rotational kinematics and dynamics principles. The problems are divided into four groups according to the major principles required for solution: (1) center of mass, moment of inertia, and/or rotational kinematics; (2) rotational energy; (3) torques; and (4) angular momentum. The specific principles required are indicated in italics at the beginning of each problem.

Center of Mass, Moment of Inertia, and Rotational Kinematics

1. *Center of Mass:* You have been hired as part of a research team consisting of biologists, computer scientists, engineers, mathematicians, and physicists investigating the virus which causes AIDS. This effort depends on the design of a new centrifuge which separates infected cells from healthy cells by spinning a container of these cells at very high speeds. Your design team has been assigned the task of specifying the mechanical structure of the centrifuge arm which holds the sample container. For aerodynamic stability, the arm must have uniform dimensions. Your team decided the shape will be a long, thin strip of length L, width w, and thickness t. The mass of the strip is M. The actual values of these quantities will be optimized by a computer program. For mechanical reasons, the arm must be stronger at one end than at the other. Your team decided to use new composite materials to accomplish this. Using these materials changes the strength by changing the density of the arm along its length while keeping its dimensions constant. To calculate the strength of the brackets necessary to support the arm, you must determine the position of the center of mass of the arm. You decide to do this in two different ways.
   (a) First you make a crude approximation of your design by assuming that the arm is a rigid, massless rod of length L. On this rod are mounted four small objects of equal mass. One of these objects is positioned at each end of the rod, one in the center of the rod, and one midway between the center and the end.
   (b) Next you do a more exact calculation by assuming that arm is a continuous material with a density which varies linearly along its length as (A + Bx).

2. *Center of Mass, Moment of Inertia:* You are on a development team investigating a new design for computer magnetic disk drives. You have been asked to determine if the standard disk drive motor will be sufficient for the test version of the new disk. To do this you decide to calculate how much energy is needed to get the 6.4 cm diameter, 15 gram disk to its operating speed of 350 revolutions per second. The test disk also has 4 different sensors attached to its surface. These small sensors are arranged at the corners of a square with sides of 1.2 cm. To assure stability, the center of mass of the sensor array is in the same position as the center of mass of the disk. The disk's axis of rotation also goes through the center of mass. You know that the sensors have masses of 1.0 grams, 1.5 grams, 2.0 grams, and 3.0 grams. The moment of inertia of your disk is one-half that of a ring.

3. *Center of Mass, Momentum, Kinematics:* Two government agents (FBI agents Mulder and Scully) need your physics expertise to determine why an alien spaceship exploded. The wreckage of the spaceship is in three large pieces around a northern Minnesota town. The center of mass of one piece (mass = 300 kg) of the spaceship landed 6.0 km due north of the center of town. Another piece (mass = 1000 kg) landed 1.6 km to the southeast (36 degrees south of east) of the center of town. The last piece (mass = 400 kg) landed 4.0 km to the southwest (65 degrees south of west) of the center of town. There are no more pieces of the spaceship. The Army, which was watching the spaceship on its radar, claims it was hovering motionless over the center of town when the spaceship spontaneously exploded and the pieces fell to the ground. Agents Mulder and Scully do not believe that the spaceship exploded on its own accord. They think a missile hit it. They ask you to determine whether the fragments found are consistent with the spaceship exploding spontaneously. If not, determine from what direction the missile came. (For simplicity, assume that the pieces of the spaceship after the explosion are moving horizontally.)

4. *Kinematics, Moment of Inertia:* You are working in a research group investigating more energy efficient city busses. One option is to store energy in the rotation of a flywheel when the bus stops and then use it to accelerate the bus. The flywheel under consideration is disk of uniform construction except that it has a massive, thin rim on its edge. Half the mass of the flywheel is in the rim. When the bus stops, the flywheel needs to rotate at 20 revolutions per second. When the bus is going at its normal speed of 30 miles per hour, the flywheel rotates at 2 revolutions per second. The material holding the rim to the rest of the flywheel has been tested to withstand an acceleration of up to 100**g** but you are worried that it might not be strong enough. To check, you calculate the maximum radius of the rim for the case when the flywheel reaches 20 revolutions per second just as the bus going 30 miles per hour makes an emergency stop in 0.50 seconds. You assume that during this time the flywheel has a constant angular acceleration. Your trusty physics text tells you that the moment of inertia of a disk rotating about its center is half that of a ring of the same mass and radius.

