Chapter 3

Patterns of Motion

OUTLINE

Information about the mass of a hot air balloon and forces on the balloon will enable you to predict if it is going to move up, down, or drift across the river. This chapter is about such relationships among force, mass, and changes in motion.

In the previous chapter you learned how to describe motion in terms of distance, time, velocity, and acceleration. In addition, you learned about different kinds of motion, such as straight-line motion, the motion of falling objects, and the compound motion of objects projected up from the surface of the earth. You were also introduced, in general, to two concepts closely associated with motion: (1) that objects have inertia, a tendency to resist a change in motion, and (2) that forces are involved in a change of motion.

The relationship between forces and a change of motion is obvious in many everyday situations (Figure 3.1). When a car, bus, or plane starts moving, you feel a force on your back. Likewise, you feel a force on the bottoms of your feet when an elevator starts moving upward. On the other hand, you seem to be forced toward the dashboard if a car stops quickly, and it feels as if the floor pulls away from your feet when an elevator drops rapidly. These examples all involve patterns between forces and motion, patterns that can be quantified, conceptualized, and used to answer questions about why things move or stand still. These patterns are the subject of this chapter.

LAWS OF MOTION

Isaac Newton was born on Christmas Day in 1642, the same year that Galileo died. Newton was a quiet farm boy who seemed more interested in mathematics and tinkering than farming. He entered Trinity College of Cambridge University at the age of eighteen, where he enrolled in mathematics. He graduated four years later, the same year that the university was closed because the bubonic plague, or Black Death, was ravaging Europe. During this time, Newton returned to his boyhood home, where he thought out most of the ideas that would later make him famous. Here, between the ages of twenty-three and twenty-four, he invented the field of mathematics called *calculus* and clarified his ideas on motion and gravitation (Figure 3.2). After the plague he returned to Cambridge, where he was appointed professor of mathematics at the age of twenty-six. He lectured and presented papers on optics. One paper on his theory about light and colors caused such a controversy that Newton resolved never to publish another line. Newton was a shy, introspective person who was too absorbed in his work for such controversy. In 1684, Edmund Halley (of Halley's comet fame) asked Newton to resolve a dispute involving planetary motions. Newton had already worked out the solution to this problem, in addition to other problems on gravity and motion. Halley persuaded the reluctant Newton to publish the material. Two years later, in 1687, Newton published *Principia,* which was paid for by Halley. Although he feared controversy, the book was accepted almost at once and established Newton as one of the greatest thinkers who ever lived.

Newton built his theory of motion on the previous work of Galileo and others. In fact, Newton's first law is similar to the concept of inertia presented earlier by Galileo. Newton acknowledged the contribution of Galileo and others to his work, stating that if he had seen further than others "it was by standing upon the shoulders of giants."

FIGURE 3.1

In a moving airplane, you feel forces in many directions when the plane changes its motion. You cannot help but notice the forces involved when there is a change of motion.

Newton's First Law of Motion

Newton's first law of motion is also known as the *law of inertia* and is very similar to one of Galileo's findings about motion. Recall that Galileo used the term *inertia* to describe the tendency of an object to resist changes in motion. Newton's first law describes this tendency more directly. In modern terms (not Newton's words), the **first law of motion** is as follows:

> **Every object retains its state of rest or its state of uniform straight-line motion unless acted upon by an unbalanced force.**

This means that an object at rest will remain at rest unless it is put into motion by an unbalanced force; that is, the vector sum of the forces must be greater than zero if more than one

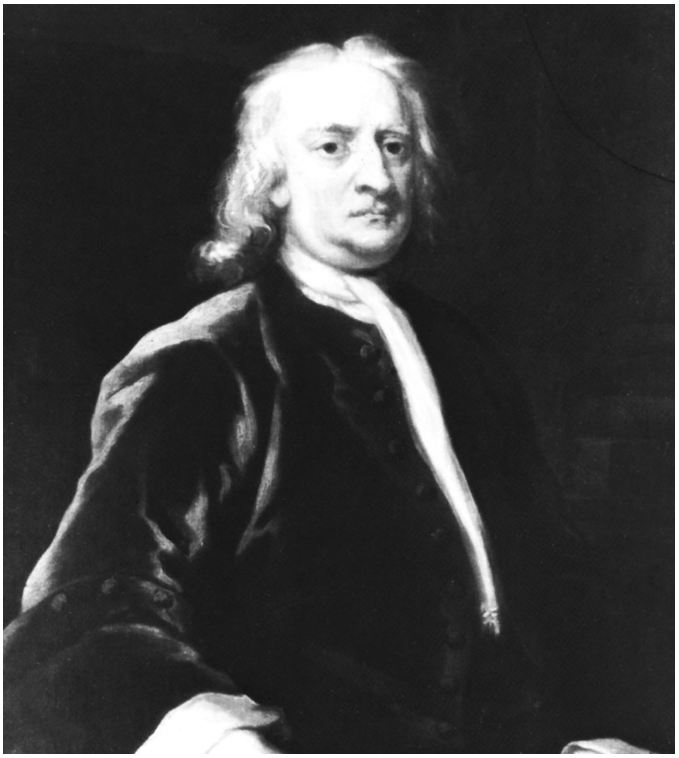


FIGURE 3.2

Among other accomplishments, Isaac Newton invented calculus, developed the laws of motion, and developed the law of gravitational attraction.

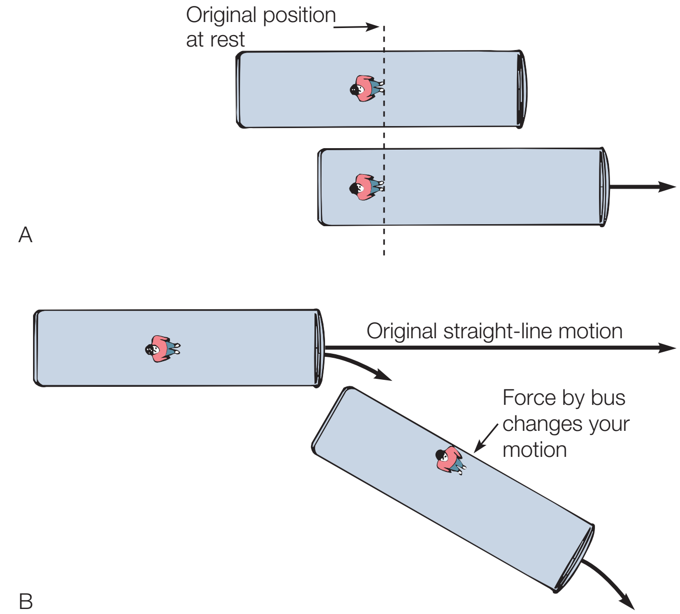


FIGURE 3.3

Top view of a person standing in the aisle of a bus. (*A*) The bus is at rest, and then starts to move forward. Inertia causes the person to remain in the original position, appearing to fall backward. (*B*) The bus turns to the right, but inertia causes the person to retain the original straight-line motion until forced in a new direction by the side of the bus.

force is involved. Likewise, an object moving with uniform straight-line motion will retain that motion unless an unbalanced force causes it to speed up, slow down, or change its direction of travel. Thus, Newton's first law describes the tendency of an object to resist *any* change in its state of motion, a property defined by inertia.

Some objects have greater inertia than other objects. For example, it is easier to push a compact car into motion than to push a heavy truck into motion. The truck has greater inertia than the compact car. It is also more difficult to stop the heavy truck from moving than it is to stop a compact car. Again the heavy truck has greater inertia. The amount of inertia an object has describes the **mass** of the object. Mass is a *measure of inertia*. The more inertia an object has, the greater its mass. Thus the heavy truck has more mass than the compact car. You know this because the truck has greater inertia. Newton originally defined mass as the "quantity of matter" in an object, and this definition is intuitively appealing. However, Newton needed to measure inertia because of its obvious role in motion and redefined mass as a measure of inertia. Thinking of mass in terms of a resistance to a change of motion may seem strange at first, but it will begin to make more sense as you explore the relationships between mass, forces, and acceleration.

