Chapter 5: FURTHER APPLICATION OF NEWTON’S LAWS: FRICTION, DRAG, AND ELASTICITY

# 5.1 FRICTION

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| 1. | *A physics major is cooking breakfast when he notices that the frictional force between his steel spatula and his Teflon frying pan is only 0.200 N. Knowing the coefficient of kinetic friction between the two materials, he quickly calculates the normal force. What is it?* |
| Solution |  |
| 2. | *(a) When rebuilding her car’s engine, a physics major must exert 300 N of force to insert a dry steel piston into a steel cylinder. What is the magnitude of the normal force between the piston and cylinder? (b) What is the magnitude of the force she would have to exert if the steel parts were oiled?* |
| Solution | (a)  (b) |
| 3. | *(a) What is the maximum frictional force in the knee joint of a person who supports 66.0 kg of her mass on that knee? (b) During strenuous exercise it is possible to exert forces to the joints that are easily ten times greater than the weight being supported. What is the maximum force of friction under such conditions? The frictional forces in joints are relatively small in all circumstances except when the joints deteriorate, such as from injury or arthritis. Increased frictional forces can cause further damage and pain.* |
| Solution | (a)  (b) Using information from part (a), |
| 4. | *Suppose you have a 120-kg wooden crate resting on a wood floor. (a) What maximum force can you exert horizontally on the crate without moving it? (b) If you continue to exert this force once the crate starts to slip, what will the magnitude of its acceleration then be?* |
| Solution | (a)  (b) |
| 5. | *(a) If half of the weight of a small  utility truck is supported by its two drive wheels, what is the magnitude of the maximum acceleration it can achieve on dry concrete? (b) Will a metal cabinet lying on the wooden bed of the truck slip if it accelerates at this rate? (c) Solve both problems assuming the truck has four-wheel drive.* |
| Solution | (a)  (b)  The cabinet will slip if , i.e., if    The cabinet will not slip.  (c)  The cabinet will slip, since  where |
| 6. | *A team of eight dogs pulls a sled with waxed wood runners on wet snow (mush!). The dogs have average masses of 19.0 kg, and the loaded sled with its rider has a mass of 210 kg. (a) Calculate the magnitude of the acceleration starting from rest if each dog exerts an average force of 185 N backward on the snow. (b) What is the magnitude of the acceleration once the sled starts to move? (c) For both situations, calculate the magnitude of the force in the coupling between the dogs and the sled.* |
| Solution | (a)  is the total mass of 362 kg (dogs + sled/rider)  is the mass of the sled and rider only (210 kg)      (b)  (c) Case 1:  Case 2: |
| 7. | *Consider the 65.0-kg ice skater being pushed by two others shown in Figure 5.21. (a) Find the direction and magnitude of , the total force exerted on her by the others, given that the magnitudes  and  are 26.4 N and 18.6 N, respectively. (b) What is her initial acceleration if she is initially stationary and wearing steel-bladed skates that point in the direction of ? (c) What is her acceleration assuming she is already moving in the direction of ? (Remember that friction always acts in the direction opposite that of motion or attempted motion between surfaces in contact.)* |
| Solution | (a)    (b)  (c) |
| 8. | *Show that the acceleration of any object down a frictionless incline that makes an angle  with the horizontal is . (Note that this acceleration is independent of mass.)* |
| Solution | The component of  down the incline leads to the acceleration:  net    The component of  perpendicular to the incline equals the normal force.  net |
| 9. | *Show that the acceleration of any object down an incline where friction behaves simply (that is, where* *) is* *. Note that the acceleration is independent of mass and reduces to the expression found in the previous problem when friction becomes negligibly small* |
| Solution |  |
| 10. | *Calculate the deceleration of a snow boarder going up a  slope assuming the coefficient of friction for waxed wood on wet snow. The result of Exercise 5.9 may be useful, but be careful to consider the fact that the snow boarder is going uphill. Explicitly show how you follow the steps in Problem-Solving Strategies.* |
