

6 Dynamics I: Motion Along a Line



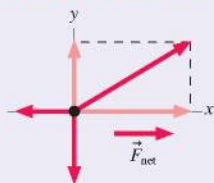
The powerful thrust of the jet engines accelerates this enormous plane to a speed of over 150 mph in less than a mile.

IN THIS CHAPTER, you will learn to solve linear force-and-motion problems.

How are Newton's laws used to solve problems?

Newton's first and second laws are **vector equations**. To use them,

- Draw a **free-body diagram**.
- Read the **x - and y -components** of the forces directly off the free-body diagram.
- Use $\sum F_x = ma_x$ and $\sum F_y = ma_y$.

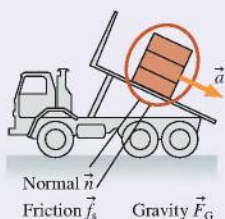


How are dynamics problems solved?

A net force on an object causes the object to accelerate.

- Identify the forces and draw a free-body diagram.
- Use **Newton's second law** to find the object's acceleration.
- Use **kinematics** for velocity and position.

◀ LOOKING BACK Sections 2.4–2.6 Kinematics

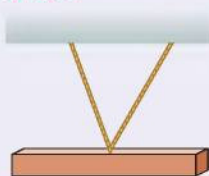


How are equilibrium problems solved?

An object at rest or moving with constant velocity is in **equilibrium** with no net force.

- Identify the forces and draw a free-body diagram.
- Use Newton's second law with $a = 0$ to solve for unknown forces.

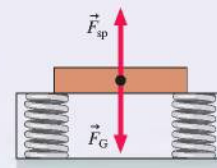
◀ LOOKING BACK Sections 5.1–5.2 Forces



What are mass and weight?

Mass and weight are not the same.

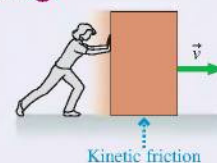
- **Mass** describes an object's inertia. Loosely speaking, it is the amount of matter in an object. It is the same everywhere.
- **Gravity** is a force.
- **Weight** is the result of weighing an object on a scale. It depends on mass, gravity, and acceleration.



How do we model friction and drag?

Friction and **drag** are complex forces, but we will develop simple models of each.

- Static, kinetic, and rolling friction depend on the **coefficients of friction** but not on the object's speed.
- Drag depends on the **square** of an object's speed and on its cross-section area.
- Falling objects reach **terminal speed** when drag and gravity are balanced.



How do we solve problems?

We will develop and use a four-part problem-solving strategy:

- **Model** the problem, using information about objects and forces.
- **Visualize** the situation with a pictorial representation.
- Set up and **solve** the problem with Newton's laws.
- **Assess** the result to see if it is reasonable.

6.1 The Equilibrium Model

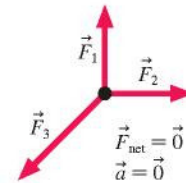
Kinematics is a description of *how* an object moves. But our goal is deeper: We would like an explanation for *why* an object moves as it does. Galileo and Newton discovered that motion is determined by forces. In the absence of a net force, an object is at rest or moves with constant velocity. **Its acceleration is zero**, and this is the basis for our first explanatory model: the **equilibrium model**.

MODEL 6.1

Mechanical equilibrium

For objects on which the net force is zero.

- Model the object as a particle with no acceleration.
 - A particle at rest is in equilibrium.
 - A particle moving in a straight line at constant speed is also in equilibrium.
- Mathematically: $\vec{a} = \vec{0}$ in equilibrium; thus
 - **Newton's second law** is $\vec{F}_{\text{net}} = \sum_i \vec{F}_i = \vec{0}$.
 - The forces are “read” from the free-body diagram,
- Limitations: Model fails if the forces aren't balanced.



The object is at rest or moves with constant velocity.



The concept of equilibrium is essential for the engineering analysis of stationary objects such as bridges.

Newton's laws are *vector equations*. The requirement for equilibrium, $\vec{F}_{\text{net}} = \vec{0}$ and thus $\vec{a} = \vec{0}$, is a shorthand way of writing two simultaneous equations:

$$(F_{\text{net}})_x = \sum_i (F_i)_x = 0 \quad \text{and} \quad (F_{\text{net}})_y = \sum_i (F_i)_y = 0 \quad (6.1)$$

In other words, the sum of all x -components and the sum of all y -components must simultaneously be zero. Although real-world situations often have forces pointing in three dimensions, thus requiring a third equation for the z -component of \vec{F}_{net} , we will restrict ourselves for now to problems that can be analyzed in two dimensions.

NOTE The equilibrium condition of Equations 6.1 applies only to particles, which cannot rotate. Equilibrium of an extended object, which can rotate, requires an additional condition that we will study in Chapter 12.

Equilibrium problems occur frequently. Let's look at a couple of examples.

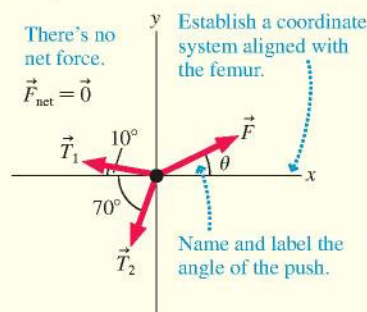
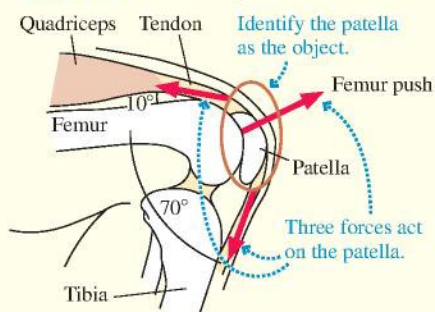
EXAMPLE 6.1 Finding the force on the kneecap

Your kneecap (patella) is attached by a tendon to your quadriceps muscle. This tendon pulls at a 10° angle relative to the femur, the bone of your upper leg. The patella is also attached to your lower leg (tibia) by a tendon that pulls parallel to the leg. To balance these forces, the end of your femur pushes outward on the patella. Bending your knee

increases the tension in the tendons, and both have a tension of 60 N when the knee is bent to make a 70° angle between the upper and lower leg. What force does the femur exert on the kneecap in this position?

MODEL Model the kneecap as a particle in equilibrium.

FIGURE 6.1 Pictorial representation of the kneecap in equilibrium.



Known
 $T_1 = 60 \text{ N}$
 $T_2 = 60 \text{ N}$

Find
 F

VISUALIZE FIGURE 6.1 shows how to draw a pictorial representation. We've chosen to align the x -axis with the femur. The three forces—shown on the free-body diagram—are labeled \vec{T}_1 and \vec{T}_2 for the tensions and \vec{F} for the femur's push. Notice that we've *defined* angle θ to indicate the direction of the femur's force on the kneecap.

SOLVE This is an equilibrium problem, with three forces on the kneecap that must sum to zero. For $\vec{a} = \vec{0}$, Newton's second law, written in component form, is

$$(F_{\text{net}})_x = \sum_i (F_i)_x = T_{1x} + T_{2x} + F_x = 0$$

$$(F_{\text{net}})_y = \sum_i (F_i)_y = T_{1y} + T_{2y} + F_y = 0$$

NOTE You might have been tempted to write $-T_{1x}$ in the equation since \vec{T}_1 points to the left. But the net force, by definition, is the *sum* of all the individual forces. The fact that \vec{T}_1 points to the left will be taken into account when we *evaluate* the components.

The components of the force vectors can be evaluated directly from the free-body diagram:

$$T_{1x} = -T_1 \cos 10^\circ \quad T_{1y} = T_1 \sin 10^\circ$$

$$T_{2x} = -T_2 \cos 70^\circ \quad T_{2y} = -T_2 \sin 70^\circ$$

$$F_x = F \cos \theta \quad F_y = F \sin \theta$$

This is where signs enter, with T_{1x} being assigned a negative value because \vec{T}_1 points to the left. Similarly, \vec{T}_2 points both to the left and down, so both T_{2x} and T_{2y} are negative. With these components, Newton's second law becomes

$$-T_1 \cos 10^\circ - T_2 \cos 70^\circ + F \cos \theta = 0$$

$$T_1 \sin 10^\circ - T_2 \sin 70^\circ + F \sin \theta = 0$$

These are two simultaneous equations for the two unknowns F and θ . We will encounter equations of this form on many occasions,

so make a note of the method of solution. First, rewrite the two equations as

$$F \cos \theta = T_1 \cos 10^\circ + T_2 \cos 70^\circ$$

$$F \sin \theta = -T_1 \sin 10^\circ + T_2 \sin 70^\circ$$

Next, divide the second equation by the first to eliminate F :

$$\frac{F \sin \theta}{F \cos \theta} = \tan \theta = \frac{-T_1 \sin 10^\circ + T_2 \sin 70^\circ}{T_1 \cos 10^\circ + T_2 \cos 70^\circ}$$

Then solve for θ :

$$\begin{aligned} \theta &= \tan^{-1} \left(\frac{-T_1 \sin 10^\circ + T_2 \sin 70^\circ}{T_1 \cos 10^\circ + T_2 \cos 70^\circ} \right) \\ &= \tan^{-1} \left(\frac{-(60 \text{ N}) \sin 10^\circ + (60 \text{ N}) \sin 70^\circ}{(60 \text{ N}) \cos 10^\circ + (60 \text{ N}) \cos 70^\circ} \right) = 30^\circ \end{aligned}$$

Finally, use θ to find F :

$$\begin{aligned} F &= \frac{T_1 \cos 10^\circ + T_2 \cos 70^\circ}{\cos \theta} \\ &= \frac{(60 \text{ N}) \cos 10^\circ + (60 \text{ N}) \cos 70^\circ}{\cos 30^\circ} = 92 \text{ N} \end{aligned}$$

The question asked What force? and force is a vector, so we must specify both the magnitude and the direction. With the knee in this position, the femur exerts a force $\vec{F} = (92 \text{ N}, 30^\circ \text{ above the femur})$ on the kneecap.

ASSESS The magnitude of the force would be 0 N if the leg were straight, 120 N if the knee could be bent 180° so that the two tendons pull in parallel. The knee is closer to fully bent than to straight, so we would expect a femur force between 60 N and 120 N. Thus the calculated magnitude of 92 N seems reasonable.

EXAMPLE 6.2 Towing a car up a hill

A car with a weight of 15,000 N is being towed up a 20° slope at constant velocity. Friction is negligible. The tow rope is rated at 6000 N maximum tension. Will it break?

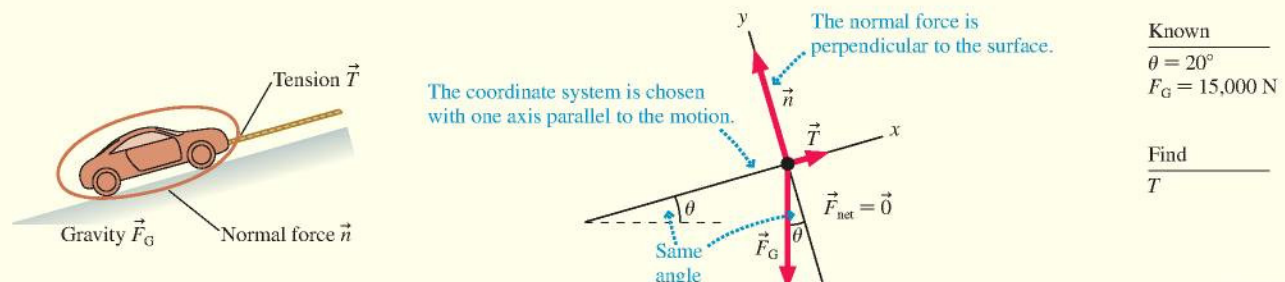
MODEL Model the car as a particle in equilibrium.

VISUALIZE Part of our analysis of the problem statement is to determine which quantity or quantities allow us to answer the yes-or-no

question. In this case, we need to calculate the tension in the rope. FIGURE 6.2 shows the pictorial representation. Note the similarities to Examples 5.2 and 5.6 in Chapter 5, which you may want to review.

We noted in Chapter 5 that the weight of an object at rest is the magnitude F_G of the gravitational force acting on it, and that information has been listed as known.

FIGURE 6.2 Pictorial representation of a car being towed up a hill.



Known
 $\theta = 20^\circ$
 $F_G = 15,000 \text{ N}$

Find
 T

Continued

SOLVE The free-body diagram shows forces \vec{T} , \vec{n} , and \vec{F}_G acting on the car. Newton's second law with $\vec{a} = \vec{0}$ is

$$(F_{\text{net}})_x = \sum F_x = T_x + n_x + (F_G)_x = 0$$

$$(F_{\text{net}})_y = \sum F_y = T_y + n_y + (F_G)_y = 0$$

From here on, we'll use $\sum F_x$ and $\sum F_y$, without the label i , as a simple shorthand notation to indicate that we're adding all the x -components and all the y -components of the forces.

We can find the components directly from the free-body diagram:

$$T_x = T \quad T_y = 0$$

$$n_x = 0 \quad n_y = n$$

$$(F_G)_x = -F_G \sin \theta \quad (F_G)_y = -F_G \cos \theta$$

NOTE The gravitational force has both x - and y -components in this coordinate system, both of which are negative due to the direction of the vector \vec{F}_G . You'll see this situation often, so be sure you understand where $(F_G)_x$ and $(F_G)_y$ come from.

With these components, the second law becomes

$$T - F_G \sin \theta = 0$$

$$n - F_G \cos \theta = 0$$

The first of these can be rewritten as

$$T = F_G \sin \theta = (15,000 \text{ N}) \sin 20^\circ = 5100 \text{ N}$$

Because $T < 6000 \text{ N}$, we conclude that the rope will *not* break. It turned out that we did not need the y -component equation in this problem.

ASSESS Because there's no friction, it would not take *any* tension force to keep the car rolling along a horizontal surface ($\theta = 0^\circ$). At the other extreme, $\theta = 90^\circ$, the tension force would need to equal the car's weight ($T = 15,000 \text{ N}$) to lift the car straight up at constant velocity. The tension force for a 20° slope should be somewhere in between, and 5100 N is a little less than half the weight of the car. That our result is reasonable doesn't prove it's right, but we have at least ruled out careless errors that give unreasonable results.

6.2 Using Newton's Second Law

The essence of Newtonian mechanics, introduced in « Section 5.4, can be expressed in two steps:

- The forces acting on an object determine its acceleration $\vec{a} = \vec{F}_{\text{net}}/m$.
- The object's trajectory can be determined by using \vec{a} in the equations of kinematics.

These two ideas are the basis of a problem-solving strategy.

PROBLEM-SOLVING STRATEGY 6.1

MP

Newtonian mechanics

MODEL Model the object as a particle. Make other simplifications depending on what kinds of forces are acting.

VISUALIZE Draw a **pictorial representation**.

- Show important points in the motion with a sketch, establish a coordinate system, define symbols, and identify what the problem is trying to find.
- Use a motion diagram to determine the object's acceleration vector \vec{a} . The acceleration is zero for an object in equilibrium.
- Identify all forces acting on the object *at this instant* and show them on a free-body diagram.
- It's OK to go back and forth between these steps as you visualize the situation.

SOLVE The mathematical representation is based on Newton's second law:

$$\vec{F}_{\text{net}} = \sum_i \vec{F}_i = m\vec{a}$$

The forces are "read" directly from the free-body diagram. Depending on the problem, either

- Solve for the acceleration, then use kinematics to find velocities and positions; or
- Use kinematics to determine the acceleration, then solve for unknown forces.

ASSESS Check that your result has correct units and significant figures, is reasonable, and answers the question.



