ANNOUNCEMENTS

- Homework #6, due Wednesday, October 3

  Conceptual questions: Chapter 6, #4 and #12
  Problems: Chapter 6, #54, #80

- Study Textbook Chapter 6 before Monday, October 1

- 5-minute quiz on Chapter 6: Friday, October 3

Problem-Solving Strategy: Applying Newton's Laws of Motion

1. Identify the physical principles involved by listing the givens and the quantities to be calculated.
2. Sketch the situation, using arrows to represent all forces.
3. Determine the system of interest. The result is a free-body diagram that is essential to solving the problem.
4. Apply Newton's second law to solve the problem. If necessary, apply appropriate kinematic equations from the chapter on motion along a straight line.
5. Check the solution to see whether it is reasonable.

$$\sum F_x = ma_x, \quad \sum F_y = ma_y.$$

MAGNITUDE OF STATIC FRICTION

The magnitude of static friction f_s is

$$f_s \leq \mu_s N, \tag{6.1}$$

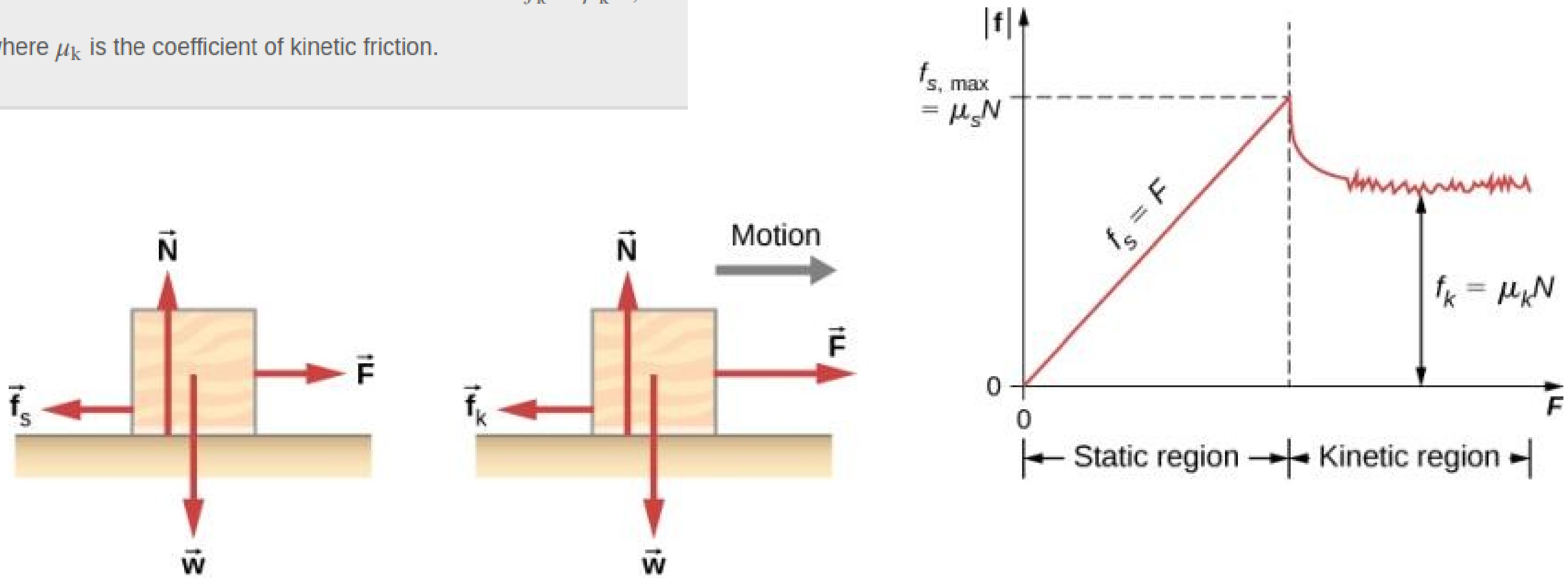
where μ_s is the coefficient of static friction and N is the magnitude of the normal force.

MAGNITUDE OF KINETIC FRICTION

The magnitude of kinetic friction f_k is given by

$$f_k = \mu_k N,$$

where μ_k is the coefficient of kinetic friction.



(a)
Impending motion

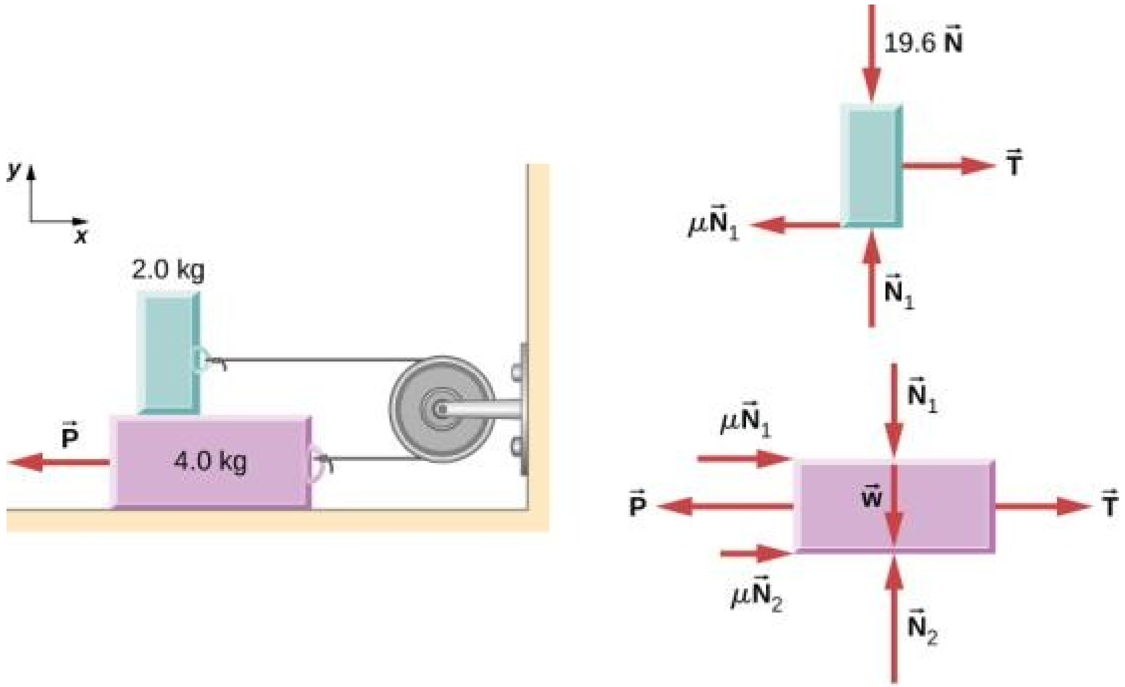
(b)
Object moves

(c)