| Solution | Using the free body diagram:  and  where .  Given  and  (from Table 5.1). Find: .  Using trigonometry gives . Also, we know  so that  Solving for  gives:  so that |
| 11. | *(a) Calculate the acceleration of a skier heading down a  slope, assuming the coefficient of friction for waxed wood on wet snow. (b) Find the angle of the slope down which this skier could coast at a constant velocity. You can neglect air resistance in both parts, and you will find the result of Exercise 5.9 to be useful. Explicitly show how you follow the steps in the Problem-Solving Strategies.* |
| Solution | (a) Using the result of Exercise 5.9:    (b) Since , find  such that  , or |
| 12. | *If an object is to rest on an incline without slipping, then friction must equal the component of the weight of the object parallel to the incline. This requires greater and greater friction for steeper slopes. Show that the maximum angle of an incline above the horizontal for which an object will not slide down is . You may use the result of the previous problem. Assume that  and that static friction has reached its maximum value.* |
| Solution |  |
| 13. | *Calculate the maximum deceleration of a car that is heading down a  slope (one that makes an angle of  with the horizontal) under the following road conditions. You may assume that the weight of the car is evenly distributed on all four tires and that the coefficient of static friction is involved—that is, the tires are not allowed to slip during the deceleration. (Ignore rolling.) Calculate for a car: (a) On dry concrete. (b) On wet concrete. (c) On ice, assuming that , the same as for shoes on ice.* |
| Solution | The positive *x*-direction is down the slope.    (a)  (b)  (c) |
| 14. | *Calculate the maximum acceleration of a car that is heading up a  slope (one that makes an angle of  with the horizontal) under the following road conditions. Assume that only half the weight of the car is supported by the two drive wheels and that the coefficient of static friction is involved—that is, the tires are not allowed to slip during the acceleration. (Ignore rolling.) (a) On dry concrete. (b) On wet concrete. (c) On ice, assuming that , the same as for shoes on ice.* |
| Solution | Take the positive *x*-direction as up the slope. For max acceleration,    So the maximum acceleration is  (a)  (b)  (c)  The negative sign indicates downwards acceleration, so the car cannot make it up the grade. |
| 15. | *Repeat Exercise 5.14 for a car with four-wheel drive.* |
| Solution | (a)  (b)  (c) |
| 16. | *A freight train consists of two  engines and 45 cars with average masses of . (a) What force must each engine exert backward on the track to accelerate the train at a rate of  if the force of friction is , assuming the engines exert identical forces? This is not a large frictional force for such a massive system. Rolling friction for trains is small, and consequently trains are very energy-efficient transportation systems. (b) What is the magnitude of the force in the coupling between the 37th and 38th cars (this is the force each exerts on the other), assuming all cars have the same mass and that friction is evenly distributed among all of the cars and engines?* |
| Solution | (a) The total mass is .    (b) There are 8 cars from car 38 to the rear, each with mass . The force between car 37 and 38 balances friction on the rear cars to give them an acceleration . The frictional force on each car is , so the total frictional force on the 8 cars is . The net force on the last 8 cars is then |
| 17. | *Consider the 52.0-kg mountain climber in Figure 5.22. (a) Find the tension in the rope and the force that the mountain climber must exert with her feet on the vertical rock face to remain stationary. Assume that the force is exerted parallel to her legs. Also, assume negligible force exerted by her arms. (b) What is the minimum coefficient of friction between her shoes and the cliff?* |
| Solution | (a)  and    (b)  Therefore |
| 18. | *A contestant in a winter sporting event pushes a 45.0-kg block of ice across a frozen lake as shown in Figure 5.23(a). (a) Calculate the minimum force  he must exert to get the block moving. (b) What is the magnitude of its acceleration once it starts to move, if that force is maintained?* |
| Solution | (a)  , so that    (b) , so that |
| 19. | *Repeat Exercise 5.18 with the contestant pulling the block of ice with a rope over his shoulder at the same angle above the horizontal as shown in Figure 5.23(b).* |
| Solution | (a)  (b) , so that |