5. *Kinematics, Force:* You did so well in your physics course that you decided to try to get a summer job working in a physics laboratory at the University. You got the job as a student lab assistant in a research group investigating the ozone depletion at the Earth's poles. This group is planning to put an atmospheric measuring device in a satellite which will pass over both poles. To collect samples of the upper atmosphere, the satellite will be in a circular orbit 200 miles above the surface of the Earth which has a radius of about 4000 miles. To adjust the instruments for the proper data taking rate, you need to calculate how many times per day the device will sample the atmosphere over the South pole.

6. *Kinematics, Force:* While listening to your professor drone on, you dream about becoming an engineer helping to design a new space station to be built in deep space far from any planetary systems. This state-of-the-(future) art station is powered by a small amount of neutron star matter which has a density of 2×10^{14} g/cm^3. The station will be a large light-weight wheel rotating about its center which contains the power generator. A control room is a tube which goes all the way around the wheel and is 10 meters from its center. The living space and laboratories are located at the outside rim of the wheel and are another tube which goes all the way around it at a distance of

200 meters from the center. To keep the environment as normal as possible, people in both the outer rim and the control room should experience the same “weight” as they had on Earth. That is if they were standing on a bathroom scale, it would read the same as if they were on Earth. This is accomplished by a combination of the rotation of the station and the gravitational attraction of the neutron star matter in the power generator. You suddenly wake up when you drop your pen but decide that the idea is interesting enough to calculate the necessary rate of rotation and generator mass. While drawing the free-body diagrams, you realize that the people are standing with their heads inward on the rim of the station and with their heads outward in the control room.

7. *Kinematics, Force:* You have a summer job at NASA where your team is responsible for specifying a rocket to lift a communications satellite into a circular orbit around the Earth. To effectively relay signals, the satellite will have to always remain over the same point on the Earth's equator just above the communications station which is located 50 miles outside or Nairobi, Kenya. The satellite will have a mass of 3500 kg. You have been assigned the task of calculating the radius of the satellite's orbit and its speed while in orbit and presenting that calculation to your team. For your own curiosity you also decide to calculate the force that the satellite exerts on the Earth while it is in orbit. From your trusty physics textbook you find the radius of the Earth is 6370 km, its mass is 5.96 x 10^{24} kg, and the universal gravitational constant is 6.67 x 10^{-11} N m^2/kg^2.

Rotational Energy

8. *Energy:* While working in an environmental engineering team to determine the quality of the air in downtown Minneapolis, you have been given the task of calibrating the spectrum analyzer. This device gives you the composition of the gasses in a sample by determining the frequency of light absorbed by the sample. Each type of molecule absorbs a certain set of frequencies (its spectrum). The frequencies actually measured are changed if the molecules have an angular velocity about their center of mass. To calibrate the analyzer, you must calculate the expected angular velocity for the Oxygen molecules (O2) in the sample of Minneapolis air. At the temperatures of your gas sample, you calculate that the center of mass speed of a typical molecule is 500 m/s. Based on you knowledge of atomic sizes, you estimate that the typical distance between the nuclei of oxygen atoms in the molecule is 10^{-8} cm. You also know that the 27 x 10^{-27} kg mass of an Oxygen atom is essentially concentrated in its very small nucleus. Your boss tells you to assume that the rotational kinetic energy of the molecule rotating about an axis through the center of the line joining the nuclei of the atoms and perpendicular to that line is 2/3 its translational kinetic energy.

9. *Energy:* While working on your latest novel about settlers crossing the Great Plains in a wagon train, you get into an argument with your co-author regarding the moment of inertia of an actual wooden wagon wheel. The 70-kg wheel is 120-cm in diameter and has heavy spokes connecting the rim to the axle. Your co-author claims that you can approximate using $I = MR^2$ (like for a hoop) but you anticipate I will be significantly less than that because of the mass located in the spokes. To find I experimentally, you mount the wheel on a low-friction bearing then wrap a light cord around the outside of the rim to which you attach a 20-kg bag of sand. When the bag is

released from rest, it drops 3.77-m in 1.6-s during which time the wheel rotates through an angle of 2p-radians. Hint: Use energy considerations.