Newton's second law is a vector equation. To apply the step labeled Solve, you must write the second law as two simultaneous equations:

$$\begin{aligned}(F_{\text{net}})_x &= \sum F_x = ma_x \\ (F_{\text{net}})_y &= \sum F_y = ma_y\end{aligned}\quad (6.2)$$

The primary goal of this chapter is to illustrate the use of this strategy.

EXAMPLE 6.3 Speed of a towed car

A 1500 kg car is pulled by a tow truck. The tension in the tow rope is 2500 N, and a 200 N friction force opposes the motion. If the car starts from rest, what is its speed after 5.0 seconds?

MODEL Model the car as an accelerating particle. We'll assume, as part of our *interpretation* of the problem, that the road is horizontal and that the direction of motion is to the right.

VISUALIZE FIGURE 6.3 shows the pictorial representation. We've established a coordinate system and defined symbols to represent kinematic quantities. We've identified the speed v_1 , rather than the velocity v_{1x} , as what we're trying to find.

SOLVE We begin with Newton's second law:

$$\begin{aligned}(F_{\text{net}})_x &= \sum F_x = T_x + f_x + n_x + (F_G)_x = ma_x \\ (F_{\text{net}})_y &= \sum F_y = T_y + f_y + n_y + (F_G)_y = ma_y\end{aligned}$$

All four forces acting on the car have been included in the vector sum. The equations are perfectly general, with + signs everywhere, because the four vectors are *added* to give \vec{F}_{net} . We can now "read" the vector components from the free-body diagram:

$$\begin{aligned}T_x &= +T & T_y &= 0 & n_x &= 0 & n_y &= +n \\ f_x &= -f & f_y &= 0 & (F_G)_x &= 0 & (F_G)_y &= -F_G\end{aligned}$$

The signs, which we had to insert by hand, depend on which way the vectors point. Substituting these into the second-law equations and dividing by m give

$$\begin{aligned}a_x &= \frac{1}{m}(T - f) \\ &= \frac{1}{1500 \text{ kg}}(2500 \text{ N} - 200 \text{ N}) = 1.53 \text{ m/s}^2 \\ a_y &= \frac{1}{m}(n - F_G)\end{aligned}$$

NOTE Newton's second law has allowed us to determine a_x exactly but has given only an algebraic expression for a_y . However, we know *from the motion diagram* that $a_y = 0$! That is, the motion is purely along the x -axis, so there is *no* acceleration along the y -axis. The requirement $a_y = 0$ allows us to conclude that $n = F_G$.

Because a_x is a constant 1.53 m/s^2 , we can finish by using constant-acceleration kinematics to find the velocity:

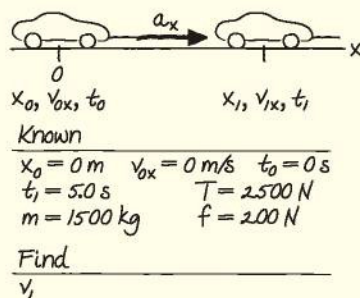
$$\begin{aligned}v_{1x} &= v_{0x} + a_x \Delta t \\ &= 0 + (1.53 \text{ m/s}^2)(5.0 \text{ s}) = 7.7 \text{ m/s}\end{aligned}$$

The problem asked for the *speed* after 5.0 s, which is $v_1 = 7.7 \text{ m/s}$.

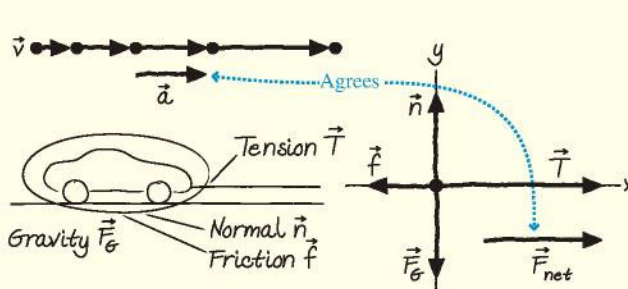
ASSESS $7.7 \text{ m/s} \approx 15 \text{ mph}$, a quite reasonable speed after 5 s of acceleration.

FIGURE 6.3 Pictorial representation of a car being towed.

Sketch



Motion diagram and forces



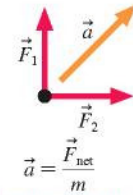
If all the forces acting on an object are constant, as in the last example, then the object moves with constant acceleration and we can deploy the uniform-acceleration model of kinetics. Now not all forces are constant—you will later meet forces that vary with position or time—but in many situations it is reasonable to model the motion as being due to constant forces. The **constant-force model** will be our most important dynamics model for the next several chapters.

MODEL 6.2

Constant force

For objects on which the net force is constant.

- Model the object as a particle with uniform acceleration.
 - The particle accelerates in the direction of the net force.
- Mathematically:
 - **Newton's second law** is $\vec{F}_{\text{net}} = \sum_i \vec{F}_i = m\vec{a}$.
 - Use the kinematics of constant acceleration.
- Limitations: Model fails if the forces aren't constant.



The object undergoes uniform acceleration.

EXAMPLE 6.4 Altitude of a rocket

A 500 g model rocket with a weight of 4.90 N is launched straight up. The small rocket motor burns for 5.00 s and has a steady thrust of 20.0 N. What maximum altitude does the rocket reach?

MODEL We'll model the rocket as a particle acted on by constant forces by neglecting the velocity-dependent air resistance (rockets have very aerodynamic shapes) and neglecting the mass loss of the burned fuel.

VISUALIZE The pictorial representation of **FIGURE 6.4** finds that this is a two-part problem. First, the rocket accelerates straight up. Second, the rocket continues going up as it slows down, a free-fall situation. The maximum altitude is at the end of the second part of the motion.

SOLVE We now know what the problem is asking, have established relevant symbols and coordinates, and know what the forces are.

We begin the mathematical representation by writing Newton's second law, in component form, as the rocket accelerates upward. The free-body diagram shows two forces, so

$$(F_{\text{net}})_x = \sum F_x = (F_{\text{thrust}})_x + (F_G)_x = ma_{0x}$$

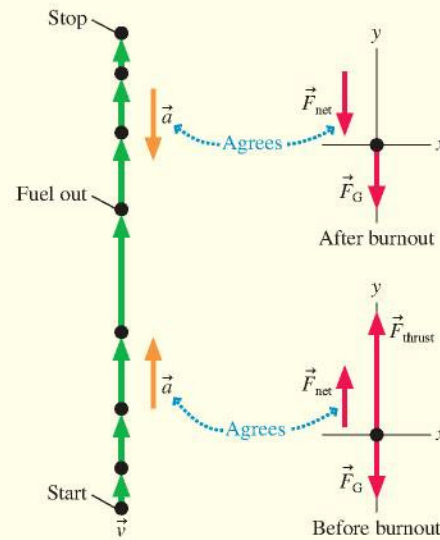
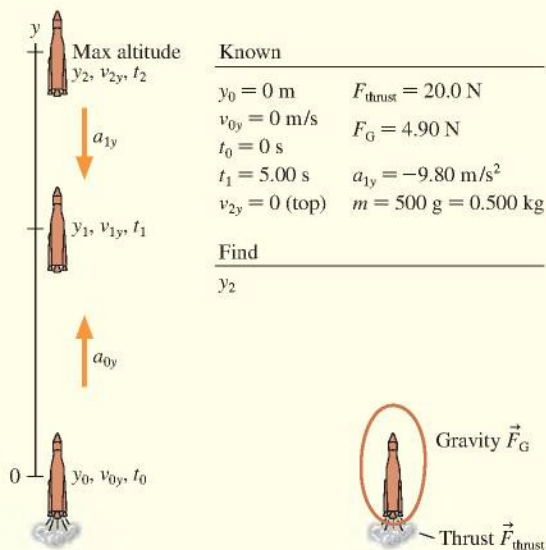
$$(F_{\text{net}})_y = \sum F_y = (F_{\text{thrust}})_y + (F_G)_y = ma_{0y}$$

The fact that vector \vec{F}_G points downward—and which might have tempted you to use a minus sign in the y -equation—will be taken into account when we *evaluate* the components. None of the vectors in this problem has an x -component, so only the y -component of the second law is needed. We can use the free-body diagram to see that

$$(F_{\text{thrust}})_y = +F_{\text{thrust}}$$

$$(F_G)_y = -F_G$$

FIGURE 6.4 Pictorial representation of a rocket launch.



This is the point at which the directional information about the force vectors enters. The y -component of the second law is then

$$\begin{aligned} a_{0y} &= \frac{1}{m} (F_{\text{thrust}} - F_G) \\ &= \frac{20.0 \text{ N} - 4.90 \text{ N}}{0.500 \text{ kg}} = 30.2 \text{ m/s}^2 \end{aligned}$$

Notice that we converted the mass to SI units of kilograms before doing any calculations and that, because of the definition of the newton, the division of newtons by kilograms automatically gives the correct SI units of acceleration.

The acceleration of the rocket is constant until it runs out of fuel, so we can use constant-acceleration kinematics to find the altitude and velocity at burnout ($\Delta t = t_1 = 5.00 \text{ s}$):

$$\begin{aligned} y_1 &= y_0 + v_{0y} \Delta t + \frac{1}{2} a_{0y} (\Delta t)^2 \\ &= \frac{1}{2} a_{0y} (\Delta t)^2 = 377 \text{ m} \\ v_{1y} &= v_{0y} + a_{0y} \Delta t = a_{0y} \Delta t = 151 \text{ m/s} \end{aligned}$$

The only force on the rocket after burnout is gravity, so the second part of the motion is free fall. We do not know how long it takes to reach the top, but we do know that the final velocity is $v_{2y} = 0$. Constant-acceleration kinematics with $a_{1y} = -g$ gives

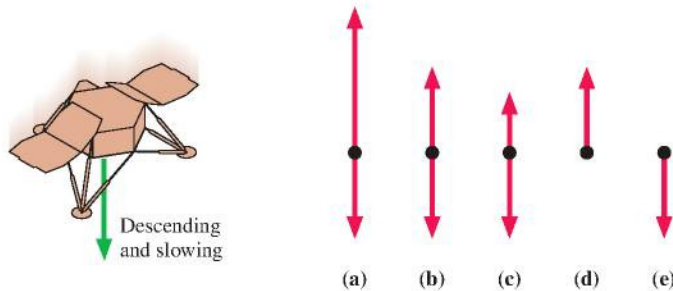
$$v_{2y}^2 = 0 = v_{1y}^2 - 2g \Delta y = v_{1y}^2 - 2g(y_2 - y_1)$$

which we can solve to find

$$\begin{aligned} y_2 &= y_1 + \frac{v_{1y}^2}{2g} = 377 \text{ m} + \frac{(151 \text{ m/s})^2}{2(9.80 \text{ m/s}^2)} \\ &= 1540 \text{ m} = 1.54 \text{ km} \end{aligned}$$

ASSESS The maximum altitude reached by this rocket is 1.54 km, or just slightly under one mile. While this does not seem unreasonable for a high-acceleration rocket, the neglect of air resistance was probably not a terribly realistic assumption.

STOP TO THINK 6.1 A Martian lander is approaching the surface. It is slowing its descent by firing its rocket motor. Which is the correct free-body diagram?



6.3 Mass, Weight, and Gravity

Ordinary language does not make a large distinction between mass and weight. However, these are separate and distinct concepts in science and engineering. We need to understand how they differ, and how they're related to gravity, if we're going to think clearly about force and motion.

Mass: An Intrinsic Property

Mass, you'll recall from « Section 5.4, is a scalar quantity that describes an object's inertia. Loosely speaking, it also describes the amount of matter in an object. **Mass is an intrinsic property of an object.** It tells us something about the object, regardless of where the object is, what it's doing, or whatever forces may be acting on it.

A *pan balance*, shown in FIGURE 6.5, is a device for measuring mass. Although a pan balance requires gravity to function, it does not depend on the strength of gravity. Consequently, the pan balance would give the same result on another planet.

FIGURE 6.5 A pan balance measures mass.

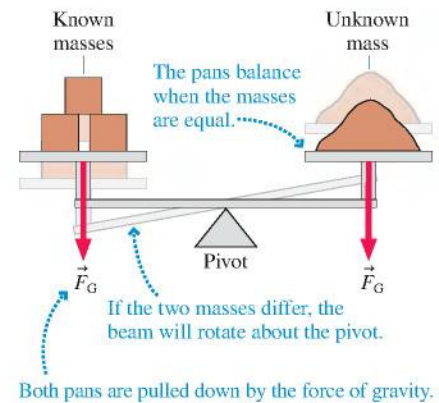


FIGURE 6.6 Newton's law of gravity.

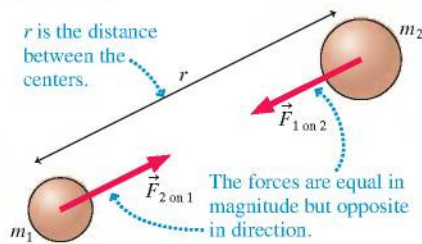


FIGURE 6.7 Gravity near the surface of a planet.

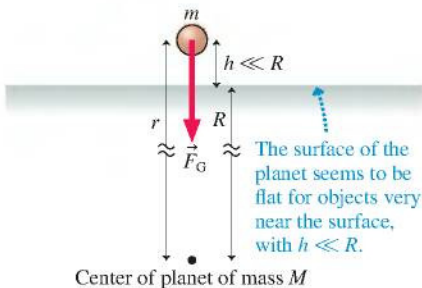
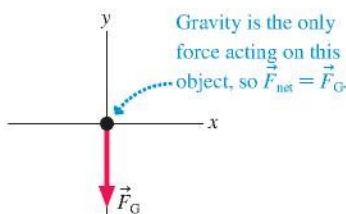


FIGURE 6.8 The free-body diagram of an object in free fall.



Gravity: A Force

The idea of gravity has a long and interesting history intertwined with our evolving ideas about the solar system. It was Newton who—along with discovering his three laws of motion—first recognized that **gravity is an attractive, long-range force between any two objects.**

FIGURE 6.6 shows two objects with masses m_1 and m_2 separated by distance r . Each object pulls on the other with a force given by *Newton's law of gravity*:

$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{Gm_1m_2}{r^2} \quad (\text{Newton's law of gravity}) \quad (6.3)$$

where $G = 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2$, called the *gravitational constant*, is one of the basic constants of nature. Notice that gravity is *not* a constant force—the force gets weaker as the distance between the objects increases.

The gravitational force between two human-sized objects is minuscule, completely insignificant in comparison with other forces. That's why you're not aware of being tugged toward everything around you. Only when one or both objects are planet-sized or larger does gravity become an important force. Indeed, Chapter 13 will explore in detail the application of Newton's law of gravity to the orbits of satellites and planets.

For objects moving near the surface of the earth (or other planet), things like balls and cars and planes that we'll be studying in the next few chapters, we can make the **flat-earth approximation** shown in FIGURE 6.7. That is, if the object's height above the surface is very small in comparison with the size of the planet, then the curvature of the surface is not noticeable and there's virtually no difference between r and the planet's radius R . Consequently, a very good approximation for the gravitational force of the planet on mass m is simply

$$\vec{F}_G = \vec{F}_{\text{planet on } m} = \left(\frac{GMm}{R^2}, \text{ straight down} \right) = (mg, \text{ straight down}) \quad (6.4)$$

The magnitude or size of the gravitational force is $F_G = mg$, where the quantity g —a property of the planet—is defined to be

$$g = \frac{GM}{R^2} \quad (6.5)$$

Also, the direction of the gravitational force defines what we *mean* by “straight down.”