EXAMPLE

Sliding Blocks

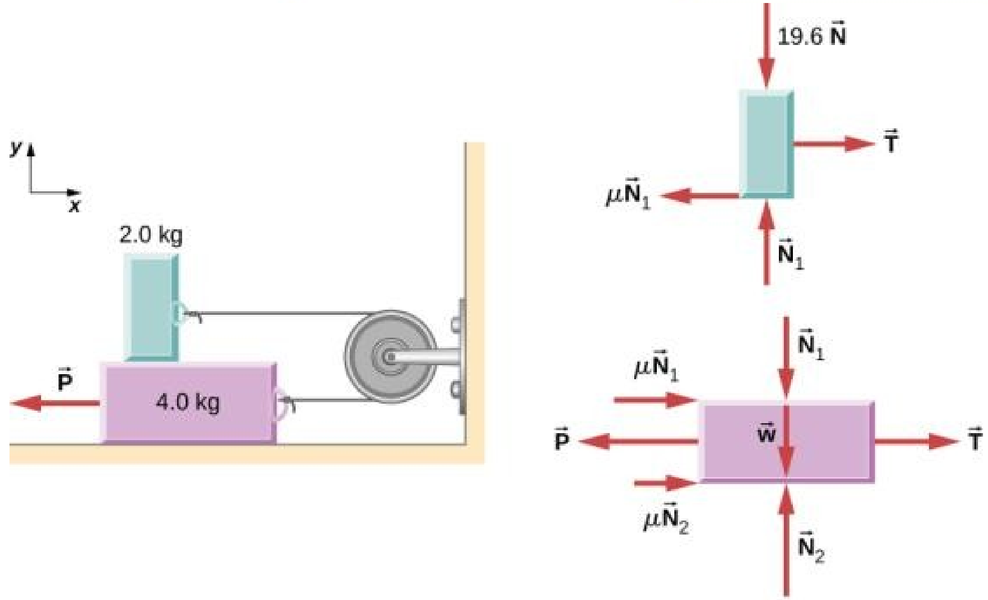
The two blocks of Figure 6.17 are attached to each other by a massless string that is wrapped around a frictionless pulley. When the bottom 4.00-kg block is pulled to the left by the constant force $\vec{\mathbf{P}}$, the top 2.00-kg block slides across it to the right. Find the magnitude of the force necessary to move the blocks at constant speed. Assume that the coefficient of kinetic friction between all surfaces is 0.400.



(a) (b)

(a) Free-body diagrams for the blocks.

(b) Each block moves at constant velocity.



Solution

Since the top block is moving horizontally to the right at constant velocity, its acceleration is zero in both the horizontal and the vertical directions. From Newton's second law,

$$\begin{aligned} \sum F_x &= m_1 a_x \\ T - 0.400 N_1 &= 0 \end{aligned} \qquad \begin{aligned} \sum F_y &= m_1 a_y \\ N_1 - 19.6\ \text{N} &= 0. \end{aligned}$$

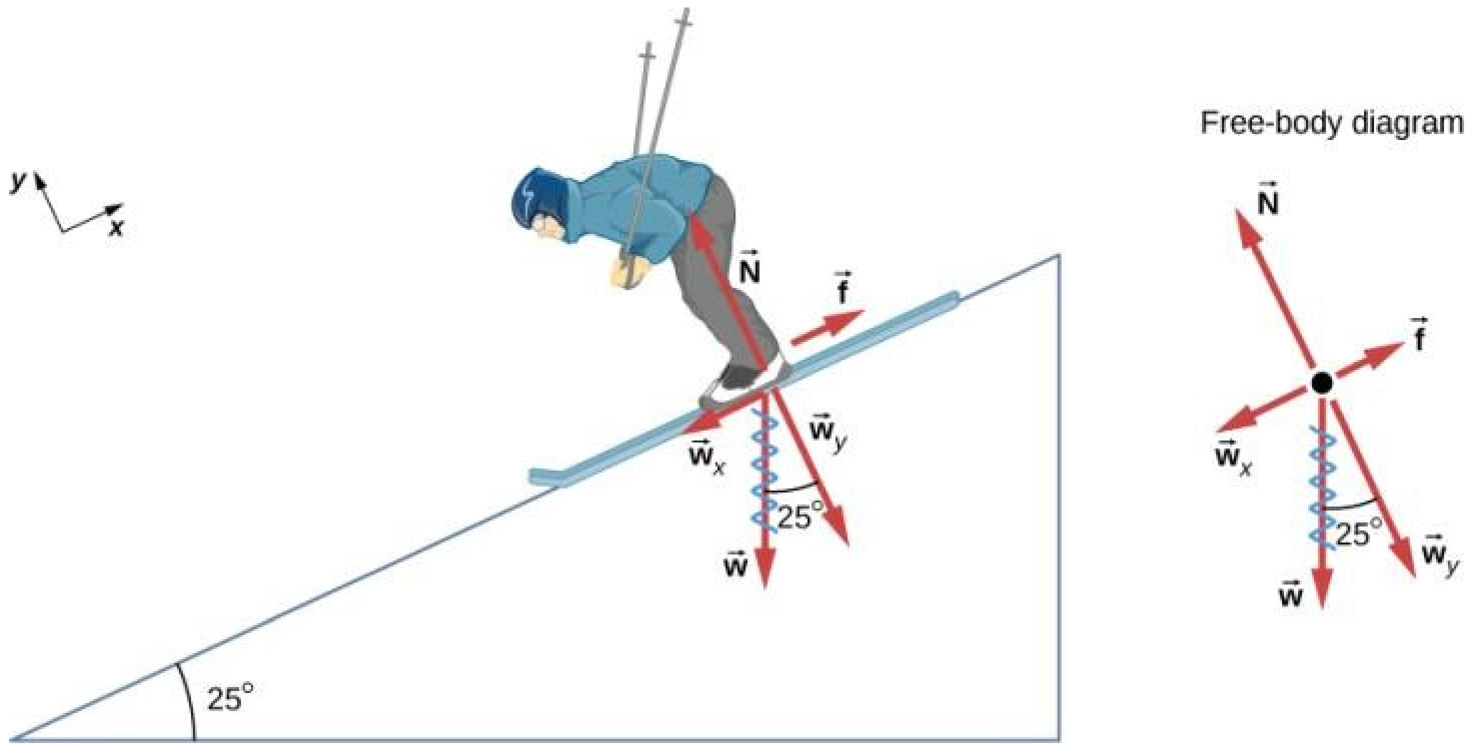
Solving for the two unknowns, we obtain $N_1 = 19.6\ \text{N}$ and $T = 0.40 N_1 = 7.84\ \text{N}$. The bottom block is also not accelerating, so the application of Newton's second law to this block gives

$$\begin{aligned} &\sum F_x = m_2 a_x \\ &T - P + 0.400\ N_1 + 0.400\ N_2 = 0 \end{aligned} \qquad \begin{aligned} &\sum F_y = m_2 a_y \\ &N_2 - 39.2\ \text{N} - N_1 = 0. \end{aligned}$$