10. *Energy:* You have a summer job helping to design the opening ceremony for the next winter Olympics. One of the choreographer's ideas is to have skaters race out onto the ice and grab a very large ring (the symbol of the Olympics). Each ring is held horizontal at shoulder height by a vertical pole stuck into the ice. The pole is attached to the ring on its circumference so that the ring can rotate horizontally around the pole. The plan is to have the skater grab the ring at a point on the opposite side from where the pole is attached and, holding on, glide around the pole in a circle. You have been assigned the job of determining the minimum speed that the skater must have before grabbing the ring in terms of the radius of the ring, the mass of the ring, the mass of the skater, and the constant frictional force between the skates and the ice. The choreographer wants the skater and ring to go around the pole at least five times. The skater is to be moving tangent to the ring just before grabbing it.

11. *Energy, Center of Mass:* As a project your team is given the task of designing a space station consisting of four different habitats. Each habitat is an enclosed sphere containing all necessary life support and laboratory facilities. The masses of these habitats are 10 x 10^5 kg, 20 x 10^5 kg, 30 x 10^5 kg, and 40 x 10^5 kg. The entire station must spin so that the inhabitants will experience an artificial gravity. Your team has decided to arrange the habitats at corners of a square with 1.0 km sides. The axis of rotation will be perpendicular to the plane of the square and through the center of mass. To help decide if this plan is practical, you calculate how much energy would be necessary to set the space station spinning at 5.0 revolutions per minute. In your team's design, the size of each habitat is small compared to the size of the space between the habitats and the structure that holds the habitats together is much less massive than any single habitat.

12. *Energy, Center of Mass:* You have a great summer job working for a movie studio. Your assignment is to check the script of an upcoming Star Wars movie for scientific accuracy. In one scene, the hero escapes by putting her spaceship through a wormhole in space. The engines have failed so the ship is coasting when it emerges in another part of the galaxy at the center of a binary star system. Both stars in the system orbit their center of mass and have equal mass. You need to determine the minimum speed of the spaceship when it emerges from the wormhole perpendicular to the plane of the orbiting stars so that it is not captured by the star system. When the movie is better defined, you will know the mass of each star, the radius of their orbit, and the mass of the spaceship. You assume that even a long time ago in a galaxy far, far away the gravitational constant is the same.

13. *Energy, Forces:* You have applied for a great summer job working with a special effects team at a movie studio. As part of your interview you have been asked to evaluate the design for a stunt in a new Indiana Jones production. A large spherical boulder starts from rest and rolls down an inclined track. At the bottom, the track curves up into a vertical circle so that the boulder can roll around on the inside of the circle and come back to ground level. It is important that the boulder not fall off the track at the top of the circle and crush the star standing below. You have been asked to determine the relationship between the height of the boulder's starting point on the ramp (measured

from the center of the boulder) and the maximum radius the circular part of the track. You can determine the mass and the radius of the boulder should you need to know them. You have also been told that the moment of inertia of a sphere is 2/5 that of a ring of the same mass and radius. After some thought you decide that the boulder will stay moving in a vertical circle if its radial acceleration at the top is just that provided by gravity.

Torques

14. *Torque:* In a budget cutting move, the University decided to replace their human mascot, Goldie Gopher, by a real gopher. Unfortunately the new 10 lb Goldie has other ideas and has escaped the clutches of the athletic department by jumping out a window onto a flagpole attached to the building. The fire department has been called in to recover the recalcitrant gopher. The plan is for a fireman to climb out on the flagpole and get Goldie. Goldie is 3 meters out on the 4 meter long flagpole. Because of your technical background, you have a part time job as a University safety officer and are asked to approve this plan. The pole is attached to the building at an angle of 37° above the horizontal and weighs 22 lbs. A horizontal cable with a rated strength of 300 lbs. connects the far end of the pole to the building seems strong enough. The other end of the pole is connected to the building by a steel pin supported by a strong steel brace.
You are worried about whether this pin is strong enough so you calculate the forces on the pin. The lightest fireman available for the job of getting Goldie weighs 150 lbs. in all of her gear. You find that the pin is strong enough so you might approve this daring rescue. You want it to be as safe as possible. You will require that the fireman wear a safety harness which is held by someone inside the building. After all, the cable holding up the flagpole has been out in the Minnesota winter for years. If the cable does break, the flagpole will rotate about the pin supporting its base.
   Doing a quick integral, you find that the moment of inertia of a pole about an axis at one end is 1/3 as much as if all its mass were concentrated at the other end of the pole. To save the fireman you must get her off before the pole goes below a horizontal orientation. The gopher will be on its own. To see if rescue is possible, you calculate the acceleration of the flagpole with the fireman and gopher clinging to it for the two extreme cases, just after the cable breaks and just as it reaches a horizontal orientation.