Think of Newton's first law of motion when you ride standing in the aisle of a bus. The bus begins to move, and you, being an independent mass, tend to remain at rest. You take a few steps back as you tend to maintain your position relative to the ground outside. You reach for a seat back or some part of the bus. Once you have a hold on some part of the bus it supplies the forces needed to give you the same motion as the bus and you no longer find it necessary to step backward. You now have the same motion as the bus, and no forces are involved, at least until the bus goes around a curve. You now feel a tendency to move to the side of the bus. The bus has changed its straight-line motion, but you, again being an independent mass, tend to move straight ahead. The side of the seat forces you into following the curved motion of the bus. The forces you feel when the bus starts moving or turning are a result of your inertia. You tend to remain at rest or follow a straight path until forces correct your motion so that it is the same as that of the bus (Figure 3.3).

Consider a second person standing next to you in the aisle of the moving bus. When the bus stops, the two of you tend to retain your straight-line motion, and you move forward in the aisle. If it is more difficult for the other person to stop moving, you know that the other person has greater inertia. Since mass is a measure of inertia, you know that the other person has more mass than you. But do not confuse this with the other person's weight. Weight is a different property than mass and is explained by Newton's second law of motion.

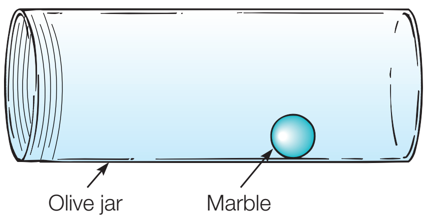


FIGURE 3.4

This marble can be used to demonstrate inertia. See the "Activities" section in the text.

Activities

1. Place a marble inside any cylindrical container, such as an olive bottle or pill vial. Place the container on its side on top of a table and push it along with the mouth at the front end (Figure 3.4). Note the position of the marble inside the container. Stop the container immediately. Explain the reaction of the marble.
2. Place the marble inside the container and push it along as before. This time push the container over a carpeted floor, a smooth floor, a waxed tabletop, and so forth. Notice the distance that the marble rolls over the different surfaces. Repeat the procedure with large and small marbles of various masses as you use the same velocity each time. Explain the differences you observe.

Newton's Second Law of Motion

Newton had successfully used Galileo's ideas to describe the nature of motion. Newton's first law of motion explains that any object, once started in motion, will continue with a constant velocity in a straight line unless a force acts on the moving object. This law not only describes motion but establishes the role of a force as well. A change of motion is therefore *evidence* of the action of some unbalanced force (net force). The association of forces and a change of motion is common in your everyday experience. You have felt forces on your back in an accelerating automobile, and you have felt other forces as the automobile turns or stops. You have also learned about gravitational forces that accelerate objects toward the surface of the earth. Unbalanced forces and acceleration are involved in any change of motion. The amount of inertia, or mass, is also involved, since inertia is a resistance to a change of motion. Newton's second law of motion is a relationship between *net force*, *acceleration*, and *mass* that describes the cause of a change of motion (Figure 3.5).

Consider the motion of you and a bicycle you are riding. Suppose you are riding your bicycle over level ground in a straight line at 3 miles per hour. Newton's first law tells you that you will continue with a constant velocity in a straight line as long as no external, unbalanced force acts on you and the bicycle. The force that you *are* exerting on the pedals seems to equal some external force that moves you and the bicycle along (more on this later). The force exerted as you move along is needed to *balance* the resisting forces of tire friction and air resistance. If these resisting forces were removed you would not need to exert any force at all to continue moving at a constant velocity. The net force is thus the force you are applying minus the forces from tire friction and air resistance. The *net force* is therefore zero when you move at a constant speed in a straight line (Figure 3.6). When the net force on an object is zero, no unbalanced force acts on it.

FIGURE 3.5

This bicycle rider knows about the relationship between force, acceleration, and mass.

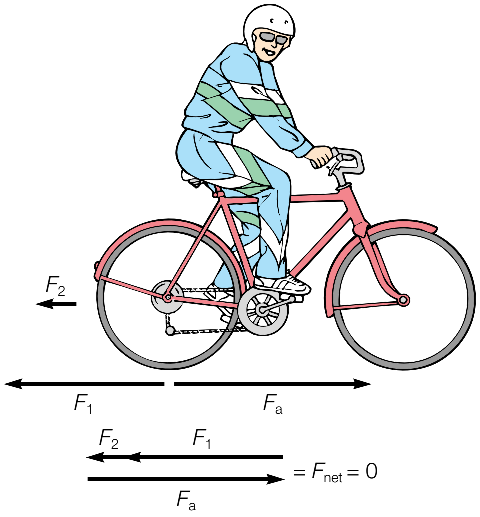


FIGURE 3.6

At a constant velocity the force of tire friction (F_1) and the force of air resistance (F_2) have a vector sum that equals the force applied (F_a). The net force is therefore 0.

If you now apply a greater force on the pedals the *extra* force you apply is unbalanced by friction and air resistance. Hence there will be a net force greater than zero, and you will accelerate. You will accelerate during, and *only* during, the time that the (unbalanced) net force is greater than zero. Likewise, you will slow down if you apply a force to the brakes, another kind of resisting friction. A third way to change your velocity is to apply a force on the handlebars, changing the direction of your velocity. Thus, *unbalanced forces* on you and your bicycle produce an *acceleration.*

Starting a bicycle from rest suggests a relationship between force and acceleration. You observe that the harder you push on the pedals, the greater your acceleration. If, for a time, you exert a force on the pedals greater than the combined forces of tire friction and air resistance, then you will create an unbalanced force and accelerate to a certain speed. If, by exerting an even greater force on the pedals, you double the net force in the direction you are moving, then you will also double the acceleration, reaching the same velocity in half the time. Likewise, if you triple the unbalanced force you will increase the acceleration threefold. Recall that when quantities increase or decrease together in the same ratio, they are said to be *directly proportional.* The acceleration is therefore directly proportional to the unbalanced force applied. Recall also that the symbol ∝ means "is proportional to." The relationship between acceleration (a) and the unbalanced force (F) can thus be abbreviated as

$$\text{acceleration} \propto \text{force}$$

or in symbols,

$$a \propto F$$

Suppose that your bicycle has two seats, and you have a friend who will ride with you. Suppose also that the addition of your friend on the bicycle will double the mass of the bike and riders. If you use the same extra unbalanced force as before, the bicycle will undergo a much smaller acceleration. In fact, with all other factors equal, doubling the mass and applying the same extra force will produce an acceleration of only half as much (Figure 3.7). An even more massive friend would reduce the acceleration even more. If you triple the mass and apply the same extra force, the acceleration will be one-third as much. Recall that when a relationship between two quantities shows that one quantity increases as another decreases, in the same ratio, the quantities are said to be *inversely proportional.* The acceleration (a) of an object is therefore inversely proportional to its mass (m). This relationship can be abbreviated as

$$\text{acceleration} \propto \frac{1}{\text{mass}}$$

or in symbols,

$$a \propto \frac{1}{m}$$

Since the mass (m) is in the denominator, doubling the mass will result in one-half the acceleration, tripling the mass will result in one-third the acceleration, and so forth.