The values of N_1 and T were found with the first set of equations. When these values are substituted into the second set of equations, we can determine N_2 and P. They are

$$N_2 = 58.8\ \text{N} \quad \text{and} \quad P = 39.2\ \text{N}.$$

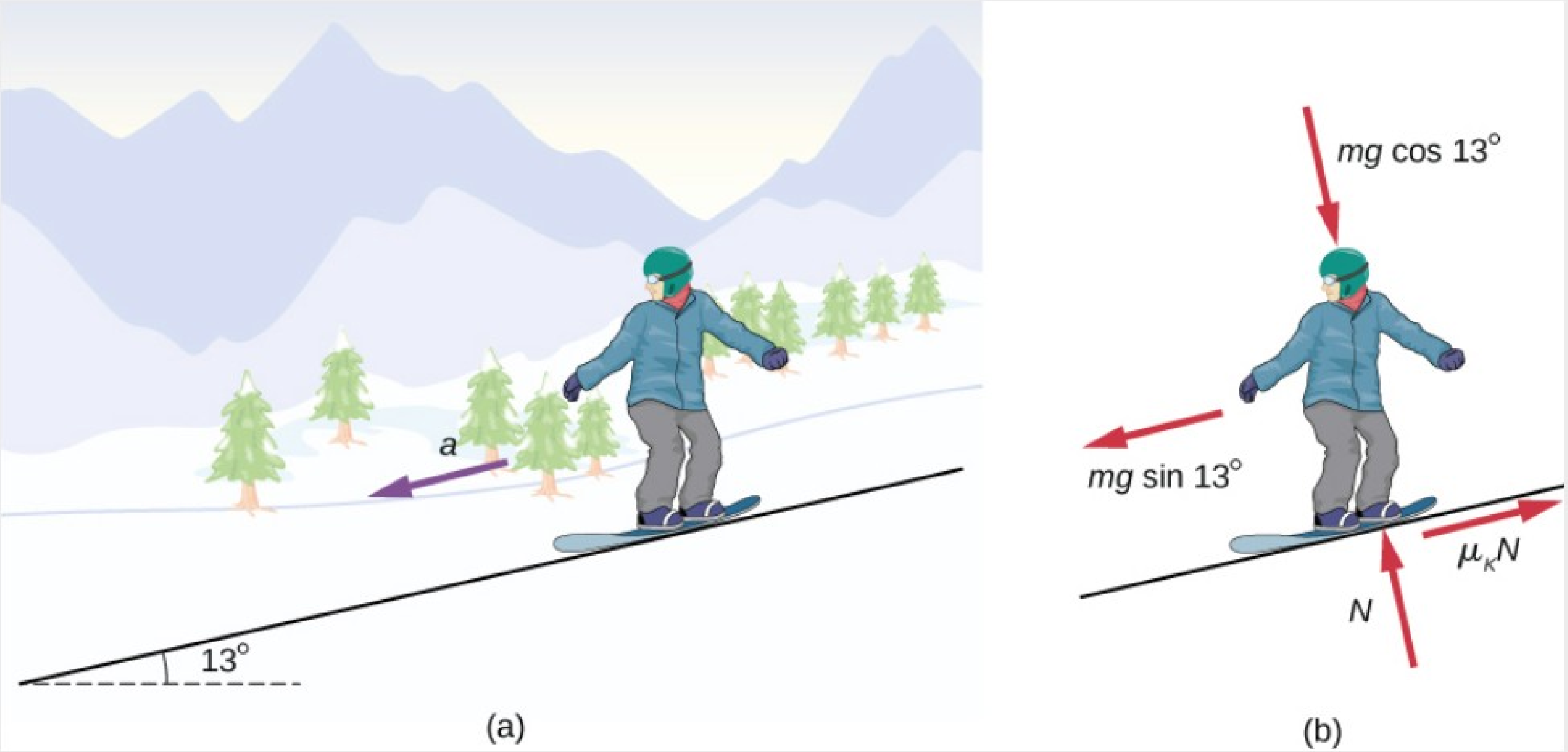
DIY!



The motion of the skier and friction are parallel to the slope, so it is most convenient to project all forces onto a coordinate system where one axis is parallel to the slope and the other is perpendicular (axes shown to left of skier). The normal force $\vec{\mathbf{N}}$ is perpendicular to the slope, and friction $\vec{\mathbf{f}}$ is parallel to the slope, but the skier's weight $\vec{\mathbf{w}}$ has components along both axes, namely $\vec{\mathbf{w}}_y$ and $\vec{\mathbf{w}}_x$. The normal force $\vec{\mathbf{N}}$ is equal in magnitude to $\vec{\mathbf{w}}_y$, so there is no motion perpendicular to the slope. However, $\vec{\mathbf{f}}$ is less than $\vec{\mathbf{w}}_x$ in magnitude, so there is acceleration down the slope (along the *x*-axis).

Snowboarding

Earlier, we analyzed the situation of a downhill skier moving at constant velocity to determine the coefficient of kinetic friction. Now let's do a similar analysis to determine acceleration. The snowboarder of Figure 6.19 glides down a slope that is inclined at $\theta = 13^0$ to the horizontal. The coefficient of kinetic friction between the board and the snow is $\mu_{\mathrm{k}} = 0.20$. What is the acceleration of the snowboarder?



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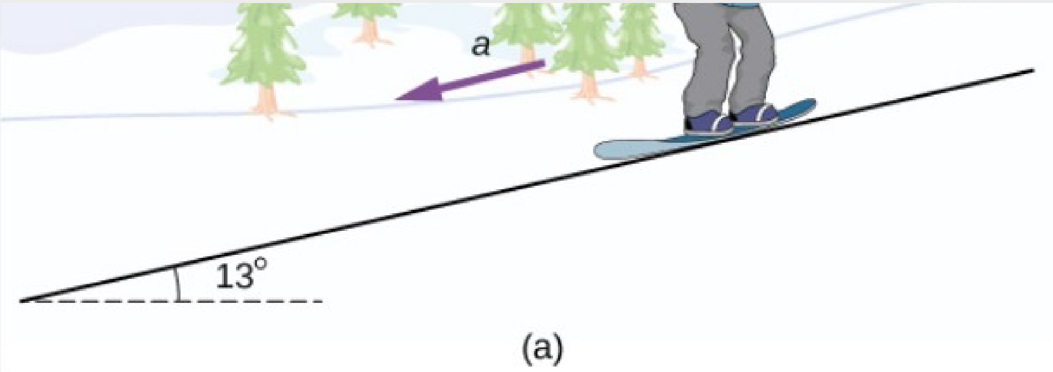
Solution