# 5.2 DRAG FORCES

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| 20. | *The terminal velocity of a person falling in air depends upon the weight and the area of the person facing the fluid. Find the terminal velocity (in meters per second and kilometers per hour) of an 80.0-kg skydiver falling in a pike (headfirst) position with a surface area of .* |
| Solution | Terminal velocity occurs when force of gravity equals the drag force. Use  Assume frontal area for head first . Drag coefficient for head first is 0.70. Therefore, |
| 21. | *A 60-kg and a 90-kg skydiver jump from an airplane at an altitude of 6000 m, both falling in the pike position. Make some assumption on their frontal areas and calculate their terminal velocities. How long will it take for each skydiver to reach the ground (assuming the time to reach terminal velocity is small)? Assume all values are accurate to three significant digits.* |
| Solution | We can use the work of the previous problem, with the same frontal area of. Make changes in the mass: ; . The time to hit the ground falling from 6000m:  and . |
| 22. | *A 560-g squirrel with a surface area of  falls from a 5.0-m tree to the ground. Estimate its terminal velocity. (Use a drag coefficient for a horizontal skydiver.) What will be the velocity of a 56-kg person hitting the ground, assuming no drag contribution in such a short distance?* |
| Solution | For the squirrel, assume frontal area . Therefore  .  For a person falling from 5 m with no drag, use  As we see for a person falling, the squirrel never reaches its terminal velocity before hitting the ground. |
| 23. | *To maintain a constant speed, the force provided by a car’s engine must equal the drag force plus the force of friction of the road (the rolling resistance). (a) What are the magnitude of the drag forces at 70 km/h and 100 km/h for a Toyota Camry? (Drag area is ) (b) What is the magnitude of the drag force at 70 km/h and 100 km/h for a Hummer H2? (Drag area is ) Assume all values are accurate to three significant digits.* |
| Solution | (a)  For a Camry,    (b) For a Hummer,    EPA Testing results for these two vehicles at 60 mph show highway gas mileages of 35 mpg and 10 mpg, respectively – comparable to our drag force calculations. |
| 24. | *By what factor does the drag force on a car increase as it goes from 65 to 110 km/h?* |
| Solution | Drag force depends on the square of the velocity, so we should use square to calculate the factor increase. Between and , then: |
| 25. | *Calculate the speed a spherical rain drop would achieve falling from 5.00 km (a) in the absence of air drag (b) with air drag. Take the size across of the drop to be 4 mm, the density to be , and the surface area to be .* |
| Solution | (a) Rain drops with no drag arrive at the ground with  (b) With drag, use . Given , where , the terminal speed for the raindrops is |
| 26. | *Using Stokes’ law, verify that the units for viscosity are kilograms per meter per second.* |
| Solution | Stokes’ Law is . Solving for the viscosity, .  Considering only the units, this becomes |
| 27. | *Find the terminal velocity of a spherical bacterium (diameter ) falling in water. You will first need to note that the drag force is equal to the weight at terminal velocity. Take the density of the bacterium to be .* |
| Solution | Using Stokes’ law, we can find the terminal velocity by equating the drag force and the weight of the bacterium. Solving for velocity, we obtain: |
| 28. | *Stokes’ law describes sedimentation of particles in liquids and can be used to measure viscosity. Particles in liquids achieve terminal velocity quickly. One can measure the time it takes for a particle to fall a certain distance and then use Stokes’ law to calculate the viscosity of the liquid. Suppose a steel ball bearing (density , diameter ) is dropped in a container of motor oil. It takes 12 s to fall a distance of 0.60 m. Calculate the viscosity of the oil.* |
| Solution | The terminal velocity of the steel ball is . Its mass is Therefore, its viscosity is  (For heavy machine oil, see Table 12.1.) |