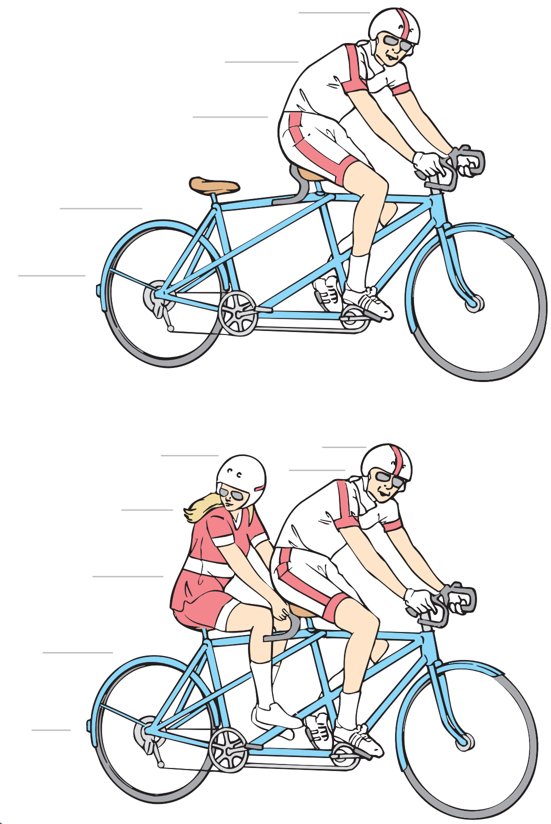


FIGURE 3.7

More mass results in less acceleration when the same force is applied. With the same force applied, the riders and bike with twice the mass will have half the acceleration, with all other factors constant. Note that the second rider is not pedaling.

Now the relationships can be combined to give

$$\text{acceleration} \propto \frac{\text{force}}{\text{mass}}$$

or

$$a \propto \frac{F}{m}$$

The acceleration of an object therefore depends on *both* the *net force applied* and the *mass* of the object. The **second law of motion** is as follows:

> **The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to the mass of the object.**

The proportion between acceleration, force, and mass is not yet an equation, because the units have not been defined. The metric unit of force is *defined* as a force that will produce an acceleration of 1.0 m/s^2 when applied to an object with a mass of 1.0 kg. This unit of force is called the **newton** (N) in honor of Isaac Newton. Now that a unit of force has been defined, the equation for Newton's second law of motion can be written. First, rearrange

$$a \propto \frac{F}{m} \text{ to } F \propto ma$$

Then replace the proportionality with the more explicit equal sign, and Newton's second law becomes

$$F = ma$$

equation 3.1

The newton unit of force is a derived unit that is based on the three fundamental units of mass, length, and time. This is readily observed if the units are placed in the second-law equation

$$F = ma$$

$$1\text{ N} = (1\text{ kg})\left(1\frac{\text{m}}{\text{s}^2}\right)$$

or

$$1\text{ N} = 1\frac{\text{kg}\cdot\text{m}}{\text{s}^2}$$

Until now, equations were used to *describe properties* of matter such as density, velocity, and acceleration. This is your first example of an equation that is used to *define a concept,* specifically the concept of what is meant by a force. Since the concept is defined by specifying a measurement procedure, it is also an example of an *operational definition.* You are not only told what a newton of force is but also how to go about measuring it. Notice that the newton is defined in terms of mass measured in kg and acceleration measured in m/s^2. Any other units must be converted to kg and m/s^2 before a problem can be solved for newtons of force.

Example 3.1

A 60 kg bicycle and rider accelerate at 0.5 m/s^2. How much extra force was applied?

Solution

The mass (*m*) of 60 kg and the acceleration (*a*) of 0.5 m/s^2 are given. The problem asked for the extra force (*F*) needed to give the mass the acquired acceleration. The relationship is found in equation 3.1, *F* = *ma*.

$$m = 60\text{ kg} \qquad F = ma$$

$$a = 0.5\frac{\text{m}}{\text{s}^2} \qquad = (60\text{ kg})\left(0.5\frac{\text{m}}{\text{s}^2}\right)$$

$$F = ? \qquad = (60)(0.5)\ (\text{kg})\left(\frac{\text{m}}{\text{s}^2}\right)$$

$$= 30\frac{\text{kg}\cdot\text{m}}{\text{s}^2}$$

$$= \boxed{30\text{ N}}$$

An *extra* force of 30 N, beyond that required to maintain constant speed must be applied to the pedals for the bike and rider to maintain an acceleration of 0.5 m/s^2. (Note that the units $kg{\cdot}m/s^2$ form the definition of a newton of force, so the symbol N is used.)

Example 3.2

What is the acceleration of a 20 kg cart if the net force on it is 40 N? (Answer: 2 m/s^2)

The difference between mass and weight can be confusing, since they are proportional to one another. If you double the mass of an object, for example, its weight is also doubled. But there is an important distinction between mass and weight and, in fact, they are different concepts. *Weight is a downward force,* the gravitational force acting on an object. Mass, on the other hand, refers to the amount of matter in the object and is *independent* of the force of gravity. Mass is a measure of inertia, the extent to which the object resists a change of motion. The force of gravity varies from place to place on the surface of the earth. It is slightly less, for example, in Colorado than in Florida. Imagine that you could be instantly transported from Florida to Colorado. You would find that you weigh less in Colorado than you did in Florida, even though the amount of matter in you has not changed. Now imagine that you could be instantly transported to the moon. You would weigh one-sixth as much on the moon because the force of gravity on the moon is one-sixth of that on the earth. Yet, your mass would be the same in both locations.

Weight is a measure of the force of gravity acting on an object, and this force can be calculated from Newton's second law of motion,

$$F = ma$$

or

$$\text{downward force} = (\text{mass})(\text{acceleration due to gravity})$$

or

$$\text{weight} = (\text{mass})(g)$$

$$\text{or} \quad w = mg$$

equation 3.2

You learned in the previous chapter that *g* is the symbol used to represent acceleration due to gravity. Near the earth's surface, *g* has an average value of 9.8 m/s^2. To understand how *g* is applied to an object not moving, consider a ball you are holding in your hand. By supporting the weight of the ball you hold it stationary, so the upward force of your hand and the downward force of the ball (its weight) must add to a net force of zero. When you let go of the ball the gravitational force is the only force acting on the ball. The ball's weight is then the net force

TABLE 3.1 Units of mass and weight in the metric and English systems of measurement

	Mass	×	Acceleration	=	Force
Metric System	kg	×	$\frac{m}{s^2}$	=	$\frac{kg \cdot m}{s^2}$ (newton)
English System	$\left(\frac{lb}{ft/s^2}\right)$	×	$\frac{ft}{s^2}$	=	lb (pound)

that accelerates it at g, the acceleration due to gravity. Thus, $F_{net} = w = ma = mg$. The weight of the ball never changes when near the surface of the earth, so its weight is always equal to $w = mg$, even if the ball is not accelerating.

In the metric system, *mass* is measured in kilograms. The acceleration due to gravity, g, is 9.8 m/s^2. According to equation 3.2, weight is mass times acceleration. A kilogram multiplied by an acceleration measured in m/s^2 results in kg·m/s^2, a unit you now recognize as a force called a newton. The *unit of weight* in the metric system is therefore the *newton* (N).

In the English system the pound is the unit of *force*. The acceleration due to gravity, g, is 32 ft/s^2. The force unit of a pound is defined as the force required to accelerate a unit of mass called the *slug*. Specifically, a force of 1.0 lb will give a 1.0 slug mass an acceleration of 1.0 ft/s^2.

The important thing to remember is that *pounds* and *newtons* are units of *force*. A *kilogram*, on the other hand, is a measure of *mass*. Thus the English unit of 1.0 lb is comparable to the metric unit of 4.5 N (or 0.22 lb is equivalent to 1.0 N). Conversion tables sometimes show how to convert from pounds (a unit of weight) to kilograms (a unit of mass). This is possible because weight and mass are proportional on the surface of the earth. It can also be confusing, since some variables depend on weight and others depend on mass. To avoid confusion, it is important to remember the distinction between weight and mass and that a kilogram is a unit of mass. Newtons and pounds are units of force that can be used to measure weight (Table 3.1).

Example 3.3

What is the weight of a 60.0 kg person on the surface of the earth?

Solution

A mass (m) of 60.0 kg is given, and the acceleration due to gravity (g) 9.8 m/s^2 is implied. The problem asked for the weight (w). The relationship is found in equation 3.2, $w = mg$, which is a form of $F = ma$.