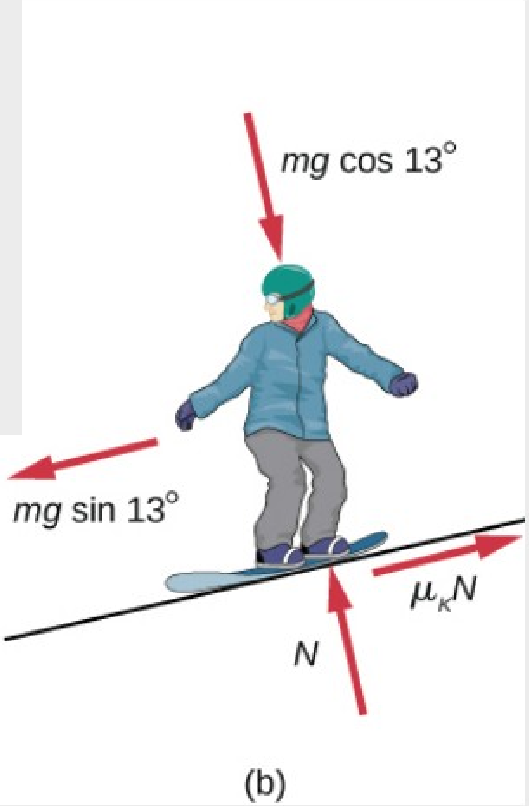
We can now apply Newton's second law to the snowboarder:

$$\begin{aligned} \sum F_x &= ma_x \qquad & \sum F_y = ma_y \\ mg\sin\theta - \mu_k N &= ma_x \qquad & N - mg\cos\theta = m(0). \end{aligned}$$

From the second equation, $N = mg\cos\theta$. Upon substituting this into the first equation, we find

$$\begin{aligned} a_x &= g(\sin\theta - \mu_{\mathrm{k}}\cos\theta) \\ &= g(\sin 13° - 0.20\cos 13°) = 0.29\ \mathrm{m/s^2}. \end{aligned}$$





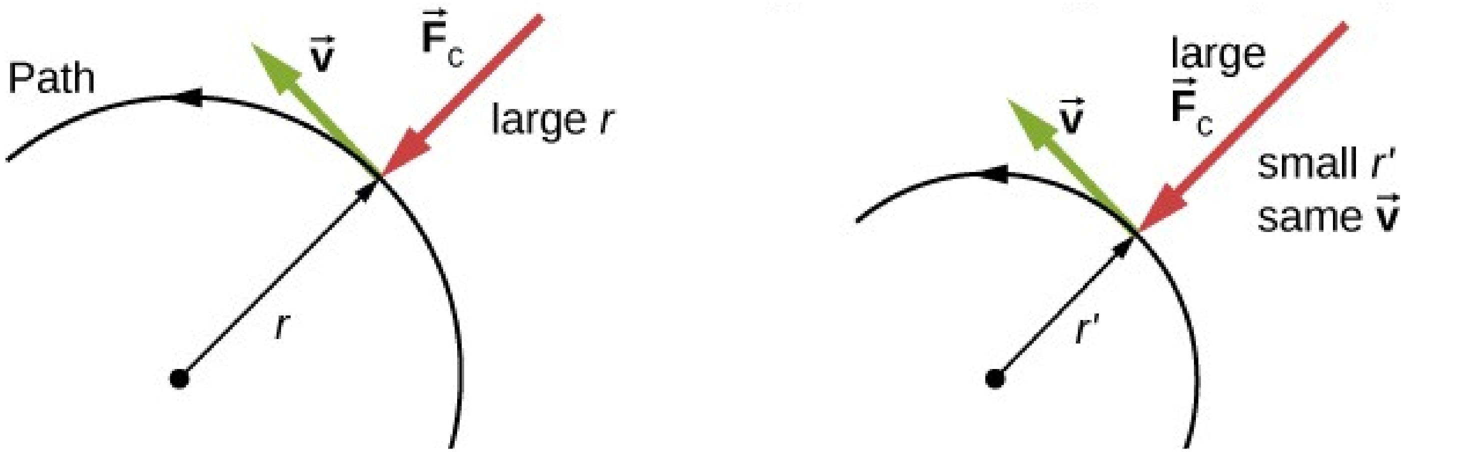
$$F_c = ma_c.$$

By substituting the expressions for centripetal acceleration $a_c (a_c = \frac{v^2}{r}; a_c = r\omega^2)$, we get two expressions for the centripetal force F_c in terms of mass, velocity, angular velocity, and radius of curvature:

$$F_c = m\frac{v^2}{r}; \quad F_c = mr\omega^2. \tag{6.3}$$

You may use whichever expression for centripetal force is more convenient. Centripetal force $\vec{\mathbf{F}}_c$ is always perpendicular to the path and points to the center of curvature, because $\vec{\mathbf{a}}_c$ is perpendicular to the velocity and points to the center of curvature. Note that if you solve the first expression for *r*, you get

$$r = \frac{mv^2}{F_c}.$$



The frictional force supplies the centripetal force and is numerically equal to it. Centripetal force is perpendicular to velocity and causes uniform circular motion. The larger the F_c, the smaller the radius of curvature *r* and the sharper the curve. The second curve has the same *v*, but a larger F_c produces a smaller r'.

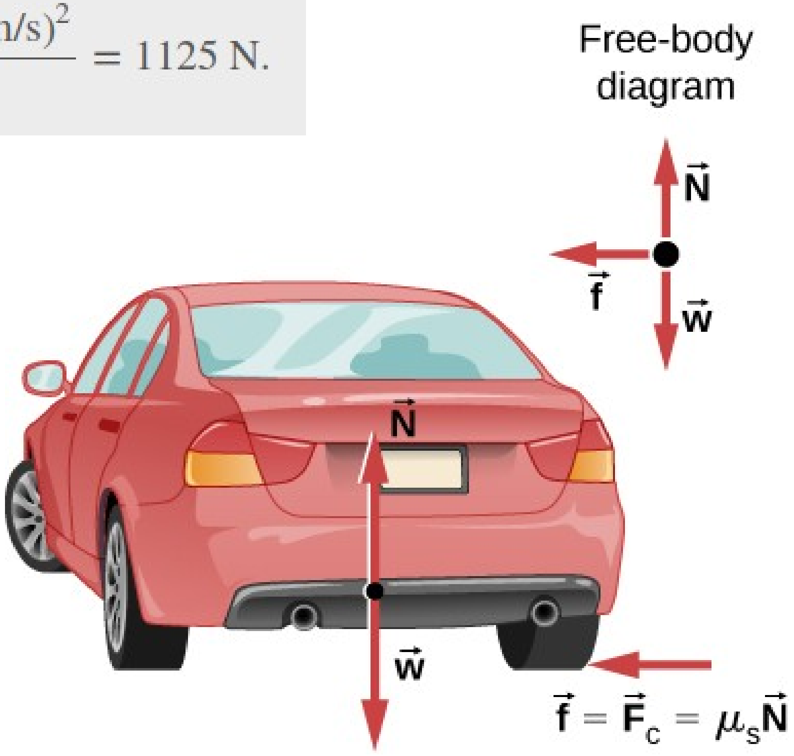
What Coefficient of Friction Do Cars Need on a Flat Curve?

(a) Calculate the centripetal force exerted on a 900.0-kg car that negotiates a 500.0-m radius curve at 25.00 m/s. (b) Assuming an unbanked curve, find the minimum static coefficient of friction between the tires and the road, static friction being the reason that keeps the car from slipping (Figure 6.21).