15. *Torque:* The automatic flag raising system on a horizontal flagpole attached to the vertical outside wall of a tall building has become stuck. The management of the building wants to send a person crawling out along the flagpole to fix the problem. Because of your physics knowledge, you have been asked to consult with a group to decide whether or not this is possible. You are all too aware that no one could survive the 250 foot fall from the flagpole to the ground. The flagpole is a 120 lb steel I-beam which is very strong and rigid. One side of the flagpole is attached to the wall of the building by a hinge so that it can rotate vertically. Nine feet away, the other end of the flagpole is attached to a strong, lightweight cable. The cable goes up from the flagpole at an angle of 30° until it reaches the building where it is bolted to the wall. The mechanic who will climb out on the flagpole weighs 150 lbs. including equipment. From the specifications of the building construction, both the bolt attaching the cable to the building and the hinge have been tested to hold a force of

500 lbs. Your boss has decided that the worse case is when the mechanic is at the far end of the flagpole, nine feet from the building.

16. *Torque:* After watching a news story about a fire in a high rise apartment building, you and your friend decide to design an emergency escape device from the top of a building. To avoid engine failure, your friend suggests a gravitational powered elevator. The design has a large, heavy turntable (a horizontal disk that is free to rotate about its center) on the roof with a cable wound around its edge. The free end of the cable goes horizontally to the edge of the building roof, passes over a heavy vertical pulley, and then hangs straight down. A strong wire cage which can hold 5 people is then attached to the hanging end of the cable. When people enter the cage and release it, the cable unrolls from the turntable lowering the people safely to the ground. To see if this design is feasible you decide to calculate the acceleration of the fully loaded elevator to make sure it is much less than g. Your friend's design has the radius of the turntable disk as 1.5 m and its mass is twice that of the fully loaded elevator. The disk which serves as the vertical pulley has 1/4 the radius of the turntable and 1/16 its mass. In your trusty Physics book you find that the moment of inertia of a disk is 1/2 that of a ring.

17. *Torques, Kinematics:* Because of your physics background, you have been asked to be a stunt consultant for a motion picture about a genetically synthesized prehistoric creature that escapes from captivity and terrorizes the city. The scene you are asked to review has the three main characters of the movie being chased by the creature through an old warehouse. At the exit of the warehouse is a thick steel fire door 10 feet high and 6.0 feet wide weighing about 2,000 pounds. In the scene, the three actors are to flee from the building and close the fire door (initially at rest), thus sealing the creature inside the building. With the creature running at 30 mph, they have 5.0 seconds to shut the door. You are asked to determine if they can do it. You estimate that each actor can each push on the door with a force of 50 pounds. When they push together, each actor needs a space of about 1.5 feet between them and the next actor. The door, which has a moment of inertia of $1/3\ M r^2$ around its hinges, needs to rotate 120 degrees for it to close completely.

18. *Torque, Kinematics:* While watching the local TV news show, you see a report about ground water contamination and how it effects farms which get their water from wells. For dramatic effect, the reporter stands next to an old style well which still works by lowering a bucket at the end of a rope into a deep hole in the ground to get water. At the top of the well a single vertical pulley is mounted to help raise and lower the bucket. The thin rope passes over the large pulley which is essentially a heavy steel ring supported by light spokes. To demonstrate the depth of the well, the reporter completely wraps the rope around the pulley and suspends the bucket from one end. She then releases the bucket, at rest near the pulley, and it descends to the bottom of the well unwinding the rope from the pulley as it falls. It takes 2.5 seconds. She doesn't tell you the depth of the well so you decide to calculate it. You estimate that the pulley has the same mass of the bucket and assume that the mass of the rope and any friction can be neglected.

19. *Energy or Torques, Kinematics:* While you watching a TV show about life in the ancient world, you see that the people in one village used a solid sphere made out of clay as a kind of pulley to help haul up water from a well. A well-greased wooden axle was placed through the center of the

sphere and fixed in a horizontal orientation above the well, allowing the sphere to rotate freely. To demonstrate the depth of the well, the host of the program completely wrapped the rope around the sphere and suspended the bucket from one end. She then released the bucket, at rest near the sphere, and allowed it to descend to the bottom of the well unwinding the string from the sphere as it went. It took 2.5 seconds. You wonder what the depth of the well was so you decide to calculate it. You estimate that the sphere has twice the mass of the bucket and assume that the mass of the rope can be neglected. You look up the moment of inertia of a sphere about an axis through its center of mass and find it is 2/5 that of a ring of the same mass and radius.