But why did we choose to call it g , a symbol we've already used for free-fall acceleration? To see the connection, recall that free fall is motion under the influence of gravity only. FIGURE 6.8 shows the free-body diagram of an object in free fall near the surface of a planet. With $\vec{F}_{\text{net}} = \vec{F}_G$, Newton's second law predicts the acceleration to be

$$\vec{a}_{\text{free fall}} = \frac{\vec{F}_{\text{net}}}{m} = \frac{\vec{F}_G}{m} = (g, \text{ straight down}) \quad (6.6)$$

Because g is a property of the planet, independent of the object, **all objects on the same planet, regardless of mass, have the same free-fall acceleration.** We introduced this idea in Chapter 2 as an experimental discovery of Galileo, but now we see that the mass independence of $\vec{a}_{\text{free fall}}$ is a prediction of Newton's law of gravity.

But does Newton's law predict the correct value, which we know from experiment to be $g = |a_{\text{free fall}}| = 9.80 \text{ m/s}^2$? We can use the average radius ($R_{\text{earth}} = 6.37 \times 10^6 \text{ m}$) and mass ($M_{\text{earth}} = 5.98 \times 10^{24} \text{ kg}$) of the earth to calculate

$$g_{\text{earth}} = \frac{GM_{\text{earth}}}{(R_{\text{earth}})^2} = \frac{(6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2)(5.98 \times 10^{24} \text{ kg})}{(6.37 \times 10^6 \text{ m})^2} = 9.83 \text{ N/kg}$$

You should convince yourself that N/kg is equivalent to m/s^2 , so $g_{\text{earth}} = 9.83 \text{ m/s}^2$.

NOTE Astronomical data are provided inside the back cover of the book.

Newton's prediction is very close, but it's not quite right. The free-fall acceleration *would* be 9.83 m/s^2 on a stationary earth, but, in reality, the earth is rotating on its axis. The “missing” 0.03 m/s^2 is due to the earth's rotation, a claim we'll justify when we study circular motion in Chapter 8. Because we're on the outside of a rotating sphere, rather like being on the outside edge of a merry-go-round, the effect of rotation is to “weaken” gravity.

Strictly speaking, Newton's laws of motion are not valid in an earth-based reference frame because it is rotating and thus is not an inertial reference frame. Fortunately, we can use Newton's laws to analyze motion near the earth's surface, and we can use $F_G = mg$ for the gravitational force *if* we use $g = |a_{\text{free fall}}| = 9.80 \text{ m/s}^2$ rather than $g = g_{\text{earth}}$. (This assertion is proved in more advanced classes.) In our rotating reference frame, \vec{F}_G is the *effective gravitational force*, the true gravitational force given by Newton's law of gravity plus a small correction due to our rotation. This is the force to show on free-body diagrams and use in calculations.

Weight: A Measurement

When you weigh yourself, you stand on a *spring scale* and compress a spring. The reading of a spring scale, such as the one shown in FIGURE 6.9, is F_{Sp} , the magnitude of the upward force the spring is exerting.

With that in mind, let's define the **weight** of an object to be the reading F_{Sp} of a calibrated spring scale when the object is at rest relative to the scale. That is, **weight is a measurement, the result of “weighing” an object**. Because F_{Sp} is a force, weight is measured in newtons.

If the object and scale in Figure 6.9 are stationary, then the object being weighed is in equilibrium. $\vec{F}_{\text{net}} = \vec{0}$ only if the upward spring force exactly balances the downward gravitational force of magnitude mg :

$$F_{\text{Sp}} = F_G = mg \quad (6.7)$$

Because we defined weight as the reading F_{Sp} of a spring scale, the weight of a stationary object is

$$w = mg \quad (\text{weight of a stationary object}) \quad (6.8)$$

Note that the scale does not “know” the weight of the object. All it can do is to measure how much its spring is compressed. On earth, a student with a mass of 70 kg has weight $w = (70 \text{ kg})(9.80 \text{ m/s}^2) = 686 \text{ N}$ *because* he compresses a spring until the spring pushes upward with 686 N. On a different planet, with a different value for g , the compression of the spring would be different and the student's weight would be different.

NOTE Mass and weight are not the same thing. Mass, in kg, is an intrinsic property of an object; its value is unique and always the same. Weight, in N, depends on the object's mass, but it also depends on the situation—the strength of gravity and, as we will see, whether or not the object is accelerating. Weight is *not* a property of the object, and thus weight does not have a unique value.

Surprisingly, you cannot directly feel or sense gravity. Your *sensation*—how heavy you feel—is due to contact forces pressing against you, forces that touch you and activate nerve endings in your skin. As you read this, your sensation of weight is due to the normal force exerted on you by the chair in which you are sitting. When you stand, you feel the contact force of the floor pushing against your feet.

But recall the sensations you feel while accelerating. You feel “heavy” when an elevator suddenly accelerates upward, but this sensation vanishes as soon as the elevator reaches a steady speed. Your stomach seems to rise a little and you feel lighter than normal as the upward-moving elevator brakes to a halt or a roller coaster goes over the top. Has your weight actually changed?

FIGURE 6.9 A spring scale measures weight.

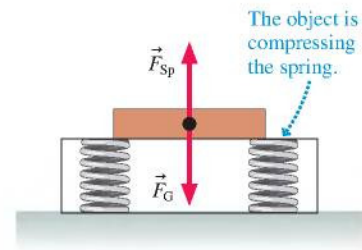
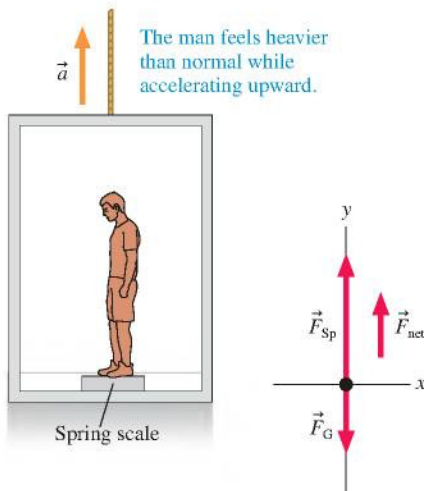


FIGURE 6.10 A man weighing himself in an accelerating elevator.



To answer this question, **FIGURE 6.10** shows a man weighing himself on a spring scale in an accelerating elevator. The only forces acting on the man are the upward spring force of the scale and the downward gravitational force. This seems to be the same situation as Figure 6.9, but there's one big difference: The man is accelerating, hence there must be a net force on the man in the direction of \vec{a} .

For the net force \vec{F}_{net} to point upward, the magnitude of the spring force must be *greater* than the magnitude of the gravitational force. That is, $F_{\text{Sp}} > mg$. Looking at the free-body diagram in Figure 6.10, we see that the y-component of Newton's second law is

$$(F_{\text{net}})_y = (F_{\text{Sp}})_y + (F_{\text{G}})_y = F_{\text{Sp}} - mg = ma_y \quad (6.9)$$

where m is the man's mass.

We defined weight as the reading F_{Sp} of a calibrated spring scale *when the object is at rest relative to the scale*. That is the case here as the scale and man accelerate upward together. Thus the man's weight as he accelerates vertically is

$$w = \text{scale reading } F_{\text{Sp}} = mg + ma_y = mg \left(1 + \frac{a_y}{g} \right) \quad (6.10)$$

If an object is either at rest or moving with constant velocity, then $a_y = 0$ and $w = mg$. That is, the weight of a stationary object is the magnitude of the (effective) gravitational force acting on it. But its weight differs if it has a vertical acceleration.

You *do* weigh more when accelerating upward ($a_y > 0$) because the reading of a scale—a weighing—increases. Similarly, your weight is less when the acceleration vector \vec{a} points downward ($a_y < 0$) because the scale reading goes down. Weight, as we've defined it, corresponds to your sensation of heaviness or lightness.*

We found Equation 6.10 by considering a person in an accelerating elevator, but it applies to any object with a vertical acceleration. Further, an object doesn't really have to be on a scale to have a weight; an object's weight is the magnitude of the contact force supporting it. It makes no difference whether this is the spring force of the scale or simply the normal force of the floor.

NOTE Informally, we sometimes say “This object weighs such and such” or “The weight of this object is” We'll interpret these expressions as meaning mg , the weight of an object of mass m at rest ($a_y = 0$) on the surface of the earth or some other astronomical body.



Astronauts are weightless as they orbit the earth.

Weightlessness

Suppose the elevator cable breaks and the elevator, along with the man and his scale, plunges straight down in free fall! What will the scale read? When the free-fall acceleration $a_y = -g$ is used in Equation 6.10, we find $w = 0$. In other words, *the man has no weight!*

Suppose, as the elevator falls, the man inside releases a ball from his hand. In the absence of air resistance, as Galileo discovered, both the man and the ball would fall at the same rate. From the man's perspective, the ball would appear to “float” beside him. Similarly, the scale would float beneath him and not press against his feet. He is what we call *weightless*. Gravity is still pulling down on him—that's why he's falling—but he has no *sensation* of weight as everything floats around him in free fall.

But isn't this exactly what happens to astronauts orbiting the earth? If an astronaut tries to stand on a scale, it does not exert any force against her feet and reads zero. She is said to be weightless. But if the criterion to be weightless is to be in free fall, and if astronauts orbiting the earth are weightless, does this mean that they are in free fall? This is a very interesting question to which we shall return in Chapter 8.

* Surprisingly, there is no universally agreed-upon definition of *weight*. Some textbooks define weight as the gravitational force on an object, $\vec{w} = (mg, \text{down})$. In that case, the scale reading of an accelerating object, and your sensation of weight, is often called *apparent weight*. This textbook prefers the definition of *weight* as being what a scale reads, the result of a weighing measurement.

STOP TO THINK 6.2 An elevator that has descended from the 50th floor is coming to a halt at the 1st floor. As it does, your weight is

- a. More than mg . b. Less than mg . c. Equal to mg . d. Zero.

6.4 Friction

Friction is absolutely essential for many things we do. Without friction you could not walk, drive, or even sit down (you would slide right off the chair!). Although friction is a complicated force, many aspects of friction can be described with a simple model.

Static Friction

« Section 5.2 defined *static friction* \vec{f}_s as the force on an object that keeps it from slipping. FIGURE 6.11 shows a rope pulling on a box that, due to static friction, isn't moving. The box is in equilibrium, so the static friction force must exactly balance the tension force:

$$f_s = T \quad (6.11)$$

To determine the direction of \vec{f}_s , decide which way the object would move if there were no friction. The static friction force \vec{f}_s points in the *opposite* direction to prevent the motion.

Unlike the gravitational force, which has the precise and unambiguous magnitude $F_G = mg$, the size of the static friction force depends on how hard you push or pull. The harder the rope in Figure 6.11 pulls, the harder the floor pulls back. Reduce the tension, and the static friction force will automatically be reduced to match. Static friction acts in *response* to an applied force. FIGURE 6.12 illustrates this idea.

But there's clearly a limit to how big f_s can get. If you pull hard enough, the object slips and starts to move. In other words, the static friction force has a *maximum* possible size $f_{s \max}$.

- An object remains at rest as long as $f_s < f_{s \max}$.
- The object slips when $f_s = f_{s \max}$.
- A static friction force $f_s > f_{s \max}$ is not physically possible.

Experiments with friction show that $f_{s \max}$ is proportional to the magnitude of the normal force. That is,

$$f_{s \max} = \mu_s n \quad (6.12)$$

where the proportionality constant μ_s is called the **coefficient of static friction**. The coefficient is a dimensionless number that depends on the materials of which the object and the surface are made. TABLE 6.1 on the next page shows some typical coefficients of friction. It is to be emphasized that these are only approximate; the exact value of the coefficient depends on the roughness, cleanliness, and dryness of the surfaces.

NOTE The static friction force is *not* given by Equation 6.12; this equation is simply the maximum possible static friction. The static friction force is not found with an equation but by determining how much force is needed to maintain equilibrium.

Kinetic Friction

Once the box starts to slide, as in FIGURE 6.13, the static friction force is replaced by a kinetic friction force \vec{f}_k . Experiments show that kinetic friction, unlike static friction, has a nearly *constant* magnitude. Furthermore, the size of the kinetic friction force

FIGURE 6.11 Static friction keeps an object from slipping.

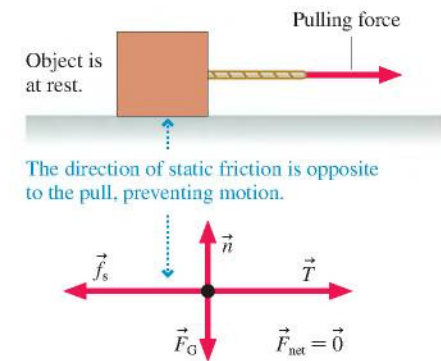


FIGURE 6.12 Static friction acts in response to an applied force.

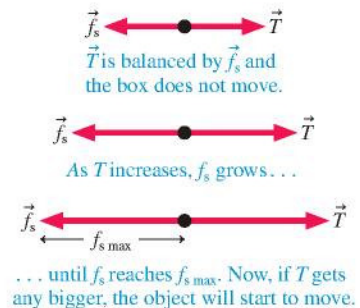
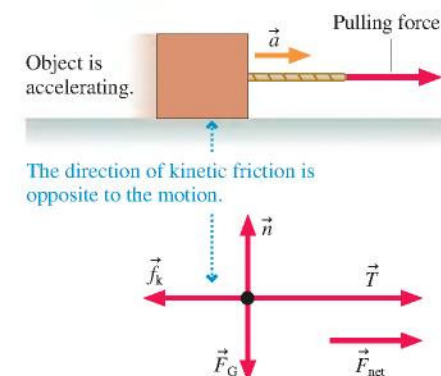


FIGURE 6.13 The kinetic friction force is opposite the direction of motion.



is *less* than the maximum static friction, $f_k < f_{s \max}$, which explains why it is easier to keep the box moving than it was to start it moving. The direction of \vec{f}_k is always opposite to the direction in which an object slides across the surface.

The kinetic friction force is also proportional to the magnitude of the normal force:

$$f_k = \mu_k n \quad (6.13)$$

where μ_k is called the **coefficient of kinetic friction**. Table 6.1 includes typical values of μ_k . You can see that $\mu_k < \mu_s$, causing the kinetic friction to be less than the maximum static friction.

Rolling Friction

If you slam on the brakes hard enough, your car tires slide against the road surface and leave skid marks. This is kinetic friction. A wheel *rolling* on a surface also experiences friction, but not kinetic friction. As FIGURE 6.14 shows, the portion of the wheel that contacts the surface is stationary with respect to the surface, not sliding. The interaction of this contact area with the surface causes **rolling friction**. The force of rolling friction can be calculated in terms of a **coefficient of rolling friction** μ_r :

$$f_r = \mu_r n \quad (6.14)$$

Rolling friction acts very much like kinetic friction, but values of μ_r (see Table 6.1) are much lower than values of μ_k . This is why it is easier to roll an object on wheels than to slide it.

FIGURE 6.14 Rolling friction is also opposite the direction of motion

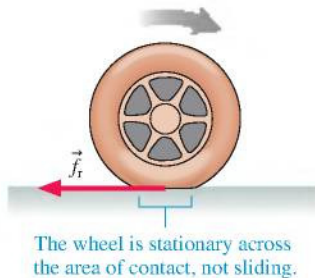


TABLE 6.1 Coefficients of friction

Materials	Static μ_s	Kinetic μ_k	Rolling μ_r
Rubber on dry concrete	1.00	0.80	0.02
Rubber on wet concrete	0.30	0.25	0.02
Steel on steel (dry)	0.80	0.60	0.002
Steel on steel (lubricated)	0.10	0.05	
Wood on wood	0.50	0.20	
Wood on snow	0.12	0.06	
Ice on ice	0.10	0.03	

A Model of Friction

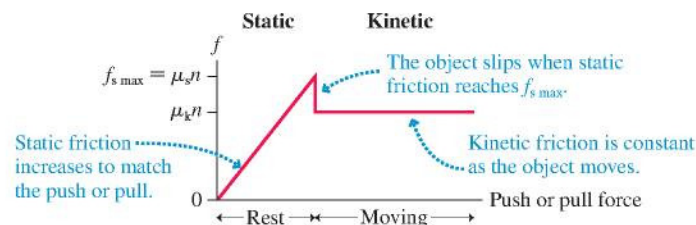
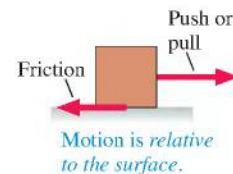
The friction equations are not “laws of nature” on a level with Newton’s laws. Instead, they provide a reasonably accurate, but not perfect, description of how friction forces act. That is, they are a *model* of friction. And because we characterize friction in terms of constant forces, this model of friction meshes nicely with our model of dynamics with constant force.