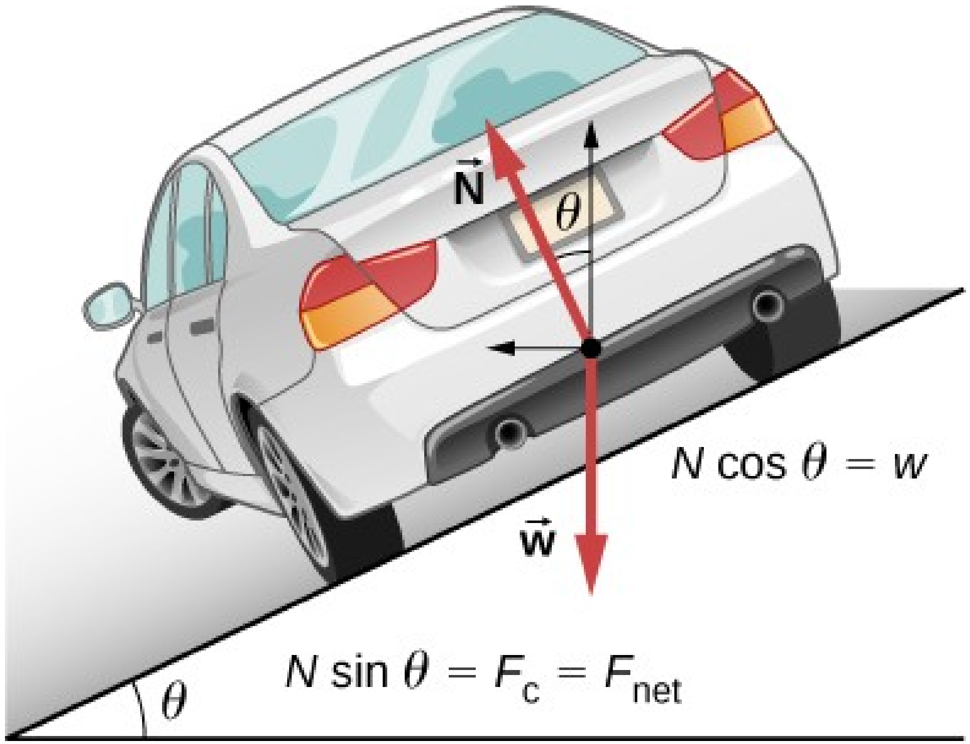
$$F_c = \frac{mv^2}{r} = \frac{(900.0\ \text{kg})(25.00\ \text{m/s})^2}{(500.0\ \text{m})} = 1125\ \text{N}.$$

$$F_c \equiv f = \mu_s N = \mu_s mg.$$

$$\mu_s = \frac{v^2}{rg}.$$



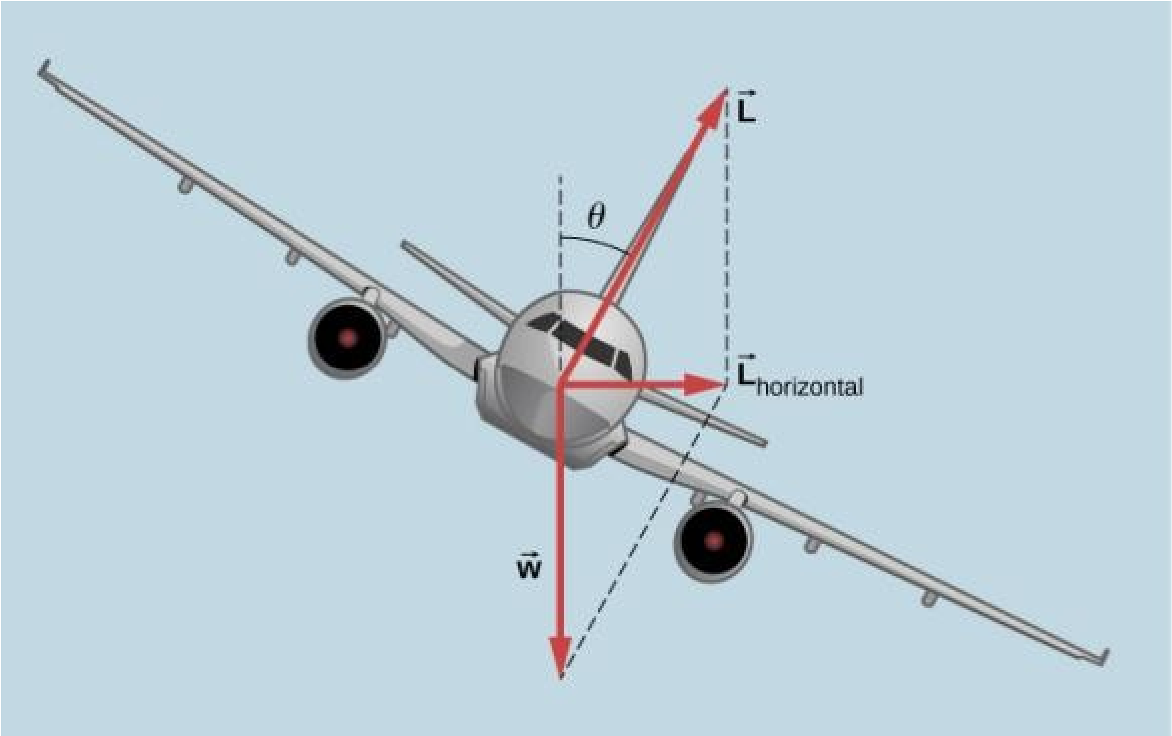
This car on level ground is moving away and turning to the left. The centripetal force causing the car to turn in a circular path is due to friction between the tires and the road. A minimum coefficient of friction is needed, or the car will move in a larger-radius curve and leave the roadway.