$m = 60.0\ kg$

$g = 9.8\frac{m}{s^2}$

$w = ?$

$$\begin{aligned} w &= mg \\ &= (60.0\ \text{kg})\left(9.8\frac{\text{m}}{\text{s}^2}\right) \\ &= (60.0)(9.8)(\text{kg})\left(\frac{\text{m}}{\text{s}^2}\right) \\ &= 588\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \\ &= \boxed{590\text{N}} \end{aligned}$$

Example 3.4

A 60.0 kg person weighs 100.0 N on the moon. What is the value of g on the moon? (Answer: 1.67 m/s^2)

Activities

1. Stand on a bathroom scale in an operating elevator and note the reading when the elevator accelerates, decelerates, or has a constant velocity. See if you can figure out how to use the readings to calculate the acceleration of the elevator.
2. Calculate the acceleration of your car (see chapter 2). Check the owner's manual of the car (or see the dealer) to obtain the weight of the car. Convert this to mass (for English units, mass equals weight in pounds divided by 32 ft/s^2), then calculate the force, mass, and acceleration relationships.

Newton's Third Law of Motion

Newton's first law of motion states that an object retains its state of motion when the net force is zero. The second law states what happens when the net force is *not* zero, describing how an object with a known mass moves when a given force is applied. The two laws give one aspect of the concept of a force; that is, if you observe that an object starts moving, speeds up, slows down, or changes its direction of travel, you can conclude that an unbalanced force is acting on the object. Thus, any change in the state of motion of an object is *evidence* that an unbalanced force has been applied.

Newton's third law of motion is also concerned with forces and considers how a force is produced. First, consider where a force comes from. A force is always produced by the interaction of two or more objects. There is always a second object pushing or pulling on the first object to produce a force. To simplify the many interactions that occur on the earth, consider a satellite freely floating in space. According to Newton's

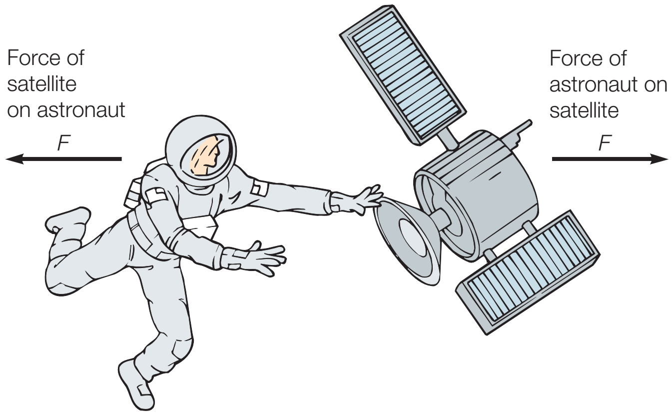


FIGURE 3.8

Forces occur in matched pairs that are equal in magnitude and opposite in direction.

second law ($F = ma$), a force must be applied to change the state of motion of the satellite. What is a possible source of such a force? Perhaps an astronaut pushes on the satellite for 1 second. The satellite would accelerate *during* the application of the force, then move away from the original position at some constant velocity. The astronaut would also move away from the original position, but in the opposite direction (Figure 3.8). A *single* force *does not exist* by itself. There is always a matched and opposite force that occurs at the same time. Thus, the astronaut exerted a momentary force on the satellite, but the satellite evidently exerted a momentary force back on the astronaut as well, for the astronaut moved away from the original position in the opposite direction. Newton did not have astronauts and satellites to think about, but this is the kind of reasoning he did when he concluded that forces always occur in matched pairs that are equal and opposite. Thus the **third law of motion** is as follows:

> **Whenever two objects interact, the force exerted on one object is equal in size and opposite in direction to the force exerted on the other object.**

The third law states that forces always occur in matched pairs that act in opposite directions and on two *different* bodies. You could express this law with symbols as

$$F_{\text{A due to B}} = F_{\text{B due to A}}$$

equation 3.3

where the force on the astronaut, for example, would be "A due to B," and the force on the satellite would be "B due to A."

Sometimes the third law of motion is expressed as follows: "For every action there is an equal and opposite reaction," but this can be misleading. Neither force is the cause of the other. The forces are at every instant the cause of each other and they appear and disappear at the same time. If you are going to describe the force exerted on a satellite by an astronaut, then you must realize that there is a simultaneous force exerted on the astronaut by the satellite. The forces (astronaut on satellite and satellite on astronaut) are equal in magnitude but opposite in direction.

FIGURE 3.9

The football player's foot is pushing against the ground, but it is the ground pushing against the foot that accelerates the player forward to catch a pass.

Perhaps it would be more common to move a satellite with a small rocket. A satellite is maneuvered in space by firing a rocket in the direction opposite to the direction someone wants to move the satellite. Exhaust gases (or compressed gases) are accelerated in one direction, and the expelled gases exert an equal but opposite force on the satellite that accelerates it in the opposite direction. This is another example of the third law.

Consider how the pairs of forces work on the earth's surface. You walk by pushing your feet against the ground (Figure 3.9). Of course you could not do this if it were not for friction. You would slide as on slippery ice without friction. But since friction does exist, you exert a backward horizontal force on the ground, and, as the third law explains, the ground exerts an equal and opposite force on you. You accelerate forward from the unbalanced force as explained by the second law. If the earth had the same mass as you, however, it would accelerate backward at the same rate that you were accelerated forward. The earth is much more massive than you, however, so any acceleration of the earth is a vanishingly small amount. The overall effect is that you are accelerated forward by the force the ground exerts on you.

Return now to the example of riding a bicycle that was discussed previously. What is the source of the *external* force that accelerates you and the bike? Pushing against the pedals is not external to you and the bike so that force will *not* accelerate you and the bicycle forward. This force is transmitted through the bike mechanism to the rear tire, which pushes against the ground. It is the ground exerting an equal and opposite force against the system of you and the bike that accelerates you forward. You must consider the forces that act on the system of the bike and you before you can apply $F = ma$. The only forces that will affect the forward motion of the bike system are the force of the ground pushing it forward and the frictional forces that oppose the forward motion. This is another example of the third law.

Example 3.5

A 60.0 kg astronaut is freely floating in space and pushes on a freely floating 120.0 kg satellite with a force of 30.0 N for 1.50 s. (a) Compare the forces exerted on the astronaut and the satellite, and (b) compare the acceleration of the astronaut to the acceleration of the satellite.

Solution

(a) According to Newton's third law of motion (equation 3.3),

$$F_{\text{A due to B}} = F_{\text{B due to A}}$$
$$30.0\text{ N} = 30.0\text{ N}$$

Both feel a 30.0 N force for 1.50 s but in opposite directions.

(b) Newton's second law describes a relationship between force, mass, and acceleration, $F = ma$.

For the astronaut:

$m = 60.0$ kg
$F = 30.0$ N
$a = ?$

$$F = ma \therefore a = \frac{F}{m}$$

$$a = \frac{30.0\,\frac{\text{kg}\cdot\text{m}}{\text{s}^2}}{60.0\text{ kg}}$$

$$= \frac{30.0}{60.0}\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\left(\frac{1}{\text{kg}}\right)$$

$$= 0.500\,\frac{\cancel{\text{kg}}\cdot\text{m}}{\cancel{\text{kg}}\cdot\text{s}^2}$$

$$= \boxed{0.500\,\frac{\text{m}}{\text{s}^2}}$$

For the satellite:

$m = 120.0$ kg
$F = 30.0$ N
$a = ?$

$$F = ma \therefore a = \frac{F}{m}$$

$$a = \frac{30.0\,\frac{\text{kg}\cdot\text{m}}{\text{s}^2}}{120.0\text{ kg}}$$

$$= \frac{30.0}{120.0}\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\left(\frac{1}{\text{kg}}\right)$$

$$= 0.250\,\frac{\cancel{\text{kg}}\cdot\text{m}}{\cancel{\text{kg}}\cdot\text{s}^2}$$

$$= \boxed{0.250\,\frac{\text{m}}{\text{s}^2}}$$

Example 3.6

After the interaction and acceleration between the astronaut and satellite described previously, they both move away from their original positions. What is the new speed for each? (Answer: Astronaut $v_f = 0.750$ m/s. Satellite $v_f = 0.375$ m/s) (Hint: $v_f = at + v_i$)