# 5.3 ELASTICITY: STRESS AND STRAIN

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| 29. | *During a circus act, one performer swings upside down hanging from a trapeze holding another, also upside-down, performer by the legs. If the upward force on the lower performer is three times her weight, how much do the bones (the femurs) in her upper legs stretch? You may assume each is equivalent to a uniform rod 35.0 cm long and 1.80 cm in radius. Her mass is 60.0 kg.* |
| Solution | Use the equation , where (from Table 5.3), ,, and  , so that the force on each leg is  Substituting in the value gives:    So each leg is stretched by |
| 30. | *During a wrestling match, a 150 kg wrestler briefly stands on one hand during a maneuver designed to perplex his already moribund adversary. By how much does the upper arm bone shorten in length? The bone can be represented by a uniform rod 38.0 cm in length and 2.10 cm in radius.* |
| Solution |  |
| 31. | *(a) The “lead” in pencils is a graphite composition with a Young’s modulus of about . Calculate the change in length of the lead in an automatic pencil if you tap it straight into the pencil with a force of 4.0 N. The lead is 0.50 mm in diameter and 60 mm long. (b) Is the answer reasonable? That is, does it seem to be consistent with what you have observed when using pencils?* |
| Solution | (a)  (b) This does seem reasonable, since the lead does seem to shrink a little when you push on it. |
| 32. | *TV broadcast antennas are the tallest artificial structures on Earth. In 1987, a 72.0-kg physicist placed himself and 400 kg of equipment at the top of one 610-m high antenna to perform gravity experiments. By how much was the antenna compressed, if we consider it to be equivalent to a steel cylinder 0.150 m in radius?* |
| Solution |  |
| 33. | *(a) By how much does a 65.0-kg mountain climber stretch her 0.800-cm diameter nylon rope when she hangs 35.0 m below a rock outcropping? (b) Does the answer seem to be consistent with what you have observed for nylon ropes? Would it make sense if the rope were actually a bungee cord?* |
| Solution | (a)  (b) This seems reasonable for nylon climbing rope, since it is not supposed to stretch that much. For a bungee cord, we would expect a much larger stretch when a person hangs from it. |
| 34. | *A 20.0-m tall hollow aluminum flagpole is equivalent in strength to a solid cylinder 4.00 cm in diameter. A strong wind bends the pole much as a horizontal force of 900 N exerted at the top would. How far to the side does the top of the pole flex?* |
| Solution |  |
| 35. | *As an oil well is drilled, each new section of drill pipe supports its own weight and that of the pipe and drill bit beneath it. Calculate the stretch in a new 6.00 m length of steel pipe that supports 3.00 km of pipe having a mass of 20.0 kg/m and a 100-kg drill bit. The pipe is equivalent in strength to a solid cylinder 5.00 cm in diameter.* |
| Solution | The force on the pipe is: |
| 36. | *Calculate the force a piano tuner applies to stretch a steel piano wire 8.00 mm, if the wire is originally 0.850 mm in diameter and 1.35 m long.* |
| Solution |  |
| 37. | *A vertebra is subjected to a shearing force of 500 N. Find the shear deformation, taking the vertebra to be a cylinder 3.00 cm high and 4.00 cm in diameter.* |
| Solution |  |
| 38. | *A disk between vertebrae in the spine is subjected to a shearing force of 600 N. Find its shear deformation, taking it to have the shear modulus of . The disk is equivalent to a solid cylinder 0.700 cm high and 4.00 cm in diameter.* |
| Solution |  |
| 39. | *When using a pencil eraser, you exert a vertical force of 6.00 N at a distance of 2.00 cm from the hardwood-eraser joint. The pencil is 6.00 mm in diameter and is held at an angle of  to the horizontal. (a) By how much does the wood flex perpendicular to its length? (b) How much is it compressed lengthwise?* |
| Solution | (a)  flex of wood    (b) |
| 40. | *To consider the effect of wires hung on poles, we take data from Example 4.8, in which tensions in wires supporting a traffic light were calculated. The left wire made an angle  below the horizontal with the top of its pole and carried a tension of 108 N. The 12.0 m tall hollow aluminum pole is equivalent in strength to a 4.50 cm diameter solid cylinder. (a) How far is it bent to the side? (b) By how much is it compressed?* |
| Solution | (a)  (b) |
| 41. | *A farmer making grape juice fills a glass bottle to the brim and caps it tightly. The juice expands more than the glass when it warms up, in such a way that the volume increases by 0.2% (that is, ) relative to the space available. Calculate the magnitude of the normal force exerted by the juice per square centimeter if its bulk modulus is , assuming the bottle does not break. In view of your answer, do you think the bottle will survive?* |
| Solution | Using the equation  gives:    Since , the pressure is about 36 atmospheres, far greater than the average jar is designed to withstand. |
| 42. | *(a) When water freezes, its volume increases by 9.05% (that is, ). What force per unit area is water capable of exerting on a container when it freezes? (It is acceptable to use the bulk modulus of water in this problem.) (b) Is it surprising that such forces can fracture engine blocks, boulders, and the like?* |
| Solution | (a)  (b) It is not surprising, given this large value, that the volume expansion of freezing water can do major damage to solids such as engine blocks and boulders. |
| 43. | *This problem returns to the tightrope walker studied in Example 4.6, who created a tension of  in a wire making an angle  below the horizontal with each supporting pole. Calculate how much this tension stretches the steel wire if it was originally 15 m long and 0.50 cm in diameter.* |
| Solution | (Note: We can calculate over the entire length of wire because the results from the two half-lengths add.) |
| 44. | *The pole in Figure 5.24 is at a  bend in a power line and is therefore subjected to more shear force than poles in straight parts of the line. The tension in each line is , at the angles shown. The pole is 15.0 m tall, has an 18.0 cm diameter, and can be considered to have half the strength of hardwood. (a) Calculate the compression of the pole. (b) Find how much it bends and in what direction. (c) Find the tension in a guy wire used to keep the pole straight if it is attached to the top of the pole at an angle of  with the vertical. (Clearly, the guy wire must be in the opposite direction of the bend.)* |
| Solution | (a)    (b)    (c) |