$$N \sin \theta = \frac{mv^2}{r}. \qquad N \cos \theta = mg.$$

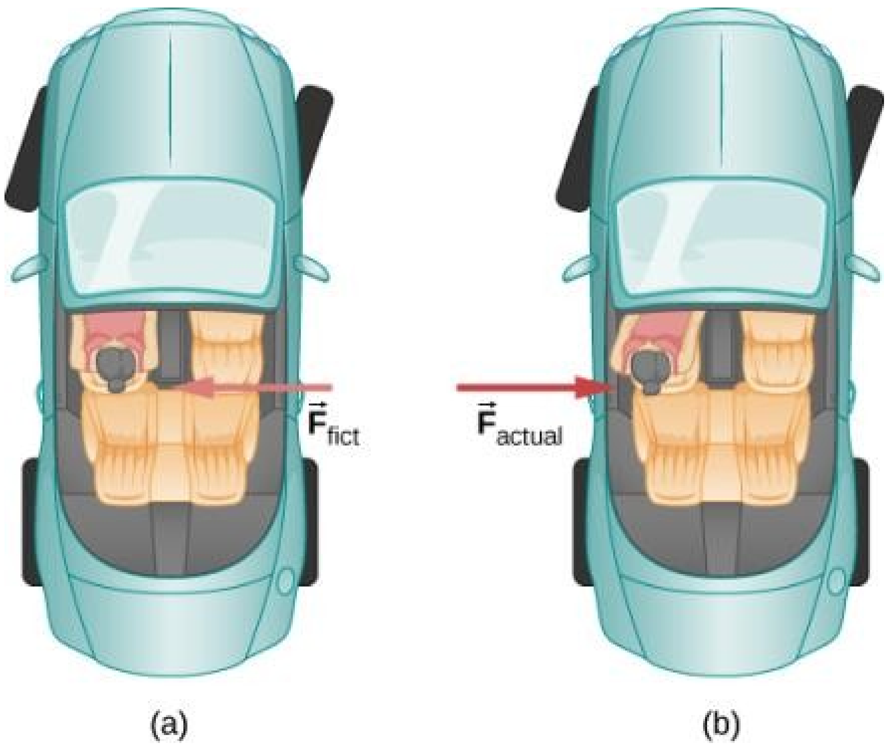
$$\theta = \tan^{-1}\left(\frac{v^2}{rg}\right). \tag{6.4}$$

FIGURE 6.23



In a banked turn, the horizontal component of lift is unbalanced and accelerates the plane. The normal component of lift balances the plane's weight. The banking angle is given by θ. Compare the vector diagram with that shown in **Figure 6.22**.

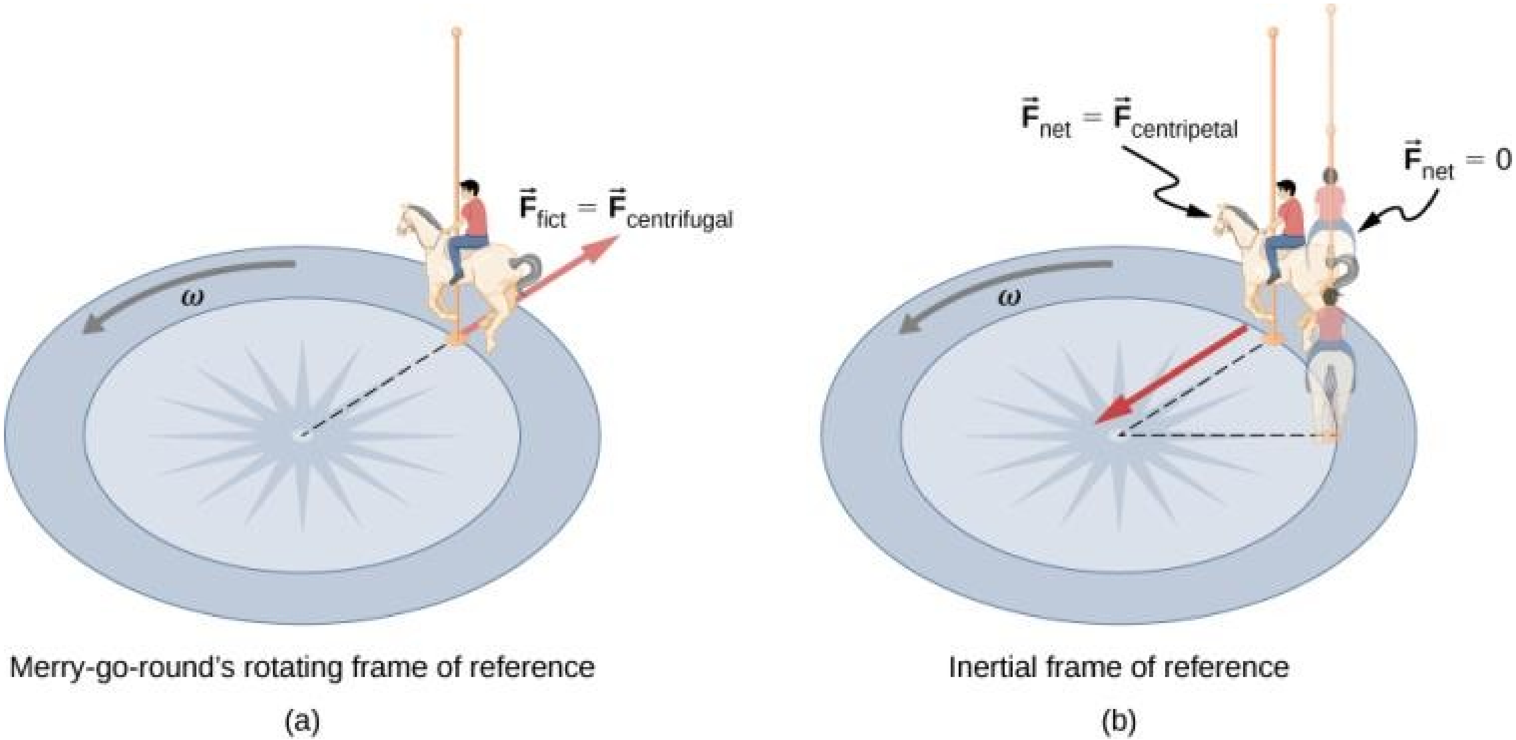
FIGURE 6.24



(a) The car driver feels herself forced to the left relative to the car when she makes a right turn. This is an inertial force arising from the use of the car as a frame of reference.

(b) In Earth's frame of reference, the driver moves in a straight line, obeying Newton's first law, and the car moves to the right. There is no force to the left on the driver relative to Earth. Instead, there is a force to the right on the car to make it turn.