MOMENTUM

Sportscasters often refer to the *momentum* of a team, and newscasters sometimes refer to an election where one of the candidates has *momentum*. Both situations describe a competition where one side is moving toward victory and it is difficult to stop. It seems appropriate to borrow this term from the physical sciences because momentum is a property of movement. It takes a longer time to stop something from moving when it has a lot of momentum. The physical science concept of momentum is closely related to Newton's laws of motion. **Momentum** (p) is defined as the product of the mass (m) of an object and its velocity (v),

$$\text{momentum} = \text{mass} \times \text{velocity}$$

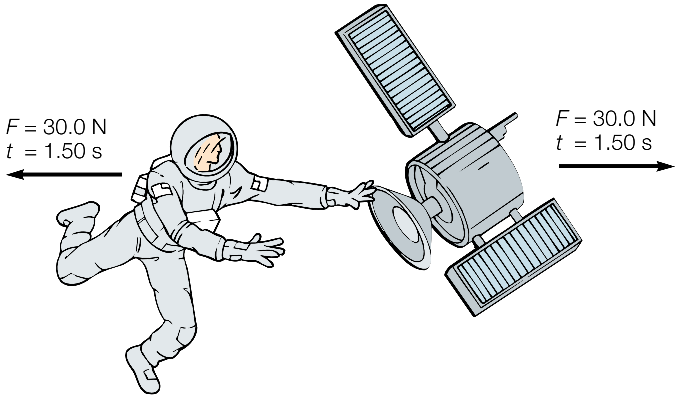
or

$$p = mv$$

equation 3.4

The astronaut in example 3.5 had a mass of 60.0 kg and a velocity of 0.750 m/s as a result of the interaction with the satellite. The resulting momentum was therefore (60.0 kg) (0.750 m/s, or 45.0 kg·m/s. As you can see, the momentum would be greater if the astronaut had acquired a greater velocity or if the astronaut had a greater mass and acquired the same velocity. Momentum involves both the inertia and the velocity of a moving object.

Notice that the momentum acquired by the satellite in example 3.5 is *also* 45.0 kg·m/s. The astronaut gained a certain



$m = 60.0\ \text{kg}$
$v = 0.750\ \text{m/s}$
$p = mv$

$$= (60.0\ \text{kg})\left(0.750\ \frac{\text{m}}{\text{s}}\right) = \boxed{45.0\ \frac{\text{kg}\cdot\text{m}}{\text{s}}}$$

$m = 120.0\ \text{kg}$
$v = 0.375\ \text{m/s}$
$p = mv$

$$= (120.0\ \text{kg})\left(0.375\ \frac{\text{m}}{\text{s}}\right) = \boxed{45.0\ \frac{\text{kg}\cdot\text{m}}{\text{s}}}$$

FIGURE 3.10

Both the astronaut and the satellite received a force of 30.0 N for 1.50 s when they pushed on each other. Both then have a momentum of 45.0 kg·m/s in the opposite direction. This is an example of the law of conservation of momentum.

FIGURE 3.11

According to the law of conservation of momentum, the momentum of the expelled gases in one direction equals the momentum of the rocket in the other direction in the absence of external forces.

momentum in one direction, and the satellite gained the *very same momentum in the opposite direction.* Newton originally defined the second law in terms of a rate of change of momentum being proportional to the net force acting on an object. Since the third law explains that the forces exerted on both the astronaut and satellite were equal and opposite, you would expect both objects to acquire equal momentum in the opposite direction. This result is observed any time objects in a system interact and the only forces involved are those between the interacting objects (Figure 3.10). This statement leads to a particular kind of relationship called a *law of conservation.* In this case, the law applies to momentum and is called the **law of conservation of momentum:**

> **The total momentum of a group of interacting objects remains the same in the absence of external forces.**

Conservation of momentum, energy, and charge are among examples of conservation laws that apply to everyday situations. These situations always illustrate two understandings, that (1) each conservation law is an expression of symmetry that describes a physical principle that can be observed; and, (2) each law holds regardless of the details of an interaction or how it took place. Since the conservation laws express symmetry that always occurs, they tell us what might be expected to happen, and what might be expected not to happen in a given situation. The symmetry also allows unknown quantities to be found by analysis. The law of conservation of momentum, for example, is useful in analyzing motion in simple systems of collisions such as those of billiard balls, automobiles, or railroad cars. It is also useful in measuring action and reaction interactions, as in rocket propulsion, where the backward momentum of the expelled gases equals the momentum given to the rocket in the opposite direction (Figure 3.11). When this is done, momentum is always found to be conserved.

Compared to the other concepts of motion, there are two aspects of momentum that are unusual: (1) the symbol for momentum (p) does not give a clue about the quantity it represents, and (2) the combination of metric units that results from a momentum calculation (kg·m/s) does not have a name of its own. So far, you have been introduced to one combination of units with a name. The units kg·m/s^2 are known as a unit of force called the *newton* (*N*). More combinations of metric units, all with names of their own, will be introduced later.

FORCES AND CIRCULAR MOTION

Consider a communications satellite that is moving at a uniform speed around the earth in a circular orbit. According to the first law of motion there *must be* forces acting on the satellite, since it

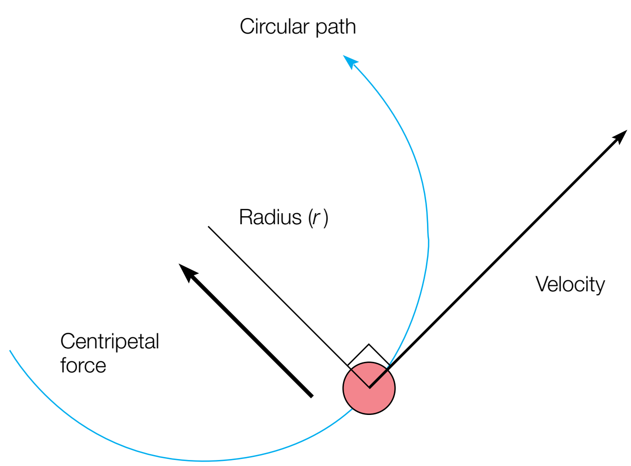


FIGURE 3.12

Centripetal force on the ball causes it to change direction continuously, or accelerate into a circular path. Without the unbalanced force acting on it, the ball would continue in a straight line.

does *not* move off in a straight line. The second law of motion also indicates forces, since an unbalanced force is required to change the motion of an object.

Recall that acceleration is defined as a change in velocity, and that velocity is a vector quantity, having both magnitude and direction. The vector quantity velocity is changed by a change in speed, direction, or both speed and direction. The satellite in a circular orbit is continuously being accelerated. This means that there is a continuously acting unbalanced force on the satellite that pulls it out of a straight-line path.

The force that pulls an object out of its straight-line path and into a circular path is called a **centripetal** (center-seeking) **force.** Perhaps you have swung a ball on the end of a string in a horizontal circle over your head. Once you have the ball moving, the only unbalanced force (other than gravity) acting on the ball is the centripetal force your hand exerts on the ball through the string. This centripetal force pulls the ball from its natural straight-line path into a circular path. There are no outward forces acting on the ball. The force that you feel on the string is a consequence of the third law; the ball exerts an equal and opposite force on your hand. If you were to release the string, the ball would move away from the circular path in a *straight line* that has a right angle to the radius at the point of release (Figure 3.12). When you release the string, the centripetal force ceases, and the ball then follows its natural straight-line motion. If other forces were involved, it would follow some other path. Nonetheless, the apparent outward force has been given a name just as if it were a real force. The outward tug is called a **centrifugal force.**

The magnitude of the centripetal force required to keep an object in a circular path depends on the inertia, or mass, of the object and the acceleration of the object, just as you learned in the second law of motion. The acceleration of an object moving in a circle can be shown by geometry or calculus to be directly proportional to the square of the speed around the circle (v^2) and inversely proportional to the radius of the circle (r). (A smaller radius requires a greater acceleration.) Therefore, the acceleration of an object moving in uniform circular motion (a_c) is

$$a_c = \frac{v^2}{r}$$

equation 3.5

The magnitude of the centripetal force of an object with a mass (m) that is moving with a velocity (v) in a circular orbit of a radius (r) can be found by substituting equation 3.5 in $F = ma$, or

$$F = \frac{mv^2}{r}$$

equation 3.6

Example 3.7

A 0.25 kg ball is attached to the end of a 0.5 m string and moved in a horizontal circle at 2.0 m/s. What force is needed to keep the ball in its circular path?