# Test Prep for Ap® courses

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| 1. | | *When a force of 20N is applied to a stationary box weighing 40N, the box does not move. This means the coefficient of static friction*  (A) is equal to 0.5.  (B) is greater than 0.5.  (C) is less than 0.5.  (D) can’t be determined. |
| Solution | | (b) |
| 2. | | *A 2 kg block slides down a ramp which is at an incline of 25º. If the frictional force is 4.86 N, what is the coefficient of friction? At what incline will the box slide at a constant velocity? Assume g = 10 m/s2.* |
| Solution | | 0.268, 15º |
| 3. | | *A block is given a short push and then slides with constant friction across a horizontal floor. Which statement best explains the direction of the force that friction applies on the moving block?*  (A) Friction will be in the same direction as the block’s motion because molecular interactions between the block and the floor will deform the block in the direction of motion.  (B) Friction will be in the same direction as the block’s motion because thermal energy generated at the interface between the block and the floor adds kinetic energy to the block.  (C) Friction will be in the opposite direction of the block’s motion because molecular interactions between the block and the floor will deform the block in the opposite direction of motion.  (D) Friction will be in the opposite direction of the block’s motion because thermal energy generated at the interface between the block and the floor converts some of the block’s kinetic energy to potential energy. |
| Solution | | (c) |
| 4. | | *A student pushes a cardboard box across a carpeted floor and afterwards notices that the bottom of the box feels warm. Explain how interactions between molecules in the cardboard and molecules in the carpet produced this heat.* |
| Solution | | When surfaces rub, the surface atoms adhere and cause atomic lattices to vibrate, creating waves that move through the material. As the waves diminish with distance, their energy is converted into heat. |
| 5. | CNX_APPhysics_04_M7_Q19_img  *The figure above shows the forces exerted on a block that is sliding on a horizontal surface: the gravitational force of 40 N, the 40 N normal force exerted by the surface, and a frictional force exerted to the left. The coefficient of friction between the block and the surface is 0.20. The acceleration of the block is most nearly*  (A) 1.0 m/s2 to the right  (B) 1.0 m/s2 to the left  (C) 2.0 m/s2 to the right  (D) 2.0 m/s2 to the left | |
| Solution | (d) | |

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