20. *Energy or Torque, Kinematics:* You have been asked to help design a safety mechanism which will automatically drops a rope from the window of an apartment in the case of fire. One end of the rope is fastened to a ledge on the outside wall of the building while the other is rolled tightly around a hollow cylinder. When a fire is detected, the mechanism drops the hollow cylinder so that it is parallel to the ground. The cylinder falls straight down without touching the side of the building and the rope unwinds from around a point midway along its length. To optimize your design, you need to calculate how long it takes to fall to the ground as a function of the height of the fall, the radius of the cylinder, the mass of the cylinder, and the length of the cylinder.

21. *Torques, Forces:* A friend of yours who likes to fix his own car has improvised a car-lifting device in his garage. He explains that he plans to park the car on a rectangular platform which is lifted into the air by four ropes each attached to a corner of the platform. The platform is constructed of steel I-beams and has a weight of 250 lbs. It is 12 feet long and 5.0 feet wide with its center of mass 5.0 feet from the front and 2.5 feet from either side. His car has a weight of 1400 lbs. and 75% of that weight is carried by the front tires. The distance between the centers of the tires is 7.2 feet. His plan is to park the car in the middle of the platform with the front tire 2.4 feet from the front of the platform over the midpoint of the platform. In that way, the two front ropes have the equal tensions and the two back ropes will also have equal tensions. The ropes are certified to hold a load of 5000 N each. Before he uses his device, he has asked your advice on its safety.

22. *Torques, Forces:* You have been asked to design a machine to move a large cable spool up a factory ramp in 30 seconds. The spool is made of two 6.0 ft diameter disks of wood with iron rims connected together at their centers by a solid cylinder 1.0 ft wide and 3.0 ft long. Sometime later in the manufacturing process, cable will be wound around the cylinder. For now the cylinder is bare but the spool still weighs 200 lbs. Your plan is to attach a thin ring around the cylinder and pull the spool up the ramp with a rope attached to the top of this ring. The spool will then roll without slipping up the ramp on its two outside disks at a constant speed. To finish the design you need to calculate how strong the rope must be to pull the spool when it is moving up the ramp at a constant speed. The ramp has an angle of 27^{o} from the horizontal and the rope will be parallel to the ramp. A set of light weight bearings minimizes the friction between the ring and the cylinder and fixes the orientation of the ring so that the rope always pulls from its top. The diameter of the ring is essentially the same as that of the cylinder.

23. *Torques, Forces:* You have been chosen to be part of a team investigating an explosion in a virology laboratory. When you enter the lab, you see that a large utility conduit, which was originally

suspended horizontally overhead, has fallen on top of a chemical workbench. You decide to determine if a mechanical failure made the conduit break, crashing into the chemicals and causing the explosion or if the chemical explosion caused the conduit to fall. The heavy conduit, essentially a bar with a non-uniform mass distribution, was held up in the air by two lightweight cables attached to the ceiling at different angles. One cable was attached at each end of the conduit. To check out the possibility of a mechanical failure, you first decide to calculate the position of the center of mass from one end of the conduit based on the known weight of the conduit, the length of the conduit, and the angles of the cables with the ceiling.

24. *Torques, Forces:* You have a summer job working downtown washing windows on skyscrapers (the pay is great and so are the medical benefits). The platform you and your partner are using to get to the windows is a meter wide and four meters long. You know from hauling the platform out of your truck countless times that it has a mass of 70 kg. It is supported by two cables, one at each end, mounted on-center to prevent the platform from tipping over as it is pulled up the side of the building at a constant speed. If you (mass of 55 kg) are standing on the platform 1 meter from one cable while your partner (mass of 87 kg) is 1.3 meters from the other cable and both of you are half a meter from the side, what is the tension in each cable? Assume the platform has a uniform mass distribution and is of negligible thickness.

Angular Momentum

25. *Angular Momentum:* You are part of a team in an engineering contest trying to design a mechanical "cat" which, when dropped motionless, upside down from 2.5 m, can right itself before it hits the ground by rotating its "tail." The body of the "cat," aptly named Katt, is a solid cylinder 1 foot in length and 6 inches in diameter, with a mass of 5.44 kg. Attached to the center of one end of the body is Katt's "tail," a 1 foot long rod which extends out perpendicular to Katt's body and has only 1% the mass of the body. Your task is to determine the energy demand put on the small electric motor in the body which rotates the "tail." Based on your work, have you any design improvements to suggest to the rest of the team? Remember: a solid cylinder rotated about it's central axis has a moment of inertia 1/2 that of a cylinder with all it's mass on it's circumference; a rod rotated about one end has a moment of inertia 1/3 of that if mass were concentrated at the opposite end.