MODEL 6.3

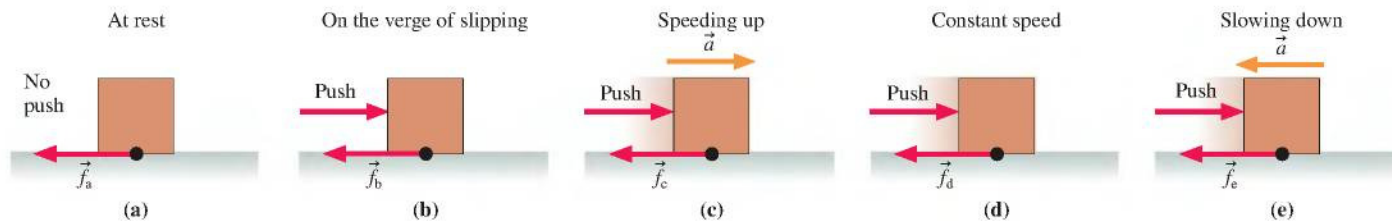
Friction

The friction force is *parallel* to the surface.

- Static friction: Acts as needed to prevent motion. Can have *any* magnitude up to $f_{s \max} = \mu_s n$.
- Kinetic friction: Opposes motion with $f_k = \mu_k n$.
- Rolling friction: Opposes motion with $f_r = \mu_r n$.
- Graphically:



STOP TO THINK 6.3 Rank in order, from largest to smallest, the sizes of the friction forces \vec{f}_a to \vec{f}_e in these 5 different situations. The box and the floor are made of the same materials in all situations.



EXAMPLE 6.5 How far does a box slide?

Carol pushes a 25 kg wood box across a wood floor at a steady speed of 2.0 m/s. How much force does Carol exert on the box? If she stops pushing, how far will the box slide before coming to rest?

MODEL This situation can be modeled as dynamics with constant force—one of the forces being friction. Notice that this is a two-part problem: first while Carol is pushing the box, then as it slides after she releases it.

VISUALIZE This is a fairly complex situation, one that calls for careful visualization. **FIGURE 6.15** shows the pictorial representation both while Carol pushes, when $\vec{a} = \vec{0}$, and after she stops. We've placed $x = 0$ at the point where she stops pushing because this is the point where the kinematics calculation for How far? will begin. Notice that each part of the motion needs its own free-body diagram. The box is moving until the very instant that the problem ends, so only kinetic friction is relevant.

SOLVE We'll start by finding how hard Carol has to push to keep the box moving at a steady speed. The box is in equilibrium (constant velocity, $\vec{a} = \vec{0}$), and Newton's second law is

$$\begin{aligned}\sum F_x &= F_{\text{push}} - f_k = 0 \\ \sum F_y &= n - F_G = n - mg = 0\end{aligned}$$

where we've used $F_G = mg$ for the gravitational force. The negative sign occurs in the first equation because \vec{f}_k points to the left and thus the *component* is negative: $(f_k)_x = -f_k$. Similarly, $(F_G)_y = -F_G$ because the gravitational force vector—with magnitude mg —points down. In addition to Newton's laws, we also have our model of kinetic friction:

$$f_k = \mu_k n$$

Altogether we have three simultaneous equations in the three unknowns F_{push} , f_k , and n . Fortunately, these equations are easy to solve. The y -component of Newton's second law tells us that $n = mg$. We can then find the friction force to be

$$f_k = \mu_k mg$$

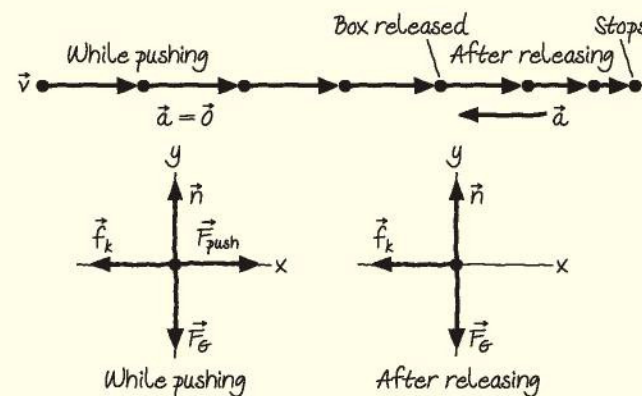
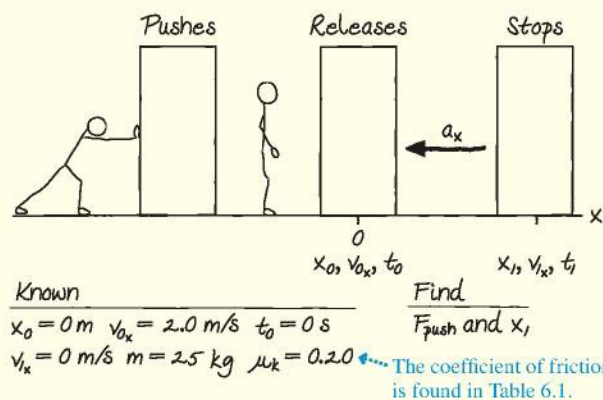
We substitute this into the x -component of the second law, giving

$$\begin{aligned}F_{\text{push}} &= f_k = \mu_k mg \\ &= (0.20)(25 \text{ kg})(9.80 \text{ m/s}^2) = 49 \text{ N}\end{aligned}$$

Carol pushes this hard to keep the box moving at a steady speed.

The box is not in equilibrium after Carol stops pushing it. Our strategy for the second half of the problem is to use Newton's second law to find the acceleration, then use constant-acceleration kinematics to find how far the box moves before stopping. We know

FIGURE 6.15 Pictorial representation of a box sliding across a floor.



Continued

from the motion diagram that $a_y = 0$. Newton's second law, applied to the second free-body diagram of Figure 6.15, is

$$\begin{aligned}\sum F_x &= -f_k = ma_x \\ \sum F_y &= n - mg = ma_y = 0\end{aligned}$$

We also have our model of friction,

$$f_k = \mu_k n$$

We see from the y -component equation that $n = mg$, and thus $f_k = \mu_k mg$. Using this in the x -component equation gives

$$ma_x = -f_k = -\mu_k mg$$

This is easily solved to find the box's acceleration:

$$a_x = -\mu_k g = -(0.20)(9.80 \text{ m/s}^2) = -1.96 \text{ m/s}^2$$

The acceleration component a_x is negative because the acceleration vector \vec{a} points to the left, as we see from the motion diagram.

Now we are left with a problem of constant-acceleration kinematics. We are interested in a distance, rather than a time interval, so the easiest way to proceed is

$$v_{1x}^2 = 0 = v_{0x}^2 + 2a_x \Delta x = v_{0x}^2 + 2a_x x_1$$

from which the distance that the box slides is

$$x_1 = \frac{-v_{0x}^2}{2a_x} = \frac{-(2.0 \text{ m/s})^2}{2(-1.96 \text{ m/s}^2)} = 1.0 \text{ m}$$

ASSESS Carol was pushing at $2 \text{ m/s} \approx 4 \text{ mph}$, which is fairly fast. The box slides 1.0 m , which is slightly over 3 feet. That sounds reasonable.

NOTE Example 6.5 needed both the horizontal and the vertical components of the second law even though the motion was entirely horizontal. This need is typical when friction is involved because we must find the normal force before we can evaluate the friction force.

EXAMPLE 6.6 Dumping a file cabinet

A 50 kg steel file cabinet is in the back of a dump truck. The truck's bed, also made of steel, is slowly tilted. What is the size of the static friction force on the cabinet when the bed is tilted 20° ? At what angle will the file cabinet begin to slide?

MODEL Model the file cabinet as a particle in equilibrium. We'll also use the model of static friction. The file cabinet will slip when the static friction force reaches its maximum value $f_{s \text{ max}}$.

VISUALIZE FIGURE 6.16 shows the pictorial representation when the truck bed is tilted at angle θ . We can make the analysis easier if we tilt the coordinate system to match the bed of the truck.

SOLVE The file cabinet is in equilibrium. Newton's second law is

$$\begin{aligned}(F_{\text{net}})_x &= \sum F_x = n_x + (F_G)_x + (f_s)_x = 0 \\ (F_{\text{net}})_y &= \sum F_y = n_y + (F_G)_y + (f_s)_y = 0\end{aligned}$$

From the free-body diagram we see that f_s has only a *negative* x -component and that n has only a positive y -component. The gravitational force vector can be written $\vec{F}_G = +F_G \sin \theta \hat{i} - F_G \cos \theta \hat{j}$,

so \vec{F}_G has both x - and y -components in this coordinate system. Thus the second law becomes

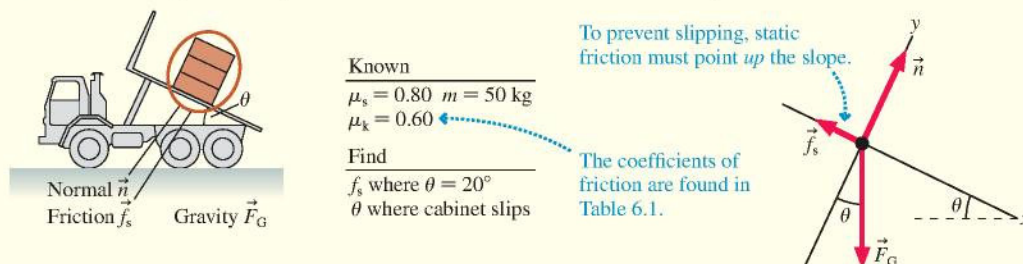
$$\begin{aligned}\sum F_x &= F_G \sin \theta - f_s = mg \sin \theta - f_s = 0 \\ \sum F_y &= n - F_G \cos \theta = n - mg \cos \theta = 0\end{aligned}$$

where we've used $F_G = mg$.

You might be tempted to solve the y -component equation for n , then to use Equation 6.12 to calculate the static friction force as $\mu_s n$. **But Equation 6.12 does not say $f_s = \mu_s n$.** Equation 6.12 gives only the maximum possible static friction force $f_{s \text{ max}}$, the point at which the object slips. In nearly all situations, the actual static friction force is less than $f_{s \text{ max}}$. In this problem, we can use the x -component equation—which tells us that static friction has to exactly balance the component of the gravitational force along the incline—to find the size of the static friction force:

$$\begin{aligned}f_s &= mg \sin \theta = (50 \text{ kg})(9.80 \text{ m/s}^2) \sin 20^\circ \\ &= 170 \text{ N}\end{aligned}$$

FIGURE 6.16 The pictorial representation of a file cabinet in a tilted dump truck.



Slipping occurs when the static friction reaches its maximum value

$$f_s = f_{s \max} = \mu_s n$$

From the y -component of Newton's law we see that $n = mg \cos \theta$. Consequently,

$$f_{s \max} = \mu_s mg \cos \theta$$

Substituting this into the x -component of the first law gives

$$mg \sin \theta - \mu_s mg \cos \theta = 0$$

The mg in both terms cancels, and we find

$$\frac{\sin \theta}{\cos \theta} = \tan \theta = \mu_s$$

$$\theta = \tan^{-1} \mu_s = \tan^{-1}(0.80) = 39^\circ$$

ASSESS Steel doesn't slide all that well on unlubricated steel, so a fairly large angle is not surprising. The answer seems reasonable.

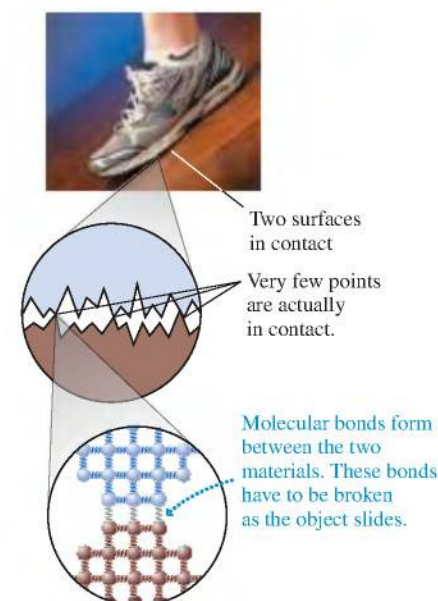
NOTE A common error is to use simply $n = mg$. Be sure to evaluate the normal force within the context of each specific problem. In this example, $n = mg \cos \theta$.

Causes of Friction

It is worth a brief pause to look at the *causes* of friction. All surfaces, even those quite smooth to the touch, are very rough on a microscopic scale. When two objects are placed in contact, they do not make a smooth fit. Instead, as **FIGURE 6.17** shows, the high points on one surface become jammed against the high points on the other surface, while the low points are not in contact at all. The amount of contact depends on how hard the surfaces are pushed together, which is why friction forces are proportional to n .

At the points of actual contact, the atoms in the two materials are pressed closely together and molecular bonds are established between them. These bonds are the “cause” of the static friction force. For an object to slip, you must push it hard enough to break these molecular bonds between the surfaces. Once they are broken, and the two surfaces are sliding against each other, there are still attractive forces between the atoms on the opposing surfaces as the high points of the materials push past each other. However, the atoms move past each other so quickly that they do not have time to establish the tight bonds of static friction. That is why the kinetic friction force is smaller. Friction can be minimized with lubrication, a very thin film of liquid between the surfaces that allows them to “float” past each other with many fewer points in actual contact.

FIGURE 6.17 An atomic-level view of friction.



6.5 Drag

The air exerts a drag force on objects as they move through the air. You experience drag forces every day as you jog, bicycle, ski, or drive your car. The drag force \vec{F}_{drag}

- Is opposite in direction to \vec{v} .
- Increases in magnitude as the object's speed increases.

FIGURE 6.18 illustrates the drag force.

Drag is a more complex force than ordinary friction because drag depends on the object's speed. Drag also depends on the object's shape and on the density of the medium through which it moves. Fortunately, we can use a fairly simple *model* of drag if the following three conditions are met:

- The object is moving through the air near the earth's surface.
- The object's size (diameter) is between a few millimeters and a few meters.
- The object's speed is less than a few hundred meters per second.

These conditions are usually satisfied for balls, people, cars, and many other objects in our everyday world. Under these conditions, the drag force on an object moving with speed v can be written

$$\vec{F}_{\text{drag}} = \left(\frac{1}{2} C \rho A v^2, \text{ direction opposite the motion} \right) \quad (6.15)$$

FIGURE 6.18 The drag force on a high-speed motorcyclist is significant.