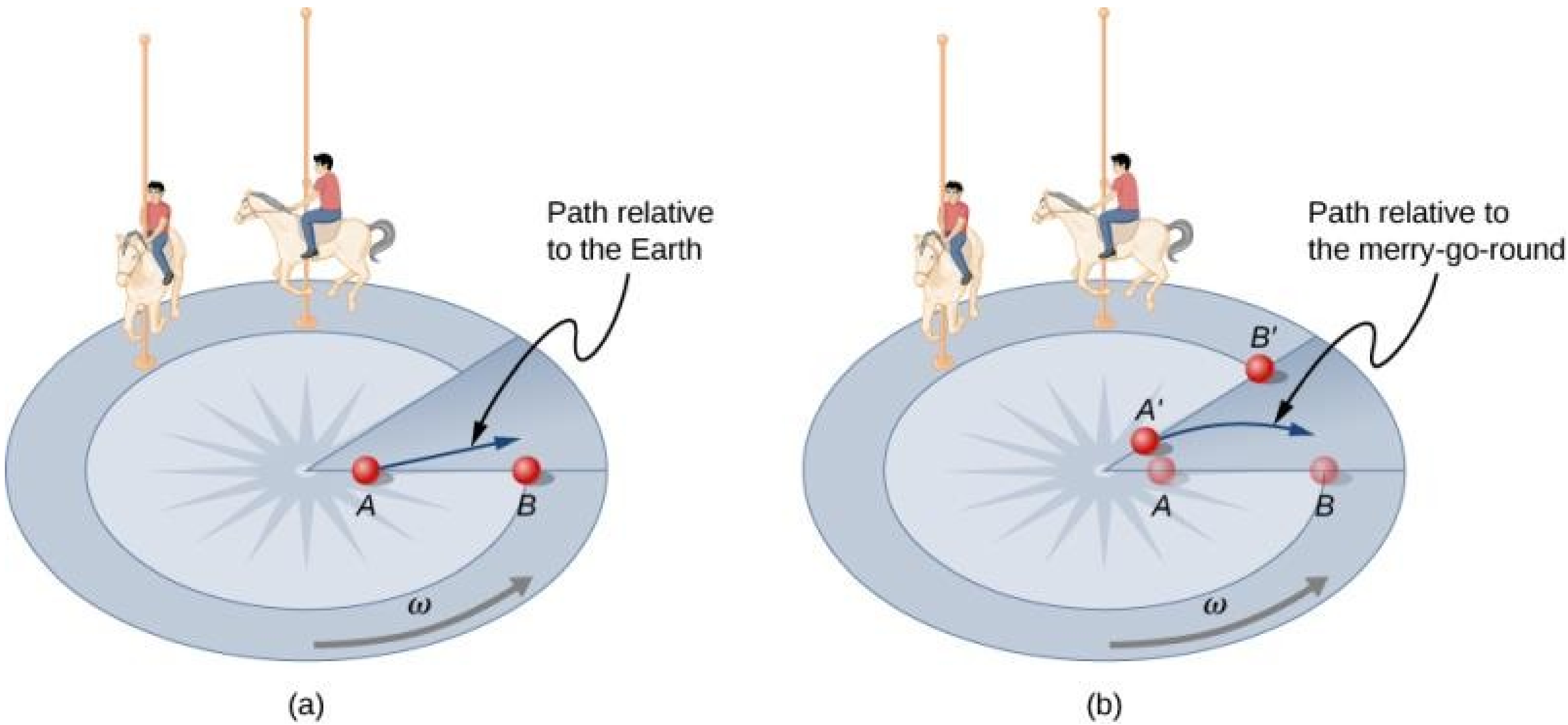
CENTRIPETAL VS CENTRIFUGAL FORCE



(a) A rider on a merry-go-round feels as if he is being thrown off. This inertial force is sometimes mistakenly called the centrifugal force in an effort to explain the rider's motion in the rotating frame of reference.

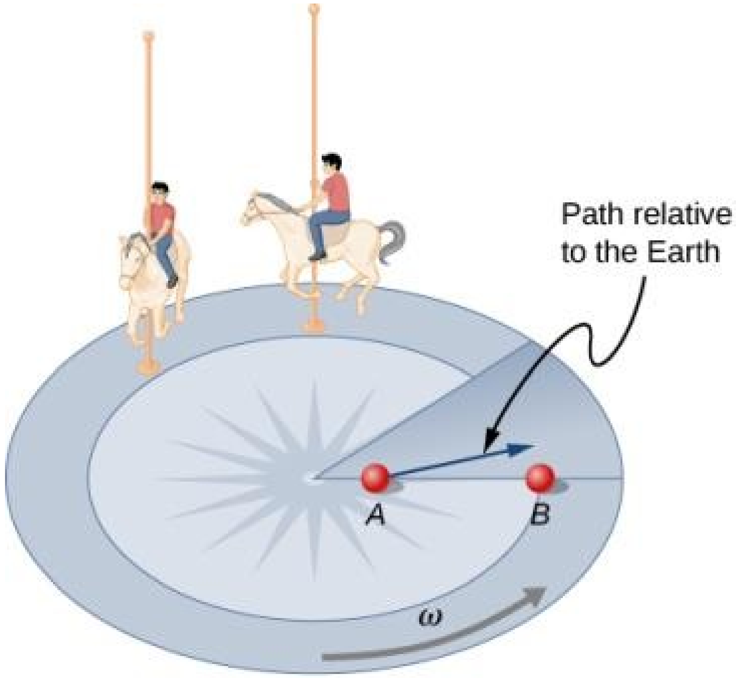
(b) In an inertial frame of reference and according to Newton's laws, it is his inertia that carries him off (the unshaded rider has $F_{\text{net}} = 0$ and heads in a straight line). A force, $F_{\text{centripetal}}$, is needed to cause a circular path.

CORIOLIS FORCE



Looking down on the counterclockwise rotation of a merry-go-round, we see that a ball slid straight toward the edge follows a path curved to the right. The person slides the ball toward point *B*, starting at point *A*. Both points rotate to the shaded positions (*A*' and *B*') shown in the time that the ball follows the curved path in the rotating frame and a straight path in Earth's frame.

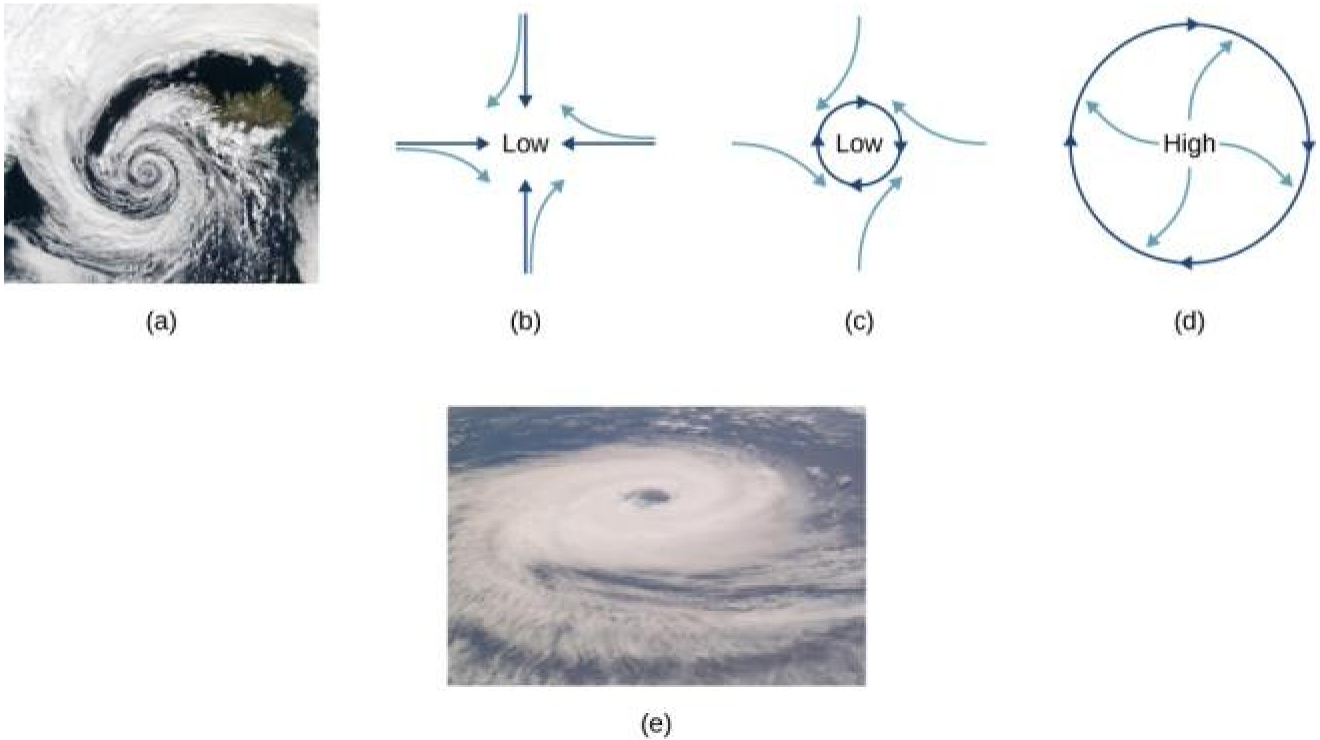
CORIOLIS FORCE



(a)