Solution

$m = 0.25\text{ kg}$
$r = 0.5\text{ m}$
$v = 2.0\text{ m/s}$
$F = ?$

$$F = \frac{mv^2}{r}$$

$$= \frac{(0.25\text{ kg})(2.0\text{ m/s})^2}{0.5\text{ m}}$$

$$= \frac{(0.25\text{ kg})(4.0\text{ m}^2/\text{s}^2)}{0.5\text{ m}}$$

$$= \frac{(0.25)(4.0)}{0.5}\ \frac{\text{kg}\cdot\text{m}^2}{\text{s}^2} \times \frac{1}{\text{m}}$$

$$= 2\ \frac{\text{kg}\cdot\text{m}^{\cancel{2}}}{\cancel{\text{m}}\cdot\text{s}^2}$$

$$= 2\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2}$$

$$= \boxed{2\text{ N}}$$

Example 3.8

Suppose you make the string in example 3.7 half as long, 0.25 m. What force is now needed? (Answer: 4.0 N)

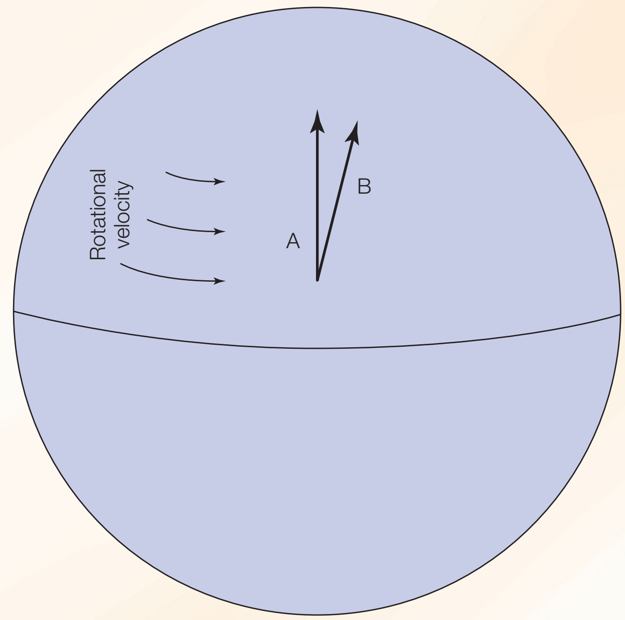
NEWTON'S LAW OF GRAVITATION

You know that if you drop an object, it always falls to the floor. You define *down* as the direction of the object's movement and *up* as the opposite direction. Objects fall because of the force of

A CLOSER LOOK | Spin Down

Does water rotate one way in the Northern Hemisphere and the other way in the Southern Hemisphere as it drains from a bathtub? This effect is observed with a large wind system, which is moving air—a fluid. People sometimes wonder if the same effect occurs with any fluid that is moving—for example, the direction water moves as it drains from the bathtub when you pull the plug.

The reason that moving air turns different ways in the two Hemispheres can be found in the observation that the earth is a rotating sphere. Since it has a spherical shape all the surface of the earth does not turn at the same rate. As shown in Box Figure 3.1, the earth has a greater rotational velocity at the equator than at the poles. As air moves north or south, the surface below has a different rotational velocity so it rotates beneath the air as it moves in a straight line. This gives the moving air an apparent deflection to the right of the direction of movement in the Northern Hemisphere and to the left in the Southern Hemisphere. The apparent deflection caused by the earth's rotation is called the *Coriolis effect.* For example, air sinking in the center of a region of atmospheric high pressure produces winds that move outward. In the Northern Hemisphere, the Coriolis effect deflects this wind to the right, producing a clockwise circulation. In the Southern Hemisphere, the wind is deflected to the left, producing a counterclockwise circulation pattern.



BOX FIGURE 3.1

The earth has a greater rotational velocity at the equator and less toward the poles. As air moves north or south (*A*), it passes over land with a different rotational velocity, which produces a deviation to the right in the Northern Hemisphere (*B*), and to the left in the Southern Hemisphere.

Now, back to our much smaller system of water draining from a bathtub. There is a small Coriolis effect on the water that is moving the very short distance to a drain. The overall result, however, is way too small to be a factor in determining what happens to the water as it leaves the tub. The perpendicular acceleration of the moving water in the tub is too small to influence which way the water turns. You might want to try a carefully controlled experiment to see for yourself. You will need to eliminate all the possible variables that might influence which way the draining water turns. Consider, for example, absolutely still water, with no noise or other sources of vibrations, and then carefully remove the plug in a way not to disturb the water.

You cannot use the direction water circulates when you flush a toilet for evidence that the Coriolis effect turns the water one way or the other. The water in a flushing toilet rotates in the direction the incoming water pipe is pointing, which has nothing to do with the Coriolis effect in either Hemisphere.

gravity, which accelerates objects at $g = 9.8\ m/s^2$ ($32\ ft/s^2$) and gives them weight, $w = mg$.

Gravity is an attractive force, a pull that exists between all objects in the universe. It is a mutual force that, just like all other forces, comes in matched pairs. Since the earth attracts you with a certain force, you must attract the earth with an exact opposite force. The magnitude of this force of mutual attraction depends on several variables. These variables were first described by Newton in *Principia,* his famous book on motion that was printed in 1687. Newton had, however, worked out his ideas much earlier, by the age of twenty-four, along with ideas about his laws of motion and the formula for centripetal acceleration. In a biography written by a friend in 1752, Newton stated that the notion of gravitation came to mind during a time of thinking that "was occasioned by the fall of an apple." He was thinking about why the Moon stays in orbit around Earth rather than

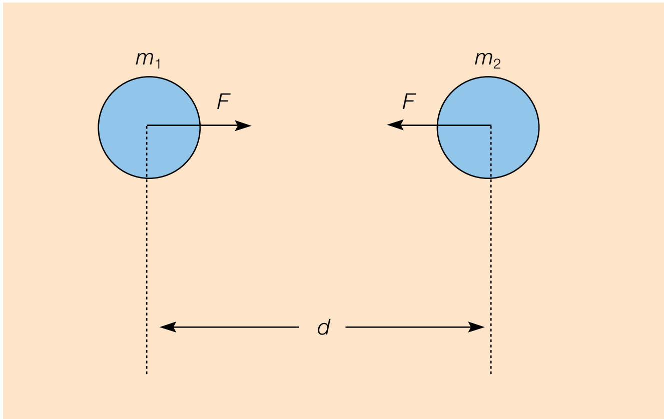


FIGURE 3.13

The variables involved in gravitational attraction. The force of attraction (F) is proportional to the product of the masses (m_1, m_2) and inversely proportional to the square of the distance (d) between the centers of the two masses.

moving off in a straight line as would be predicted by the first law of motion. Perhaps the same force that attracts the moon toward the earth, he thought, attracts the apple to the earth. Newton developed a theoretical equation for gravitational force that explained not only the motion of the moon but the motion of the whole solar system. Today, this relationship is known as the **universal law of gravitation:**

> **Every object in the universe is attracted to every other object with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distances between them.**

In symbols, m_1 and m_2 can be used to represent the masses of two objects, d the distance between their centers, and G a constant of proportionality. The equation for the law of universal gravitation is therefore

$$F = G\frac{m_1 m_2}{d^2}$$

equation 3.7

This equation gives the magnitude of the attractive force that each object exerts on the other. The two forces are oppositely directed. The constant G is a universal constant, since the law applies to all objects in the universe. It was first measured experimentally by Henry Cavendish in 1798. The accepted value today is $G = 6.67 \times 10^{-11}$ N·m^2/kg^2. Do not confuse G, the universal constant, with g, the acceleration due to gravity on the surface of the earth.