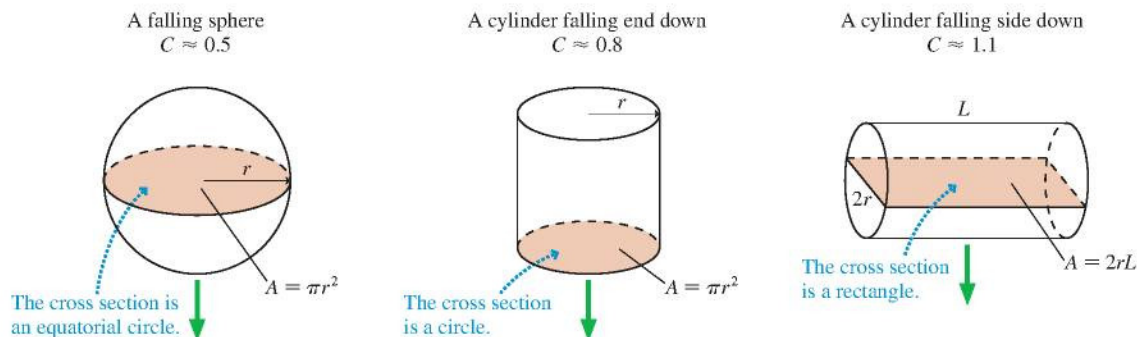
The symbols in Equation 6.15 are:

- A is the *cross-section area* of the object as it “faces into the wind,” as illustrated in **FIGURE 6.19**.
- ρ is the density of the air, which is 1.3 kg/m^3 at atmospheric pressure and 0°C , a common reference point of pressure and temperature.
- C is the **drag coefficient**. It is smaller for aerodynamically shaped objects, larger for objects presenting a flat face to the wind. Figure 6.19 gives approximate values for a sphere and two cylinders. C is dimensionless; it has no units.

Notice that the drag force is proportional to the *square* of the object’s speed. So drag is *not* a constant force (unless v is constant) and you cannot use constant-acceleration kinematics.

This model of drag fails for objects that are very small (such as dust particles), very fast (such as bullets), or that move in liquids (such as water). Motion in a liquid will be considered in Challenge Problems 6.76 and 6.77, but otherwise we’ll leave these situations to more advanced textbooks.

FIGURE 6.19 Cross-section areas for objects of different shape.



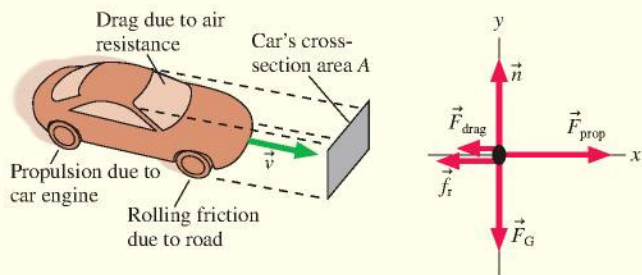
EXAMPLE 6.7 Air resistance compared to rolling friction

The profile of a typical 1500 kg passenger car, as seen from the front, is 1.6 m wide and 1.4 m high. Aerodynamic body shaping gives a drag coefficient of 0.35. At what speed does the magnitude of the drag equal the magnitude of the rolling friction?

MODEL Model the car as a particle. Use the models of rolling friction and drag. Note that this is *not* a constant-force situation.

VISUALIZE **FIGURE 6.20** shows the car and a free-body diagram. A full pictorial representation is not needed because we won’t be doing any kinematics calculations.

FIGURE 6.20 A car experiences both rolling friction and drag.



SOLVE Drag is less than friction at low speeds, where air resistance is negligible. But drag increases as v increases, so there will be a speed at which the two forces are equal in size. Above this speed, drag is more important than rolling friction.

There’s no motion and no acceleration in the vertical direction, so we can see from the free-body diagram that $n = F_G = mg$. Thus $f_r = \mu_r mg$. Equating friction and drag, we have

$$\frac{1}{2} C \rho A v^2 = \mu_r mg$$

Solving for v , we find

$$v = \sqrt{\frac{2\mu_r mg}{C\rho A}} = \sqrt{\frac{2(0.02)(1500 \text{ kg})(9.80 \text{ m/s}^2)}{(0.35)(1.3 \text{ kg/m}^3)(1.4 \text{ m} \times 1.6 \text{ m})}} = 24 \text{ m/s}$$

where the value of μ_r for rubber on concrete was taken from Table 6.1.

ASSESS 24 m/s is approximately 50 mph, a reasonable result. This calculation shows that we can reasonably ignore air resistance for car speeds less than 30 or 40 mph. Calculations that neglect drag will be increasingly inaccurate as speeds go above 50 mph.

Terminal Speed

The drag force increases as an object falls and gains speed. If the object falls far enough, it will eventually reach a speed, shown in FIGURE 6.21, at which $F_{\text{drag}} = F_G$. That is, the drag force will be equal and opposite to the gravitational force. The net force at this speed is $\vec{F}_{\text{net}} = \vec{0}$, so there is no further acceleration and the object falls with a *constant* speed. The speed at which the exact balance between the upward drag force and the downward gravitational force causes an object to fall without acceleration is called the **terminal speed** v_{term} . Once an object has reached terminal speed, it will continue falling at that speed until it hits the ground.

It's not hard to compute the terminal speed. It is the speed, by definition, at which $F_{\text{drag}} = F_G$ or, equivalently, $\frac{1}{2}C\rho Av^2 = mg$. This speed is

$$v_{\text{term}} = \sqrt{\frac{2mg}{C\rho A}} \quad (6.16)$$

A more massive object has a larger terminal speed than a less massive object of equal size and shape. A 10-cm-diameter lead ball, with a mass of 6 kg, has a terminal speed of 160 m/s, while a 10-cm-diameter Styrofoam ball, with a mass of 50 g, has a terminal speed of only 15 m/s.

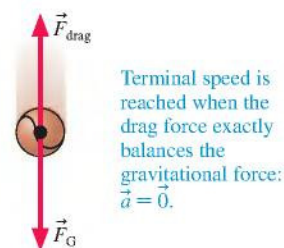
A popular use of Equation 6.16 is to find the terminal speed of a skydiver. A skydiver is rather like the cylinder of Figure 6.19 falling “side down,” for which we see that $C \approx 1.1$. A typical skydiver is 1.8 m long and 0.40 m wide ($A = 0.72 \text{ m}^2$) and has a mass of 75 kg. His terminal speed is

$$v_{\text{term}} = \sqrt{\frac{2mg}{C\rho A}} = \sqrt{\frac{2(75 \text{ kg})(9.8 \text{ m/s}^2)}{(1.1)(1.3 \text{ kg/m}^3)(0.72 \text{ m}^2)}} = 38 \text{ m/s}$$

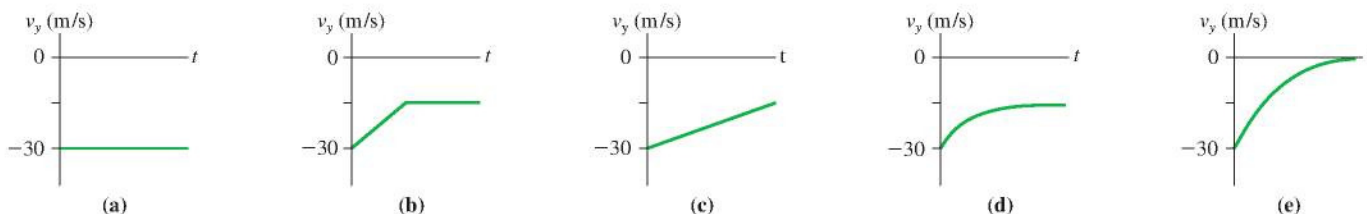
This is roughly 90 mph. A higher speed can be reached by falling feet first or head first, which reduces the area A and the drag coefficient.

Although we've focused our analysis on objects moving vertically, the same ideas apply to objects moving horizontally. If an object is thrown or shot horizontally, \vec{F}_{drag} causes the object to slow down. An airplane reaches its maximum speed, which is analogous to the terminal speed, when the drag is equal and opposite to the thrust: $F_{\text{drag}} = F_{\text{thrust}}$. The net force is then zero and the plane cannot go any faster. The maximum speed of a passenger jet is about 550 mph.

FIGURE 6.21 An object falling at terminal speed.



STOP TO THINK 6.4 The terminal speed of a Styrofoam ball is 15 m/s. Suppose a Styrofoam ball is shot straight down from a high tower with an initial speed of 30 m/s. Which velocity graph is correct?



6.6 More Examples of Newton's Second Law

We will finish this chapter with four additional examples in which we use the problem-solving strategy in more complex scenarios.

EXAMPLE 6.8 Stopping distances

A 1500 kg car is traveling at a speed of 30 m/s when the driver slams on the brakes and skids to a halt. Determine the stopping distance if the car is traveling up a 10° slope, down a 10° slope, or on a level road.

MODEL Model the car's motion as dynamics with constant force and use the model of kinetic friction. We want to solve the problem only once, not three separate times, so we'll leave the slope angle θ unspecified until the end.

VISUALIZE FIGURE 6.22 shows the pictorial representation. We've shown the car sliding uphill, but these representations work equally well for a level or downhill slide if we let θ be zero or negative, respectively. We've used a tilted coordinate system so that the motion is along one of the axes. We've *assumed* that the car is traveling to the right, although the problem didn't state this. You could equally well make the opposite assumption, but you would have to be careful with negative values of x and v_x . The car *skids* to a halt, so we've taken the coefficient of *kinetic* friction for rubber on concrete from Table 6.1.

SOLVE Newton's second law and the model of kinetic friction are

$$\begin{aligned}\sum F_x &= n_x + (F_G)_x + (f_k)_x \\ &= -mg \sin \theta - f_k = ma_x \\ \sum F_y &= n_y + (F_G)_y + (f_k)_y \\ &= n - mg \cos \theta = ma_y = 0 \\ f_k &= \mu_k n\end{aligned}$$

We've written these equations by "reading" the motion diagram and the free-body diagram. Notice that both components of the gravitational force vector \vec{F}_G are negative. $a_y = 0$ because the motion is entirely along the x -axis.

The second equation gives $n = mg \cos \theta$. Using this in the friction model, we find $f_k = \mu_k mg \cos \theta$. Inserting this result back into the first equation then gives

$$\begin{aligned}ma_x &= -mg \sin \theta - \mu_k mg \cos \theta \\ &= -mg(\sin \theta + \mu_k \cos \theta) \\ a_x &= -g(\sin \theta + \mu_k \cos \theta)\end{aligned}$$

This is a constant acceleration. Constant-acceleration kinematics gives

$$v_{1x}^2 = 0 = v_{0x}^2 + 2a_x(x_1 - x_0) = v_{0x}^2 + 2a_x x_1$$

which we can solve for the stopping distance x_1 :

$$x_1 = -\frac{v_{0x}^2}{2a_x} = \frac{v_{0x}^2}{2g(\sin \theta + \mu_k \cos \theta)}$$

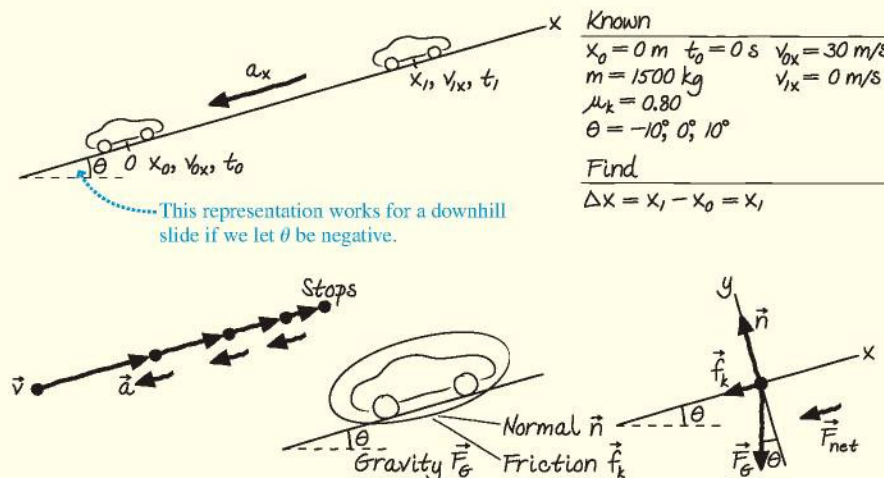
Notice how the minus sign in the expression for a_x canceled the minus sign in the expression for x_1 . Evaluating our result at the three different angles gives the stopping distances:

$$x_1 = \begin{cases} 48 \text{ m} & \theta = 10^\circ & \text{uphill} \\ 57 \text{ m} & \theta = 0^\circ & \text{level} \\ 75 \text{ m} & \theta = -10^\circ & \text{downhill} \end{cases}$$

The implications are clear about the danger of driving downhill too fast!

ASSESS 30 m/s \approx 60 mph and 57 m \approx 180 feet on a level surface. This is similar to the stopping distances you learned when you got your driver's license, so the results seem reasonable. Additional confirmation comes from noting that the expression for a_x becomes $-g \sin \theta$ if $\mu_k = 0$. This is what you learned in Chapter 2 for the acceleration on a frictionless inclined plane.

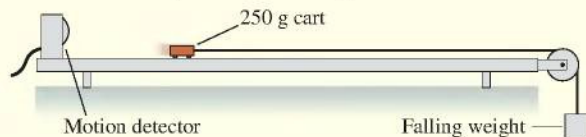
FIGURE 6.22 Pictorial representation of a skidding car.



EXAMPLE 6.9 Measuring the tension pulling a cart

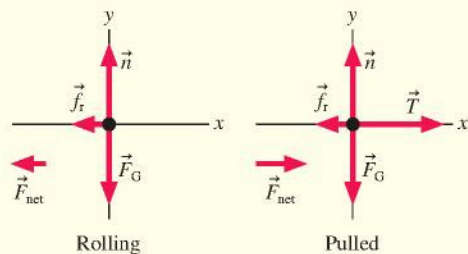
Your instructor has set up a lecture demonstration in which a 250 g cart can roll along a level, 2.00-m-long track while its velocity is measured with a motion detector. First, the instructor simply gives the cart a push and measures its velocity as it rolls down the track. The data below show that the cart slows slightly before reaching the end of the track. Then, as **FIGURE 6.23** shows, the instructor attaches a string to the cart and uses a falling weight to pull the cart. She then asks you to determine the tension in the string. For extra credit, find the coefficient of rolling friction.

Time (s)	Rolled velocity (m/s)	Pulled velocity (m/s)
0.00	1.20	0.00
0.25	1.17	0.36
0.50	1.15	0.80
0.75	1.12	1.21
1.00	1.08	1.52
1.25	1.04	1.93
1.50	1.02	2.33

FIGURE 6.23 The experimental arrangement.

MODEL Model the cart as a particle acted on by constant forces.

VISUALIZE The cart changes velocity—it accelerates—when both pulled and rolled. Consequently, there must be a net force for both motions. For rolling, force identification finds that the only horizontal force is rolling friction, a force that opposes the motion and slows the cart. There is no “force of motion” or “force of the hand” because the hand is no longer in contact with the cart. (Recall Newton’s “zeroth law”: The cart responds only to forces applied *at this instant*.) Pulling adds a tension force in the direction of motion. The two free-body diagrams are shown in **FIGURE 6.24**.

FIGURE 6.24 Pictorial representations of the cart.