26. *Angular Momentum:* You have been asked to help evaluate a proposal to build a device to determine the speed of hockey pucks shot along the ice. The device consists of a rod which rests on the ice and is fastened to the ice at one end so that it is free to rotate horizontally. The free end of the rod has a small, light basket which will catch the hockey puck. The puck slides across the ice perpendicular to the rod and is caught in the basket which is initially at rest. The rod then rotates. The designers claim that knowing the length of the rod, the mass of the rod, the mass of the puck, and the frequency of the rotation of the rod and puck, you can determine the speed of the puck as it moved across the ice.

27. *Angular Momentum, Energy:* You are a member of a group designing an air filtration system for allergy suffers. To optimize its operation you need to measure the mass of the common pollen in the air where the filter will be used. To measure the pollen's mass, you have designed a small rectangular box with a hole in one side to allow the pollen to enter. Once inside the pollen is given a positive electric charge and accelerated by an electrostatic force to a speed of 1.4 m/s. The pollen then hits the end of a very small, uniform bar which is hanging straight down from a pivot at its top. Since the bar has a negative charge at its tip, the pollen sticks to it as the bar swings up. Measuring the angle that the bar swings up would give the particle's mass. After the angle is measured, the charge of the bar is reversed, releasing that particle. It's a cool design but your friend insists it will never work. To prove it she asks you to calculate the length of the bar which would give you a reasonable angle of about 10° for a typical pollen particle of 4×10^{-9} grams. Your plan calls for a bar of 7×10^{-4} grams with a moment of inertial 1/12 as much as if all of its mass were concentrated at its end. Is she right?

28. *Angular Momentum, Energy:* You have been asked to design a new stunt for the opening of an ice show. A small 50 kg skater glides down a ramp and along a short level stretch of ice. While gliding along the level stretch she makes herself as small as possible. Keeping herself as small as possible she then grabs the bottom end of a large 180 kg vertical rod which is free to turn vertically about a axis through its center. The plan is for her to hold onto the 20 foot long rod while it swings her to the top. The rod has a uniform mass distribution. You have been asked to give the minimum height of the ramp. Doing a quick integral tells you that the moment of inertia of this rod about its center is 1/3 of what its moment of inertia would be if all of its mass were concentrated at one of its ends.

29. *Angular Momentum, Energy:* Your group has decided to revisit the lab experiment in which a metal ring was dropped onto a rotating plate. In hopes of getting better results, you now have a motor which initially spins the disk and shaft at 3.0 rev. per second. You are also using a mechanical device to drop the ring, so that it lands perfectly in the groove on every trial. Unfortunately the bearing in your apparatus is giving out (after weeks of heavy use) so you must redo your analysis, taking into account the frictional force which the bearing applies to the outside of the shaft. You assume that this force is approximately constant, except perhaps during the collision event itself. To avoid the large uncertainties associated with using a stopwatch, you decide to count revolutions -- you let the disk rotate twice after disengaging the motor, then drop the ring, then note that the entire apparatus goes around 17 more times before coming to rest. How large is the frictional force? The radii of the disk, shaft, and ring are 11 cm, 0.63 cm, and 6.5 cm (5.5 cm) outside (inside) respectively. The moments of inertia (about the appropriate axis) for the disk, shaft, and ring are 5.1×10^{-3} kg m^2, 3.7×10^{-6} kg m^2, and 8.9×10^{-3} kg m^2 respectively.

30. *Angular Momentum, Energy, Kinematics:* You have been hired by a company which is designing a new water slide for an amusement park . The conceptual design has a customer going down a curved slide ending up moving horizontally at the bottom. At the end of the of the slide, the customer grabs the end of a 16.0 m long vertical bar that is free to pivot about its center. After grabbing onto the bar, the customer swings out over a pool of water. When the bar swings out to

its maximum distance, the customer can drop off and fall straight down into the water. Your task is to determine the height of the slide so that the maximum horizontal distance that the bar swings out is 5.0 m for a 60 kg person. The bar has five times the mass of a 60 kg person. From an engineering handbook, you find that the moment of inertia of the bar is 1/12 of what it would be if all of its mass were concentrated at the bottom.