Looking down on the counterclockwise rotation of a merry-go-round, we see that a ball slid straight toward the edge follows a path curved to the right. The person slides the ball toward point *B*, starting at point *A*. Both pc

FIGURE 6.28



(a) The counterclockwise rotation of this Northern Hemisphere hurricane is a major consequence of the Coriolis force.

(b) Without the Coriolis force, air would flow straight into a low-pressure zone, such as that found in tropical cyclones.

(c) The Coriolis force deflects the winds to the right, producing a counterclockwise rotation.

(d) Wind flowing away from a high-pressure zone is also deflected to the right, producing a clockwise rotation.

(e) The opposite direction of rotation is produced by the Coriolis force in the Southern Hemisphere, leading to tropical cyclones. (credit a and credit e: modifications of work by NASA)

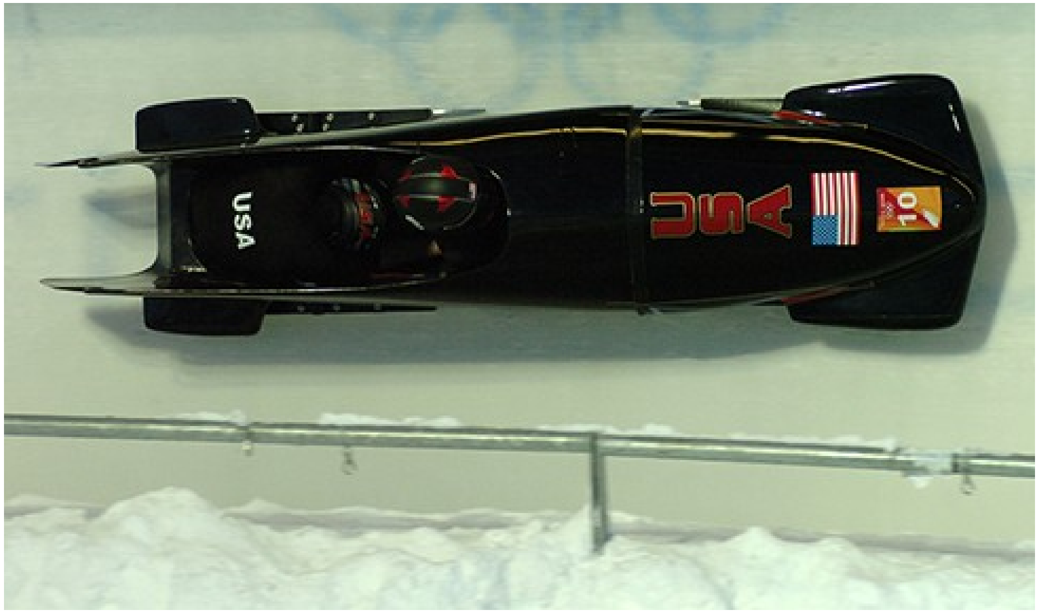
Drag Forces

Like friction, the **drag force** always opposes the motion of an object. Unlike simple friction, the drag force is proportional to some function of the velocity of the object in that fluid. This functionality is complicated and depends upon the shape of the object, its size, its velocity, and the fluid it is in. For most large objects such as cyclists, cars, and baseballs not moving too slowly, the magnitude of the drag force F_D is proportional to the square of the speed of the object. We can write this relationship mathematically as $F_D \propto v^2$. When taking into account other factors, this relationship becomes

Drag force F_D is proportional to the square of the speed of the object. Mathematically,

$$F_D = \frac{1}{2} C \rho A v^2,$$

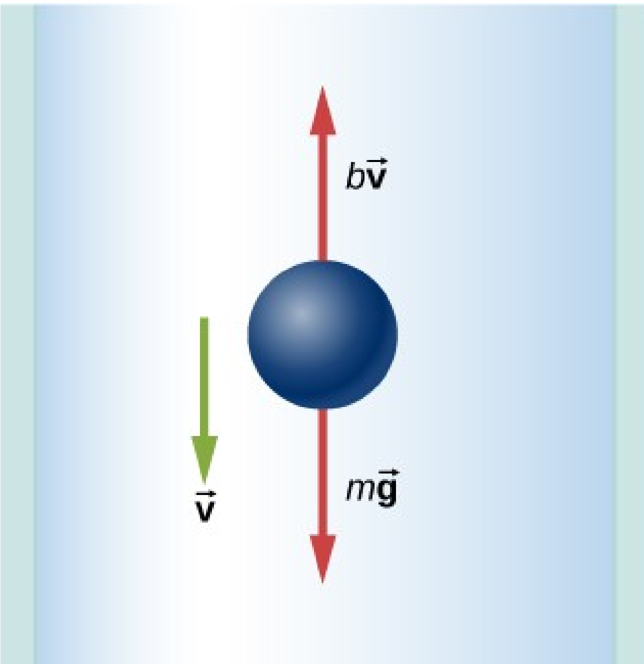
where *C* is the drag coefficient, *A* is the area of the object facing the fluid, and ρ is the density of the fluid.



From racing cars to bobsled racers, aerodynamic shaping is crucial to achieving top speeds. Bobsleds are designed for speed and are shaped like a bullet with tapered fins. (credit: “U.S. Army”/Wikimedia Commons)

FIGURE 6.30

FREE-BODY DIAGRAM AND TERMINAL VELOCITY



Free-body diagram of an object falling through a resistive medium.

At the terminal velocity,

$$F_{\text{net}} = mg - F_{\text{D}} = ma = 0.$$

Thus,

$$mg = F_{\text{D}}.$$

Using the equation for drag force, we have

$$mg = \frac{1}{2} C\rho A v_{\text{T}}^2.$$

Solving for the velocity, we obtain

$$v_{\text{T}} = \sqrt{\frac{2mg}{\rho CA}}.$$

STOKES' LAW

For a spherical object falling in a medium, the drag force is

$$F_{\text{s}} = 6\pi r\eta v,$$

where *r* is the radius of the object, η is the viscosity of the fluid, and *v* is the object's velocity.

The Calculus of Velocity-Dependent Frictional Forces