SOLVE The cart’s acceleration when pulled, which we can find from the velocity data, will allow us to find the net force. Isolating the tension force will require knowing the friction force, but we can determine that from the rolling motion. For the rolling motion, Newton’s second law can be written by “reading” the free-body diagram on the left:

$$\begin{aligned}\sum F_x &= (f_r)_x = -f_r = ma_x = ma_{\text{roll}} \\ \sum F_y &= n_y + (F_G)_y = n - mg = 0\end{aligned}$$

Make sure you understand where the signs come from and how we used our knowledge that \vec{a} has only an x -component, which we called a_{roll} . The magnitude of the friction force, which is all we’ll need to determine the tension, is found from the x -component equation:

$$f_r = -ma_{\text{roll}} = -m \times \text{slope of the rolling-velocity graph}$$

But we’ll need to do a bit more analysis to get the coefficient of rolling friction. The y -component equation tells us that $n = mg$. Using this in the model of rolling friction, $f_r = \mu_r n = \mu_r mg$, we see that the coefficient of rolling friction is

$$\mu_r = \frac{f_r}{mg}$$

The x -component equation of Newton’s second law when the cart is pulled is

$$\sum F_x = T + (f_r)_x = T - f_r = ma_x = ma_{\text{pulled}}$$

Thus the tension that we seek is

$$T = f_r + ma_{\text{pulled}} = f_r + m \times \text{slope of the pulled-velocity graph}$$

FIGURE 6.25 shows the graphs of the velocity data. The accelerations are the slopes of these lines, and from the equations of the best-fit lines we find $a_{\text{roll}} = -0.124 \text{ m/s}^2$ and $a_{\text{pulled}} = 1.55 \text{ m/s}^2$. Thus the friction force is

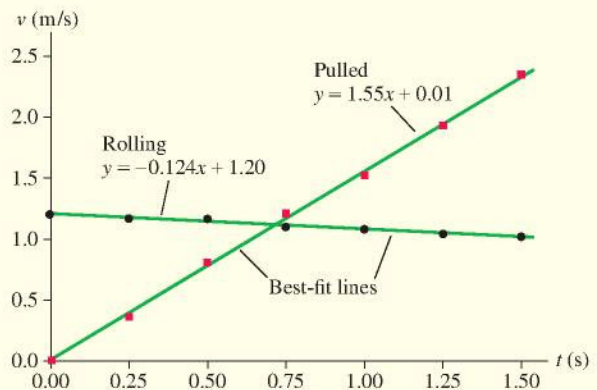
$$f_r = -ma_{\text{roll}} = -(0.25 \text{ kg})(-0.124 \text{ m/s}^2) = 0.031 \text{ N}$$

Knowing this, we find that the string tension pulling the cart is

$$T = f_r + ma_{\text{pulled}} = 0.031 \text{ N} + (0.25 \text{ kg})(1.55 \text{ m/s}^2) = 0.42 \text{ N}$$

and the coefficient of rolling friction is

$$\mu_r = \frac{f_r}{mg} = \frac{0.031 \text{ N}}{(0.25 \text{ kg})(9.80 \text{ m/s}^2)} = 0.013$$

FIGURE 6.25 The velocity graphs of the rolling and pulled motion. The slopes of these graphs are the cart’s acceleration.

ASSESS The coefficient of rolling friction is very small, but it’s similar to the values in Table 6.1 and thus believable. That gives us confidence that our value for the tension is also correct. It’s reasonable that the tension needed to accelerate the cart is small because the cart is light and there’s very little friction.

EXAMPLE 6.10 Make sure the cargo doesn't slide

A 100 kg box of dimensions 50 cm × 50 cm × 50 cm is in the back of a flatbed truck. The coefficients of friction between the box and the bed of the truck are $\mu_s = 0.40$ and $\mu_k = 0.20$. What is the maximum acceleration the truck can have without the box slipping?

MODEL This is a somewhat different problem from any we have looked at thus far. Let the box, which we'll model as a particle, be the object of interest. It contacts other objects only where it touches the truck bed, so only the truck can exert contact forces on the box. If the box does *not* slip, then there is no motion of the box *relative to the truck* and the box must accelerate *with the truck*: $a_{\text{box}} = a_{\text{truck}}$. As the box accelerates, it must, according to Newton's second law, have a net force acting on it. But from what?

Imagine, for a moment, that the truck bed is frictionless. The box would slide backward (as seen in the truck's reference frame) as the truck accelerates. The force that prevents sliding is *static friction*, so the truck must exert a static friction force on the box to "pull" the box along with it and prevent the box from sliding *relative to the truck*.

VISUALIZE This situation is shown in **FIGURE 6.26**. There is only one horizontal force on the box, \vec{f}_s , and it points in the *forward* direction to accelerate the box. Notice that we're solving the problem with the ground as our reference frame. Newton's laws are not valid in the accelerating truck because it is not an inertial reference frame.

SOLVE Newton's second law, which we can "read" from the free-body diagram, is

$$\sum F_x = f_s = ma_x$$

$$\sum F_y = n - F_G = n - mg = ma_y = 0$$

Now, static friction, you will recall, can be *any* value between 0 and $f_{s \text{ max}}$. If the truck accelerates slowly, so that the box doesn't slip, then $f_s < f_{s \text{ max}}$. However, we're interested in the acceleration a_{max} at which the box begins to slip. This is the acceleration at which f_s reaches its maximum possible value

$$f_s = f_{s \text{ max}} = \mu_s n$$

The y-equation of the second law and the friction model combine to give $f_{s \text{ max}} = \mu_s mg$. Substituting this into the x-equation, and noting that a_x is now a_{max} , we find

$$a_{\text{max}} = \frac{f_{s \text{ max}}}{m} = \mu_s g = 3.9 \text{ m/s}^2$$

The truck must keep its acceleration less than 3.9 m/s^2 if slipping is to be avoided.

ASSESS 3.9 m/s^2 is about one-third of g . You may have noticed that items in a car or truck are likely to *tip over* when you start or stop, but they slide only if you really floor it and accelerate very quickly. So this answer seems reasonable. Notice that neither the dimensions of the crate nor μ_k was needed. Real-world situations rarely have exactly the information you need, no more and no less. Many problems in this textbook will require you to assess the information in the problem statement in order to learn which is relevant to the solution.

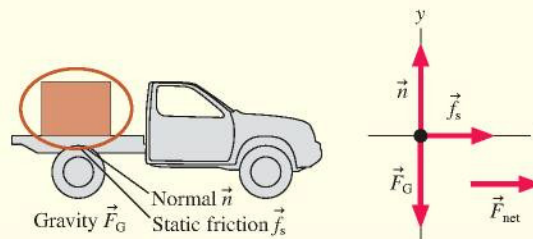
FIGURE 6.26 Pictorial representation for the box in a flatbed truck.

Known

$m = 100 \text{ kg}$
Box dimensions 50 cm × 50 cm × 50 cm
 $\mu_s = 0.40$ $\mu_k = 0.20$

Find

Acceleration at which box slips



The mathematical representation of this last example was quite straightforward. The challenge was in the analysis that preceded the mathematics—that is, in the *physics* of the problem rather than the mathematics. It is here that our analysis tools—motion diagrams, force identification, and free-body diagrams—prove their value.

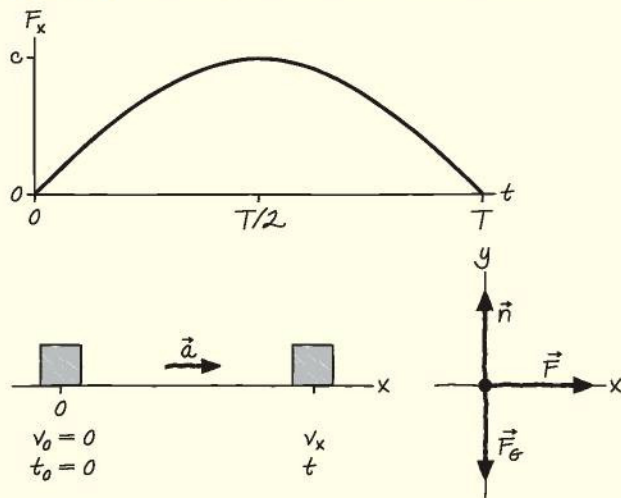
CHALLENGE EXAMPLE 6.11 Acceleration from a variable force

Force $F_x = c \sin(\pi t/T)$, where c and T are constants, is applied to an object of mass m that moves on a horizontal, frictionless surface. The object is at rest at the origin at $t = 0$.

- Find an expression for the object's velocity. Graph your result for $0 \leq t \leq T$.
- What is the maximum velocity of a 500 g object if $c = 2.5 \text{ N}$ and $T = 1.0 \text{ s}$?

MODEL Model the object as a particle. But we cannot use the constant-force model or constant-acceleration kinematics.

VISUALIZE The sine function is 0 at $t = 0$ and again at $t = T$, when the value of the argument is π rad. Over the interval $0 \leq t \leq T$, the force grows from 0 to c and then returns to 0, always pointing in the positive x -direction. **FIGURE 6.27** shows a graph of the force and a pictorial representation.

FIGURE 6.27 Pictorial representation for a variable force.


SOLVE The object's acceleration increases between 0 and $T/2$ as the force increases. You might expect the object to slow down between $T/2$ and T as the force decreases. However, *there's still a net force in the positive x -direction, so there must be an acceleration in the positive x -direction.* The object continues to speed up, only more slowly as the acceleration decreases. Maximum velocity is reached at $t = T$.

a. This is not constant-acceleration motion, so we cannot use the familiar equations of constant-acceleration kinematics. Instead, we must use the definition of acceleration as the rate of change—the time derivative—of velocity. With no friction, we need only the x -component equation of Newton's second law:

$$a_x = \frac{dv_x}{dt} = \frac{F_{\text{net}}}{m} = \frac{c}{m} \sin\left(\frac{\pi t}{T}\right)$$

First we rewrite this as

$$dv_x = \frac{c}{m} \sin\left(\frac{\pi t}{T}\right) dt$$

Then we integrate both sides from the initial conditions ($v_x = v_{0x} = 0$ at $t = t_0 = 0$) to the final conditions (v_x at the later time t):

$$\int_0^{v_x} dv_x = \frac{c}{m} \int_0^t \sin\left(\frac{\pi t}{T}\right) dt$$

The fraction c/m is a constant that we could take outside the integral. The integral on the right side is of the form

$$\int \sin(bx) dx = -\frac{1}{b} \cos(bx)$$

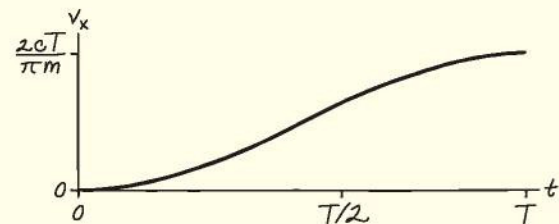
Using this, and integrating both sides of the equation, we find

$$v_x \Big|_0^{v_x} = v_x - 0 = -\frac{cT}{\pi m} \cos\left(\frac{\pi t}{T}\right) \Big|_0^t = -\frac{cT}{\pi m} \left(\cos\left(\frac{\pi t}{T}\right) - 1 \right)$$

Simplifying, we find the object's velocity at time t is

$$v_x = \frac{cT}{\pi m} \left(1 - \cos\left(\frac{\pi t}{T}\right) \right)$$

This expression is graphed in **FIGURE 6.28**, where we see that, as predicted, maximum velocity is reached at $t = T$.

FIGURE 6.28 The object's velocity as a function of time.


b. Maximum velocity, at $t = T$, is

$$v_{\text{max}} = \frac{cT}{\pi m} (1 - \cos \pi) = \frac{2cT}{\pi m} = \frac{2(2.5 \text{ N})(1.0 \text{ s})}{\pi(0.50 \text{ kg})} = 3.2 \text{ m/s}$$

ASSESS A steady 2.5 N force would cause a 0.5 kg object to accelerate at 5 m/s^2 and reach a speed of 5 m/s in 1 s. A variable force with a maximum of 2.5 N will produce less acceleration, so a top speed of 3.2 m/s seems reasonable.

SUMMARY

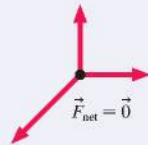
The goal of Chapter 6 has been to learn to solve linear force-and-motion problems.

GENERAL PRINCIPLES

Two Explanatory Models

An object on which there is no net force is in **mechanical equilibrium**.

- Objects at rest.
- Objects moving with constant velocity.
- Newton's second law applies with $\vec{a} = \vec{0}$.



An object on which the net force is constant undergoes **dynamics with constant force**.

- The object accelerates.
- The kinematic model is that of constant acceleration.
- Newton's second law applies.



Go back and forth between these steps as needed.

A Problem-Solving Strategy

A four-part strategy applies to both equilibrium and dynamics problems.

MODEL Make simplifying assumptions.

VISUALIZE

- Translate words into symbols.
- Draw a sketch to define the situation.
- Draw a motion diagram.
- Identify forces.
- Draw a free-body diagram.

SOLVE Use Newton's second law:

$$\vec{F}_{\text{net}} = \sum_i \vec{F}_i = m\vec{a}$$

“Read” the vectors from the free-body diagram. Use kinematics to find velocities and positions.

ASSESS Is the result reasonable? Does it have correct units and significant figures?

IMPORTANT CONCEPTS

Specific information about three important descriptive models:

Gravity $\vec{F}_G = (mg, \text{downward})$

Friction $\vec{f}_s = (0 \text{ to } \mu_s n, \text{direction as necessary to prevent motion})$

$\vec{f}_k = (\mu_k n, \text{direction opposite the motion})$

$\vec{f}_r = (\mu_r n, \text{direction opposite the motion})$

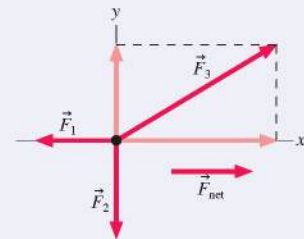
Drag $\vec{F}_{\text{drag}} = (\frac{1}{2} C \rho A v^2, \text{direction opposite the motion})$

Newton's laws are vector expressions. You must write them out by **components**:

$$(F_{\text{net}})_x = \sum F_x = ma_x$$

$$(F_{\text{net}})_y = \sum F_y = ma_y$$

The acceleration is zero in equilibrium and also along an axis perpendicular to the motion.



APPLICATIONS

Mass is an intrinsic property of an object that describes the object's inertia and, loosely speaking, its quantity of matter.

The **weight** of an object is the reading of a spring scale when the object is at rest relative to the scale. Weight is the result of weighing. An object's weight depends on its mass, its acceleration, and the strength of gravity. An object in free fall is weightless.

A falling object reaches **terminal speed**

$$v_{\text{term}} = \sqrt{\frac{2mg}{C\rho A}}$$



Terminal speed is reached when the drag force exactly balances the gravitational force: $\vec{a} = \vec{0}$.

TERMS AND NOTATION

equilibrium model
constant-force model
flat-earth approximation

weight
coefficient of static friction, μ_s
coefficient of kinetic friction, μ_k

rolling friction
coefficient of rolling friction, μ_r

drag coefficient, C
terminal speed, v_{term}

CONCEPTUAL QUESTIONS

- Are the objects described here in equilibrium while at rest, in equilibrium while in motion, or not in equilibrium at all? Explain.
 - A 200 pound barbell is held over your head.
 - A girder is lifted at constant speed by a crane.
 - A girder is being lowered into place. It is slowing down.
 - A jet plane has reached its cruising speed and altitude.
 - A box in the back of a truck doesn't slide as the truck stops.
- A ball tossed straight up has $v = 0$ at its highest point. Is it in equilibrium? Explain.
- Kat, Matt, and Nat are arguing about why a physics book on a table doesn't fall. According to Kat, "Gravity pulls down on it, but the table is in the way so it can't fall." "Nonsense," says Matt. "An upward force simply overcomes the downward force to prevent it from falling." "But what about Newton's first law?" counters Nat. "It's not moving, so there can't be any forces acting on it." None of the statements is exactly correct. Who comes closest, and how would you change his or her statement to make it correct?
- If you know all of the forces acting on a moving object, can you tell the direction the object is moving? If yes, explain how. If no, give an example.
- An elevator, hanging from a single cable, moves upward at constant speed. Friction and air resistance are negligible. Is the tension in the cable greater than, less than, or equal to the gravitational force on the elevator? Explain. Include a free-body diagram as part of your explanation.
- An elevator, hanging from a single cable, moves downward and is slowing. Friction and air resistance are negligible. Is the tension in the cable greater than, less than, or equal to the gravitational force on the elevator? Explain. Include a free-body diagram as part of your explanation.
- Are the following statements true or false? Explain.
 - The mass of an object depends on its location.
 - The weight of an object depends on its location.
 - Mass and weight describe the same thing in different units.
- An astronaut takes his bathroom scale to the moon and then stands on it. Is the reading of the scale his weight? Explain.
- The four balls in **FIGURE Q6.9** have been thrown straight up. They have the same size, but different masses. Air resistance is negligible. Rank in order, from largest to smallest, the magnitude of the net force acting on each ball. Some may be equal. Give your answer in the form $a > b > c = d$ and explain your ranking.