Thus, the magnitude of the force of gravitational attraction is determined by the mass of the two objects and the distance between them (Figure 3.13). The law also states that *every* object is attracted to every other object. You are attracted to all the objects around you—chairs, tables, other people, and so forth. Why don't you notice the forces between you and other objects? The answer is in example 3.9.

Example 3.9

What is the force of gravitational attraction between two 60.0 kg (132 lb) students who are standing 1.00 m apart?

Solution

$G = 6.67 \times 10^{-11}$ N·m^2/kg^2

$m_1 = 60.0$ kg

$m_2 = 60.0$ kg

$d = 1.00$ m

$F = ?$

$$F = G\frac{m_1 m_2}{d^2}$$

$$= \frac{(6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2)(60.0\ \text{kg})(60.0\ \text{kg})}{(1.00\ \text{m})^2}$$

$$= (6.67 \times 10^{-11})(3.60 \times 10^3)\frac{\frac{\text{N}\cdot\text{m}^2\cdot\cancel{\text{kg}^2}}{\cancel{\text{kg}^2}}}{\text{m}^2}$$

$$= 2.40 \times 10^{-7}\ (\text{N}\cdot\text{m}^2)\left(\frac{1}{\text{m}^2}\right)$$

$$= 2.40 \times 10^{-7}\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{m}^2}}$$

$$= \boxed{2.40 \times 10^{-7}\ \text{N}}$$

(Note: A force of 2.40×10^{-7} (0.00000024) N is equivalent to a force of 5.40×10^{-8} lb (0.00000005 lb), a force that you would not notice. In fact, it would be difficult to measure such a small force.)

As you can see in example 3.9, one or both of the interacting objects must be quite massive before a noticeable force results from the interaction. That is why you do not notice the force of gravitational attraction between you and objects that are not very massive compared to the earth. The attraction between you and the earth overwhelmingly predominates, and that is all you notice.

Newton was able to show that the distance used in the equation is the distance from the center of one object to the center of the second object. This does not mean that the force originates at the center, but that the overall effect is the same as if you considered all the mass to be concentrated at a center point. The weight of an object, for example, can be calculated by using a form of Newton's second law, $F = ma$. This general law shows a relationship between *any* force acting *on* a body, the mass of a body, and the resulting acceleration. When the acceleration is due to gravity, the equation becomes $F = mg$. The law of gravitation deals *specifically with the force of gravity* and how it varies with distance

A CLOSER LOOK | Space Station Weightlessness

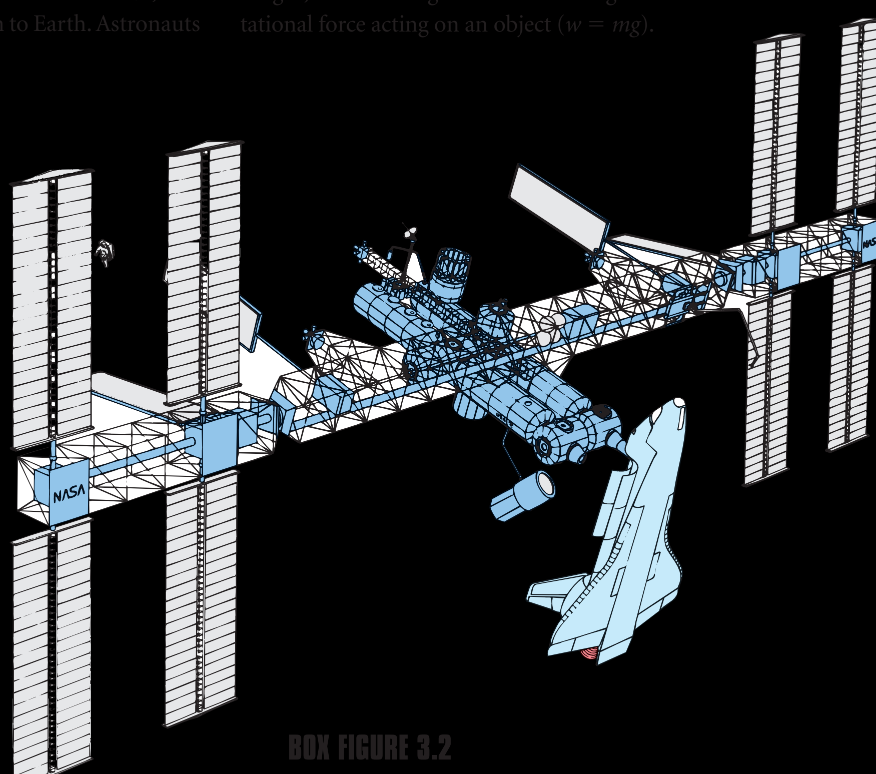
When do astronauts experience weightlessness, or "zero gravity"? Theoretically, the gravitational field of Earth extends to the whole universe. You know that it extends to the Moon, and indeed, even to the Sun some 93 million miles away. There is a distance, however, at which the gravitational force must become immeasurably small. But even at an altitude of 20,000 miles above the surface of Earth, gravity is measurable. At 20,000 miles, the value of *g* is about 1 ft/s^2 (0.3 m/s^2) compared to 32 ft/s^2 (9.8 m/s^2) on the surface. Since gravity does exist at these distances, how can an astronaut experience "zero gravity"?

Gravity does act on astronauts in spacecraft that are in orbit around Earth. The [redacted]

fire their retro-rockets, which slow the tangential speed, causing the spacecraft to fall down to the earth. If the tangential speed were more than 7 mi/s, the spacecraft would fly off into space. The spacecraft stays in orbit because it has the right tangential speed to continuously "fall" around and around the earth. Gravity provides the necessary centripetal force that causes the spacecraft to fall out of its natural straight-line motion.

Since gravity is acting on the astronaut and spacecraft, the term *zero gravity* is not an accurate description of what is happening. The astronaut, spacecraft, and everything in it are experiencing *apparent weightlessness* because they are continuously falling toward [redacted]

Whether weightlessness is apparent or real, however, the effects on people are the same. Long-term orbital flights have provided evidence that the human body changes from the effect of weightlessness. Bones lose calcium and minerals, the heart shrinks to a much smaller size, and leg muscles shrink so much on prolonged flights that astronauts cannot walk when they return to the earth. These and other problems resulting from prolonged weightlessness must be worked out before long-term weightless flights can take place. One solution to these problems might be a large, uniformly spinning spacecraft. The astronauts tend to move in a straight line, and the side of the turning [redacted]



[redacted]

PEOPLE BEHIND THE SCIENCE

Jean Bernard Léon Foucault (1819–1868)

Jean Foucault was a French physicist who invented the gyroscope, demonstrated the rotation of the earth, and obtained the first accurate value for the velocity of light.

Foucault was born in Paris on September 19, 1819. He was educated at home because his health was poor, and he went on to study medicine, hoping that the manual skills he developed in his youth would stand him in good stead as a surgeon. But Foucault soon abandoned medicine for science and supported himself from 1844 onward by writing scientific textbooks and then popular articles on science for a newspaper. He [redacted]


Foucault.

[redacted] abandoned this method after parting from Foucault and developed a similar method involving a rotating toothed wheel. With this, he first obtained in 1849 a fairly accurate numerical value for the speed of light.

Foucault persevered with the rotating mirror method and in 1850 succeeded in showing that light travels faster in air than in water, just beating Fizeau to the same conclusion. He then refined the method and in 1862 used it to make the first accurate determination of the velocity of light. His value of 298,000 km/185,177 mi per second was within 1% of the correct value, Fizeau's previous estimate having been about 5% too high.