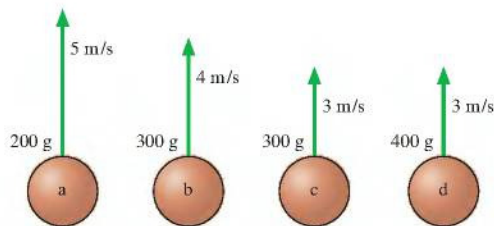


FIGURE Q6.9

- Suppose you attempt to pour out 100 g of salt, using a pan balance for measurements, while in a rocket accelerating upward. Will the quantity of salt be too much, too little, or the correct amount? Explain.

- An astronaut orbiting the earth is handed two balls that have identical outward appearances. However, one is hollow while the other is filled with lead. How can the astronaut determine which is which? Cutting or altering the balls is not allowed.
- A hand presses down on the book in **FIGURE Q6.12**. Is the normal force of the table on the book larger than, smaller than, or equal to mg ?

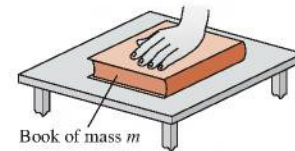


FIGURE Q6.12

- Boxes A and B in **FIGURE Q6.13** both remain at rest. Is the friction force on A larger than, smaller than, or equal to the friction force on B? Explain.

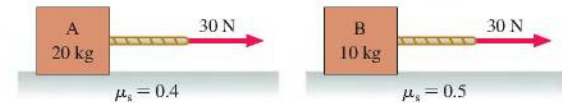


FIGURE Q6.13

- Suppose you push a hockey puck of mass m across frictionless ice for 1.0 s, starting from rest, giving the puck speed v after traveling distance d . If you repeat the experiment with a puck of mass $2m$, pushing with the same force,
 - How long will you have to push for the puck to reach the same speed v ?
 - How long will you have to push for the puck to travel the same distance d ?
- A block pushed along the floor with velocity v_{0x} slides a distance d after the pushing force is removed.
 - If the mass of the block is doubled but its initial velocity is not changed, what distance does the block slide before stopping?
 - If the initial velocity is doubled to $2v_{0x}$ but the mass is not changed, what distance does the block slide before stopping?
- A crate of fragile dishes is in the back of a pickup truck. The truck accelerates north from a stop sign, and the crate moves without slipping. Does the friction force on the crate point north or south? Or is the friction force zero? Explain.
- Five balls move through the air as shown in **FIGURE Q6.17**. All five have the same size and shape. Air resistance is not negligible. Rank in order, from largest to smallest, the magnitudes of the accelerations a_a to a_e . Some may be equal. Give your answer in the form $a > b = c > d > e$ and explain your ranking.

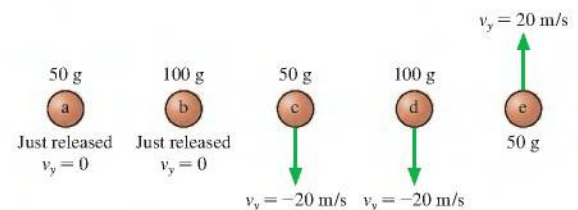


FIGURE Q6.17

EXERCISES AND PROBLEMS

Exercises

Section 6.1 The Equilibrium Model

1. || The three ropes in **FIGURE EX6.1** are tied to a small, very light ring. Two of these ropes are anchored to walls at right angles with the tensions shown in the figure. What are the magnitude and direction of the tension \vec{T}_3 in the third rope?

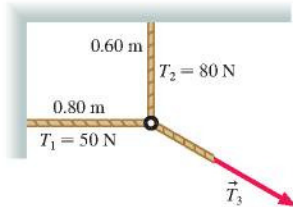


FIGURE EX6.1

2. | The three ropes in **FIGURE EX6.2** are tied to a small, very light ring. Two of the ropes are anchored to walls at right angles, and the third rope pulls as shown. What are T_1 and T_2 , the magnitudes of the tension forces in the first two ropes?

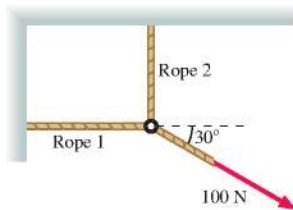


FIGURE EX6.2

3. | A football coach sits on a sled while two of his players build their strength by dragging the sled across the field with ropes. The friction force on the sled is 1000 N, the players have equal pulls, and the angle between the two ropes is 20° . How hard must each player pull to drag the coach at a steady 2.0 m/s?
4. || A 20 kg loudspeaker is suspended 2.0 m below the ceiling by two 3.0-m-long cables that angle outward at equal angles. What is the tension in the cables?
5. | A 65 kg gymnast wedges himself between two closely spaced vertical walls by pressing his hands and feet against the walls. What is the magnitude of the friction force on each hand and foot? Assume they are all equal.
6. || A construction worker with a weight of 850 N stands on a roof that is sloped at 20° . What is the magnitude of the normal force of the roof on the worker?
7. || In an electricity experiment, a 1.0 g plastic ball is suspended on a 60-cm-long string and given an electric charge. A charged rod brought near the ball exerts a horizontal electrical force \vec{F}_{elec} on it, causing the ball to swing out to a 20° angle and remain there.
- What is the magnitude of \vec{F}_{elec} ?
 - What is the tension in the string?

Section 6.2 Using Newton's Second Law

8. | The forces in **FIGURE EX6.8** act on a 2.0 kg object. What are the values of a_x and a_y , the x - and y -components of the object's acceleration?

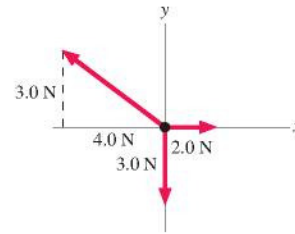


FIGURE EX6.8

9. | The forces in **FIGURE EX6.9** act on a 2.0 kg object. What are the values of a_x and a_y , the x - and y -components of the object's acceleration?

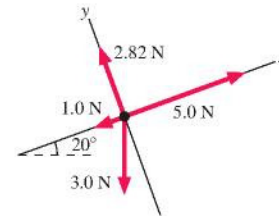


FIGURE EX6.9

10. | **FIGURE EX6.10** shows the velocity graph of a 2.0 kg object as it moves along the x -axis. What is the net force acting on this object at $t = 1$ s? At 4 s? At 7 s?

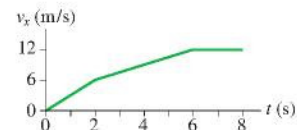


FIGURE EX6.10

11. || **FIGURE EX6.11** shows the force acting on a 2.0 kg object as it moves along the x -axis. The object is at rest at the origin at $t = 0$ s. What are its acceleration and velocity at $t = 6$ s?

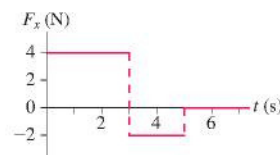


FIGURE EX6.11

12. | A horizontal rope is tied to a 50 kg box on frictionless ice. What is the tension in the rope if:
- The box is at rest?
 - The box moves at a steady 5.0 m/s?
 - The box has $v_x = 5.0$ m/s and $a_x = 5.0$ m/s²?
13. | A 50 kg box hangs from a rope. What is the tension in the rope if:
- The box is at rest?
 - The box moves up at a steady 5.0 m/s?
 - The box has $v_y = 5.0$ m/s and is speeding up at 5.0 m/s²?
 - The box has $v_y = 5.0$ m/s and is slowing down at 5.0 m/s²?

14. I A 2.0×10^7 kg train applies its brakes with the intent of slowing down at a 1.2 m/s^2 rate. What magnitude force must its brakes provide?
15. II A 8.0×10^4 kg spaceship is at rest in deep space. Its thrusters provide a force of 1200 kN. The spaceship fires its thrusters for 20 s, then coasts for 12 km. How long does it take the spaceship to coast this distance?
16. II The position of a 2.0 kg mass is given by $x = (2t^3 - 3t^2) \text{ m}$, where t is in seconds. What is the net horizontal force on the mass at (a) $t = 0 \text{ s}$ and (b) $t = 1 \text{ s}$?

Section 6.3 Mass, Weight, and Gravity

17. I A woman has a mass of 55 kg.
- What is her weight while standing on earth?
 - What are her mass and her weight on Mars, where $g = 3.76 \text{ m/s}^2$?
18. I It takes the elevator in a skyscraper 4.0 s to reach its cruising speed of 10 m/s. A 60 kg passenger gets aboard on the ground floor. What is the passenger's weight
- Before the elevator starts moving?
 - While the elevator is speeding up?
 - After the elevator reaches its cruising speed?
19. II Zach, whose mass is 80 kg, is in an elevator descending at 10 m/s. The elevator takes 3.0 s to brake to a stop at the first floor.
- What is Zach's weight before the elevator starts braking?
 - What is Zach's weight while the elevator is braking?
20. II **FIGURE EX6.20** shows the velocity graph of a 75 kg passenger in an elevator. What is the passenger's weight at $t = 1 \text{ s}$? At 5 s ? At 9 s ?

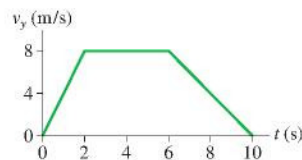


FIGURE EX6.20

21. I What thrust does a 200 g model rocket need in order to have a vertical acceleration of 10 m/s^2
- On earth?
 - On the moon, where $g = 1.62 \text{ m/s}^2$?
22. II A 20,000 kg rocket has a rocket motor that generates $3.0 \times 10^5 \text{ N}$ of thrust. Assume no air resistance.
- What is the rocket's initial upward acceleration?
 - At an altitude of 5000 m the rocket's acceleration has increased to 6.0 m/s^2 . What mass of fuel has it burned?
23. II The earth is $1.50 \times 10^{11} \text{ m}$ from the sun. The earth's mass is $5.98 \times 10^{24} \text{ kg}$, while the mass of the sun is $1.99 \times 10^{30} \text{ kg}$. What is earth's acceleration toward the sun?

Section 6.4 Friction

24. I Bonnie and Clyde are sliding a 300 kg bank safe across the floor to their getaway car. The safe slides with a constant speed if Clyde pushes from behind with 385 N of force while Bonnie pulls forward on a rope with 350 N of force. What is the safe's coefficient of kinetic friction on the bank floor?
25. I A stubborn, 120 kg mule sits down and refuses to move. To drag the mule to the barn, the exasperated farmer ties a rope around the mule and pulls with his maximum force of 800 N. The coefficients of friction between the mule and the ground are $\mu_s = 0.8$ and $\mu_k = 0.5$. Is the farmer able to move the mule?

26. II A 10 kg crate is placed on a horizontal conveyor belt. The materials are such that $\mu_s = 0.5$ and $\mu_k = 0.3$.
- Draw a free-body diagram showing all the forces on the crate if the conveyor belt runs at constant speed.
 - Draw a free-body diagram showing all the forces on the crate if the conveyor belt is speeding up.
 - What is the maximum acceleration the belt can have without the crate slipping?
27. II Bob is pulling a 30 kg filing cabinet with a force of 200 N, but the filing cabinet refuses to move. The coefficient of static friction between the filing cabinet and the floor is 0.80. What is the magnitude of the friction force on the filing cabinet?
28. II A rubber-wheeled 50 kg cart rolls down a 15° concrete incline. What is the cart's acceleration if rolling friction is (a) neglected and (b) included?
29. II A 4000 kg truck is parked on a 15° slope. How big is the friction force on the truck? The coefficient of static friction between the tires and the road is 0.90.
30. I A 1500 kg car skids to a halt on a wet road where $\mu_k = 0.50$. How fast was the car traveling if it leaves 65-m-long skid marks?
31. II A 50,000 kg locomotive is traveling at 10 m/s when its engine and brakes both fail. How far will the locomotive roll before it comes to a stop? Assume the track is level.
32. II You and your friend Peter are putting new shingles on a roof pitched at 25° . You're sitting on the very top of the roof when Peter, who is at the edge of the roof directly below you, 5.0 m away, asks you for the box of nails. Rather than carry the 2.5 kg box of nails down to Peter, you decide to give the box a push and have it slide down to him. If the coefficient of kinetic friction between the box and the roof is 0.55, with what speed should you push the box to have it gently come to rest right at the edge of the roof?
33. II An Airbus A320 jetliner has a takeoff mass of 75,000 kg. It reaches its takeoff speed of 82 m/s (180 mph) in 35 s. What is the thrust of the engines? You can neglect air resistance but not rolling friction.

Section 6.5 Drag

34. II A medium-sized jet has a 3.8-m-diameter fuselage and a loaded mass of 85,000 kg. The drag on an airplane is primarily due to the cylindrical fuselage, and aerodynamic shaping gives it a drag coefficient of 0.37. How much thrust must the jet's engines provide to cruise at 230 m/s at an altitude where the air density is 1.0 kg/m^3 ?
35. III A 75 kg skydiver can be modeled as a rectangular "box" with dimensions 20 cm \times 40 cm \times 180 cm. What is his terminal speed if he falls feet first? Use 0.8 for the drag coefficient.
36. III A 6.5-cm-diameter ball has a terminal speed of 26 m/s. What is the ball's mass?

Problems

37. II A 2.0 kg object initially at rest at the origin is subjected to the time-varying force shown in **FIGURE P6.37**. What is the object's velocity at $t = 4 \text{ s}$?

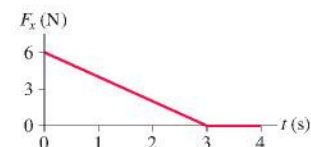


FIGURE P6.37

38. || A 5.0 kg object initially at rest at the origin is subjected to the time-varying force shown in **FIGURE P6.38**. What is the object's velocity at $t = 6$ s?

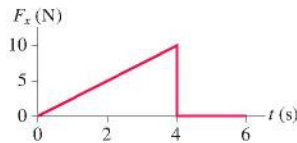


FIGURE P6.38

39. || The 1000 kg steel beam in **FIGURE P6.39** is supported by two ropes. What is the tension in each?

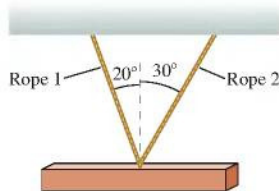


FIGURE P6.39

40. || Henry, whose mass is 95 kg, stands on a bathroom scale in an elevator. The scale reads 830 N for the first 3.0 s after the elevator starts moving, then 930 N for the next 3.0 s. What is the elevator's velocity 6.0 s after starting?

41. || An accident victim with a broken leg is being placed in traction. The patient wears a special boot with a pulley attached to the sole. The foot and boot together have a mass of 4.0 kg, and the doctor has decided to hang a 6.0 kg mass from the rope. The boot is held suspended by the ropes, as shown in **FIGURE P6.41**, and does not touch the bed.

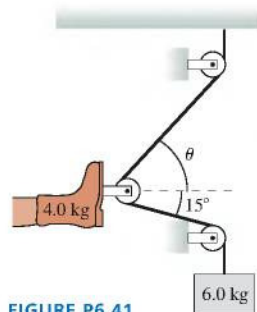


FIGURE P6.41

- a. Determine the amount of tension in the rope by using Newton's laws to analyze the hanging mass.
- b. The net traction force needs to pull straight out on the leg. What is the proper angle θ for the upper rope?
- c. What is the net traction force pulling on the leg?
- Hint:** If the pulleys are frictionless, which we will assume, the tension in the rope is constant from one end to the other.
42. || Seat belts and air bags save lives by reducing the forces exerted on the driver and passengers in an automobile collision. Cars are designed with a "crumple zone" in the front of the car. In the event of an impact, the passenger compartment decelerates over a distance of about 1 m as the front of the car crumples. An occupant restrained by seat belts and air bags decelerates with the car. By contrast, an unrestrained occupant keeps moving forward with no loss of speed (Newton's first law!) until hitting the dashboard or windshield. These are unyielding surfaces, and the unfortunate occupant then decelerates over a distance of only about 5 mm.
- a. A 60 kg person is in a head-on collision. The car's speed at impact is 15 m/s. Estimate the net force on the person if he or she is wearing a seat belt and if the air bag deploys.
- b. Estimate the net force that ultimately stops the person if he or she is not restrained by a seat belt or air bag.

- | | Mass (g) | Speed (m/s) |
|-----|----------|-------------|
| 43. | 200 | 9.4 |
| | 400 | 6.3 |
| | 600 | 5.2 |
| | 800 | 4.9 |
| | 1000 | 4.0 |
43. || The piston of a machine exerts a constant force on a ball as it moves horizontally through a distance of 15 cm. You use a motion detector to measure the speed of five different balls as they come off the piston; the data are shown in the table. Use theory to find two quantities that, when graphed, should give a straight line. Then use the graph to find the size of the piston's force.
44. || Compressed air is used to fire a 50 g ball vertically upward from a 1.0-m-tall tube. The air exerts an upward force of 2.0 N on the ball as long as it is in the tube. How high does the ball go above the top of the tube?
45. || a. A rocket of mass m is launched straight up with thrust \vec{F}_{thrust} . Find an expression for the rocket's speed at height h if air resistance is neglected.
- b. The motor of a 350 g model rocket generates 9.5 N thrust. If air resistance can be neglected, what will be the rocket's speed as it reaches a height of 85 m?
46. || A rifle with a barrel length of 60 cm fires a 10 g bullet with a horizontal speed of 400 m/s. The bullet strikes a block of wood and penetrates to a depth of 12 cm.
- a. What resistive force (assumed to be constant) does the wood exert on the bullet?
- b. How long does it take the bullet to come to rest?
47. || A truck with a heavy load has a total mass of 7500 kg. It is climbing a 15° incline at a steady 15 m/s when, unfortunately, the poorly secured load falls off! Immediately after losing the load, the truck begins to accelerate at 1.5 m/s^2 . What was the mass of the load? Ignore rolling friction.
48. || An object of mass m is at rest at the top of a smooth slope of height h and length L . The coefficient of kinetic friction between the object and the surface, μ_k , is small enough that the object will slide down the slope after being given a very small push to get it started. Find an expression for the object's speed at the bottom of the slope.
49. || Sam, whose mass is 75 kg, takes off across level snow on his jet-powered skis. The skis have a thrust of 200 N and a coefficient of kinetic friction on snow of 0.10. Unfortunately, the skis run out of fuel after only 10 s.
- a. What is Sam's top speed?
- b. How far has Sam traveled when he finally coasts to a stop?
50. || A baggage handler drops your 10 kg suitcase onto a conveyor belt running at 2.0 m/s. The materials are such that $\mu_s = 0.50$ and $\mu_k = 0.30$. How far is your suitcase dragged before it is riding smoothly on the belt?
51. || A 2.0 kg wood block is launched up a wooden ramp that is inclined at a 30° angle. The block's initial speed is 10 m/s.
- a. What vertical height does the block reach above its starting point?
- b. What speed does it have when it slides back down to its starting point?
52. || It's a snowy day and you're pulling a friend along a level road on a sled. You've both been taking physics, so she asks what you think the coefficient of friction between the sled and the snow is. You've been walking at a steady 1.5 m/s, and the rope pulls up on the sled at a 30° angle. You estimate that the mass of the sled, with your friend on it, is 60 kg and that you're pulling with a force of 75 N. What answer will you give?

53. || A large box of mass M is pulled across a horizontal, frictionless surface by a horizontal rope with tension T . A small box of mass m sits on top of the large box. The coefficients of static and kinetic friction between the two boxes are μ_s and μ_k , respectively. Find an expression for the maximum tension T_{\max} for which the small box rides on top of the large box without slipping.
54. || A large box of mass M is moving on a horizontal surface at speed v_0 . A small box of mass m sits on top of the large box. The coefficients of static and kinetic friction between the two boxes are μ_s and μ_k , respectively. Find an expression for the shortest distance d_{\min} in which the large box can stop without the small box slipping.
55. || You're driving along at 25 m/s with your aunt's valuable antiques in the back of your pickup truck when suddenly you see a giant hole in the road 55 m ahead of you. Fortunately, your foot is right beside the brake and your reaction time is zero!
- Can you stop the truck before it falls into the hole?
 - If your answer to part a is yes, can you stop without the antiques sliding and being damaged? Their coefficients of friction are $\mu_s = 0.60$ and $\mu_k = 0.30$.
- Hint:** You're not trying to stop in the shortest possible distance. What's your best strategy for avoiding damage to the antiques?
56. || The 2.0 kg wood box in **FIGURE P6.56** slides down a vertical wood wall while you push on it at a 45° angle. What magnitude of force should you apply to cause the box to slide down at a constant speed?

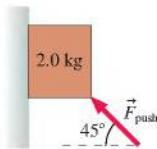


FIGURE P6.56

57. || A 1.0 kg wood block is pressed against a vertical wood wall by the 12 N force shown in **FIGURE P6.57**. If the block is initially at rest, will it move upward, move downward, or stay at rest?

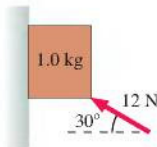


FIGURE P6.57

58. || A person with compromised pinch strength in his fingers can exert a force of only 6.0 N to either side of a pinch-held object, such as the book shown in **FIGURE P6.58**. What is the heaviest book he can hold vertically before it slips out of his fingers? The coefficient of static friction between his fingers and the book cover is 0.80.



FIGURE P6.58

59. || A ball is shot from a compressed-air gun at twice its terminal speed.
- What is the ball's initial acceleration, as a multiple of g , if it is shot straight up?
 - What is the ball's initial acceleration, as a multiple of g , if it is shot straight down?
60. || Starting from rest, a 2500 kg helicopter accelerates straight up at a constant 2.0 m/s^2 . What is the helicopter's height at the moment its blades are providing an upward force of 26 kN? The helicopter can be modeled as a 2.6-m-diameter sphere.

61. || Astronauts in space "weigh" themselves by oscillating on a spring. Suppose the position of an oscillating 75 kg astronaut is given by $x = (0.30 \text{ m}) \sin((\pi \text{ rad/s}) \times t)$, where t is in s. What force does the spring exert on the astronaut at (a) $t = 1.0$ s and (b) 1.5 s? Note that the angle of the sine function is in radians.
62. || A particle of mass m moving along the x -axis experiences the net force $F_x = ct$, where c is a constant. The particle has velocity v_{0x} at $t = 0$. Find an algebraic expression for the particle's velocity v_x at a later time t .
63. || At $t = 0$, an object of mass m is at rest at $x = 0$ on a horizontal, frictionless surface. A horizontal force $F_x = F_0(1 - t/T)$, which decreases from F_0 at $t = 0$ to zero at $t = T$, is exerted on the object. Find an expression for the object's (a) velocity and (b) position at time T .
64. || At $t = 0$, an object of mass m is at rest at $x = 0$ on a horizontal, frictionless surface. Starting at $t = 0$, a horizontal force $F_x = F_0 e^{-t/T}$ is exerted on the object.
- Find and graph an expression for the object's velocity at an arbitrary later time t .
 - What is the object's velocity after a very long time has elapsed?
65. || Large objects have inertia and tend to keep moving—Newton's first law. Life is very different for small microorganisms that swim through water. For them, drag forces are so large that they instantly stop, without coasting, if they cease their swimming motion. To swim at constant speed, they must exert a constant propulsion force by rotating corkscrew-like flagella or beating hair-like cilia. The quadratic model of drag of Equation 6.15 fails for very small particles. Instead, a small object moving in a liquid experiences a linear drag force, $\vec{F}_{\text{drag}} = (bv)$, direction opposite the motion, where b is a constant. For a sphere of radius R , the drag constant can be shown to be $b = 6\pi\eta R$, where η is the viscosity of the liquid. Water at 20°C has viscosity $1.0 \times 10^{-3} \text{ N s/m}^2$.
- A *paramecium* is about $100 \mu\text{m}$ long. If it's modeled as a sphere, how much propulsion force must it exert to swim at a typical speed of 1.0 mm/s? How about the propulsion force of a 2.0- μm -diameter *E. coli* bacterium swimming at $30 \mu\text{m/s}$?
 - The propulsion forces are very small, but so are the organisms. To judge whether the propulsion force is large or small relative to the organism, compute the acceleration that the propulsion force could give each organism if there were no drag. The density of both organisms is the same as that of water, 1000 kg/m^3 .
66. || A 60 kg skater is gliding across frictionless ice at 4.0 m/s. Air resistance is not negligible. You can model the skater as a 170-cm-tall, 36-cm-diameter cylinder. What is the skater's speed 2.0 s later?
67. || Very small objects, such as dust particles, experience a linear drag force, $\vec{F}_{\text{drag}} = (bv)$, direction opposite the motion, where b is a constant. That is, the quadratic model of drag of Equation 6.15 fails for very small particles. For a sphere of radius R , the drag constant can be shown to be $b = 6\pi\eta R$, where η is the viscosity of the gas.
- Find an expression for the terminal speed v_{term} of a spherical particle of radius R and mass m falling through a gas of viscosity η .
 - Suppose a gust of wind has carried a 50- μm -diameter dust particle to a height of 300 m. If the wind suddenly stops, how long will it take the dust particle to settle back to the ground? Dust has a density of 2700 kg/m^3 , the viscosity of 25°C air is $2.0 \times 10^{-5} \text{ N s/m}^2$, and you can assume that the falling dust particle reaches terminal speed almost instantly.

Problems 68 and 69 show a free-body diagram. For each:

- Write a realistic dynamics problem for which this is the correct free-body diagram. Your problem should ask a question that can be answered with a value of position or velocity (such as “How far?” or “How fast?”), and should give sufficient information to allow a solution.
- Solve your problem!

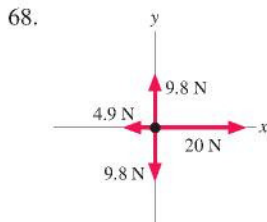


FIGURE P6.68

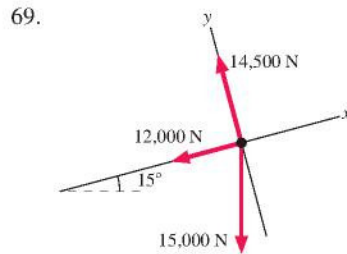


FIGURE P6.69

In Problems 70 through 72 you are given the dynamics equations that are used to solve a problem. For each of these, you are to

- Write a realistic problem for which these are the correct equations.
- Draw the free-body diagram and the pictorial representation for your problem.
- Finish the solution of the problem.

70. $-0.80n = (1500 \text{ kg})a_x$
 $n - (1500 \text{ kg})(9.80 \text{ m/s}^2) = 0$
71. $T - 0.20n - (20 \text{ kg})(9.80 \text{ m/s}^2) \sin 20^\circ = (20 \text{ kg})(2.0 \text{ m/s}^2)$
 $n - (20 \text{ kg})(9.80 \text{ m/s}^2) \cos 20^\circ = 0$
72. $(100 \text{ N}) \cos 30^\circ - f_k = (20 \text{ kg})a_x$
 $n + (100 \text{ N}) \sin 30^\circ - (20 \text{ kg})(9.80 \text{ m/s}^2) = 0$
 $f_k = 0.20n$

Challenge Problems

73. **III** A block of mass m is at rest at the origin at $t = 0$. It is pushed with constant force F_0 from $x = 0$ to $x = L$ across a horizontal surface whose coefficient of kinetic friction is $\mu_k = \mu_0(1 - x/L)$. That is, the coefficient of friction decreases from μ_0 at $x = 0$ to zero at $x = L$.

- Use what you've learned in calculus to prove that

$$a_x = v_x \frac{dv_x}{dx}$$

- Find an expression for the block's speed as it reaches position L .

74. **III** A spring-loaded toy gun exerts a variable force on a plastic ball as the spring expands. Consider a horizontal spring and a ball of mass m whose position when barely touching a fully expanded spring is $x = 0$. The ball is pushed to the left, compressing the spring. You'll learn in Chapter 9 that the spring force on the ball, when the ball is at position x (which is negative), can be written as $(F_{sp})_x = -kx$, where k is called the *spring constant*. The minus sign is needed to make the x -component of the force positive. Suppose the ball is initially pushed to $x_0 = -L$, then released and shot to the right.

- Use what you've learned in calculus to prove that

$$a_x = v_x \frac{dv_x}{dx}$$

- Find an expression, in terms of m , k , and L , for the speed of the ball as it comes off the spring at $x = 0$.

75. **III** **FIGURE CP6.75** shows an **accelerometer**, a device for measuring the horizontal acceleration of cars and airplanes. A ball is free to roll on a parabolic track described by the equation $y = x^2$, where both x and y are in meters. A scale along the bottom is used to measure the ball's horizontal position x .

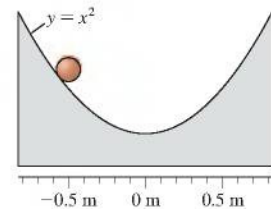


FIGURE CP6.75

- Find an expression that allows you to use a measured position x (in m) to compute the acceleration a_x (in m/s^2). (For example, $a_x = 3x$ is a possible expression.)
 - What is the acceleration if $x = 20 \text{ cm}$?
76. **III** An object moving in a liquid experiences a *linear drag force*: $\vec{F}_{\text{drag}} = (bv, \text{direction opposite the motion})$, where b is a constant called the *drag coefficient*. For a sphere of radius R , the drag constant can be computed as $b = 6\pi\eta R$, where η is the *viscosity* of the liquid.
- Find an algebraic expression for $v_x(t)$, the x -component of velocity as a function of time, for a spherical particle of radius R and mass m that is shot horizontally with initial speed v_0 through a liquid of viscosity η .
 - Water at 20°C has viscosity $\eta = 1.0 \times 10^{-3} \text{ N s/m}^2$. Suppose a 4.0-cm-diameter, 33 g ball is shot horizontally into a tank of 20°C water. How long will it take for the horizontal speed to decrease to 50% of its initial value?
77. **III** An object moving in a liquid experiences a *linear drag force*: $\vec{F}_{\text{drag}} = (bv, \text{direction opposite the motion})$, where b is a constant called the *drag coefficient*. For a sphere of radius R , the drag constant can be computed as $b = 6\pi\eta R$, where η is the *viscosity* of the liquid.
- Use what you've learned in calculus to prove that

$$a_x = v_x \frac{dv_x}{dx}$$

- Find an algebraic expression for $v_x(x)$, the x -component of velocity as a function of distance traveled, for a spherical particle of radius R and mass m that is shot horizontally with initial speed v_0 through a liquid of viscosity η .
 - Water at 20°C has viscosity $\eta = 1.0 \times 10^{-3} \text{ N s/m}^2$. Suppose a 1.0-cm-diameter, 1.0 g marble is shot horizontally into a tank of 20°C water at 10 cm/s. How far will it travel before stopping?
78. **III** An object with cross section A is shot horizontally across frictionless ice. Its initial velocity is v_{0x} at $t_0 = 0 \text{ s}$. Air resistance is not negligible.
- Show that the velocity at time t is given by the expression

$$v_x = \frac{v_{0x}}{1 + C\rho A v_{0x} t / 2m}$$

- A 1.6-m-wide, 1.4-m-high, 1500 kg car with a drag coefficient of 0.35 hits a very slick patch of ice while going 20 m/s. If friction is neglected, how long will it take until the car's speed drops to 10 m/s? To 5 m/s?
- Assess whether or not it is reasonable to neglect kinetic friction.