[redacted]

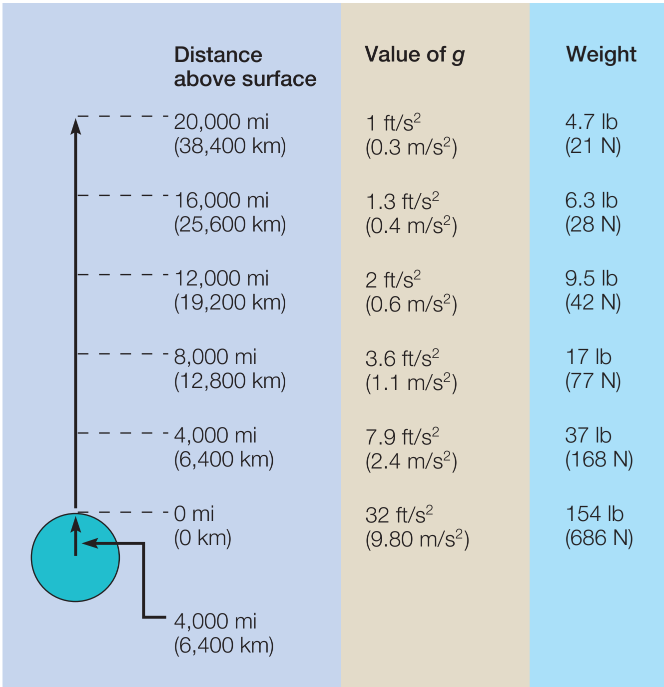


FIGURE 3.14

The force of gravitational attraction decreases inversely with the square of the distance from the earth's center. Note the weight of a 70.0 kg person at various distances above the earth's surface.

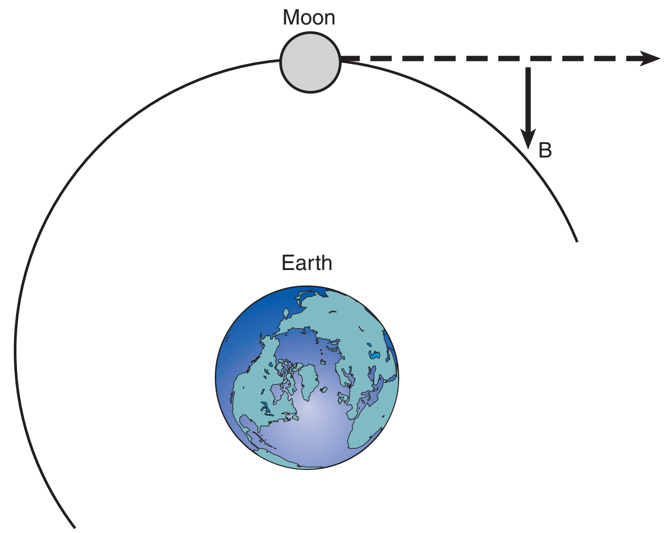


FIGURE 3.15

Gravitational attraction acts as a centripetal force that keeps the Moon from following the straight-line path shown by the dashed line to position A. It was pulled to position B by gravity (0.0027 m/s^2) and thus "fell" toward Earth the distance from the dashed line to B, resulting in a somewhat circular path.

and mass. Since weight is a force, then $F = mg$. You can write the two equations together,

$$mg = G\frac{mm_e}{d^2}$$

where m is the mass of some object on earth, m_e is the mass of the earth, g is the acceleration due to gravity, and d is the distance between the centers of the masses. Canceling the m's in the equation leaves

$$g = G\frac{m_e}{d^2}$$

which tells you that on the surface of the earth the acceleration due to gravity, 9.8 m/s^2, is a constant because the other two variables (mass of the earth and the distance to center of earth) are constant. Since the m's canceled, you also know that the mass of an object does not affect the rate of free fall; all objects fall at the same rate, with the same acceleration, no matter what their masses are.

Example 3.10 shows that the acceleration due to gravity, g, is about 9.8 m/s^2 and is practically a constant for relatively short distances above the surface. Notice, however, that Newton's law of gravitation is an inverse square law. This means if you double the distance, the force is $1/(2)^2$ or 1/4 as great. If you triple the distance, the force is $1/(3)^2$ or 1/9 as great. In other words, the force of gravitational attraction and g decrease inversely with the square of the distance from the earth's center. The weight of an object and the value of g are shown for several distances in Figure 3.14. If you have the time, a good calculator, and the inclination, you could check the values given in Figure 3.14 for a 70.0 kg person by doing problems similar to example 3.10. In fact, you could even calculate the mass of the earth, since you already have the value of g.

Using reasoning similar to that found in example 3.10, Newton was able to calculate the acceleration of the Moon toward Earth, about 0.0027 m/s^2. The Moon "falls" toward Earth because it is accelerated by the force of gravitational attraction. This attraction acts as a *centripetal force* that keeps the Moon from following a straight-line path as would be predicted from the first law. Thus, the acceleration of the Moon keeps it in a somewhat circular orbit around Earth. Figure 3.15 shows that the Moon would be in position A if it followed a straight-line path instead of "falling" to position B as it does. The Moon thus "falls" around Earth. Newton was able to analyze the motion of the Moon quantitatively as evidence that it is gravitational force that keeps the Moon in its orbit. The law of gravitation was extended to the Sun, other planets, and eventually the universe. The quantitative predictions of observed relationships among the planets were strong evidence that all objects obey the same law of gravitation. In addition, the law provided a means to calculate the mass of Earth, the Moon, the planets, and the Sun. Newton's law of gravitation, laws of motion, and work with mathematics formed the basis of most physics and technology for the next two centuries, as well as accurately describing the world of everyday experience.

Example 3.10

The surface of the earth is approximately 6,400 km from its center. If the mass of the earth is 6.0×10^{24} kg, what is the acceleration due to gravity, g, near the surface?

$G = 6.67 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2}$

$m_e = 6.0 \times 10^{24}$ kg

$d = 6{,}400$ km (6.4×10^6 m)

$g = ?$

$$g = \frac{Gm_e}{d^2}$$

$$= \frac{(6.67 \times 10^{-11}\,\mathrm{N{\cdot}m^2/kg^2})(6.0 \times 10^{24}\,\mathrm{kg})}{(6.4 \times 10^6\,\mathrm{m})^2}$$

$$= \frac{(6.67 \times 10^{-11})(6.0 \times 10^{24})}{4.1 \times 10^{13}} \; \frac{\frac{\mathrm{N{\cdot}\cancel{m^2}{\cdot}\cancel{kg}}}{\cancel{kg^2}}}{\cancel{m^2}}$$

$$= \frac{4.0 \times 10^{14}}{4.1 \times 10^{13}} \; \frac{\frac{\mathrm{kg{\cdot}m}}{\mathrm{s^2}}}{\mathrm{kg}}$$

$$= \boxed{9.8\ \mathrm{m/s^2}}$$

(Note: In the unit calculation, remember that a newton is a $\mathrm{kg{\cdot}m/s^2}$.)

SUMMARY

Isaac Newton developed a complete explanation of motion with three laws of motion. The laws explain the role of a *force* and the *mass* of an object involved in a *change of motion.*

Newton's *first law of motion* is concerned with the motion of an object and the *lack* of an unbalanced force. Also known as the *law of inertia,* the first law states that an object will retain its state of straight-line motion (or state of rest) unless an unbalanced force acts on it. The amount of resistance to a change of motion, *inertia,* describes the *mass* of an object.

The *second law of motion* describes a relationship between *net force, mass,* and *acceleration.* The relationship is $F = ma$. A *newton* of force is the force needed to give a 1.0 kg mass an acceleration of 1.0 $\mathrm{m/s^2}$. *Weight* is the downward force that results from the earth's gravity acting on the mass of an object. Weight can be calculated from $w = mg$, a special case of $F = ma$. Weight is measured in *newtons* in the metric system and *pounds* in the English system.

Newton's *third law of motion* states that forces are produced by the interaction of *two different* objects and that these forces *always* occur in *matched pairs* that are *equal in size* and *opposite in direction.* These forces are capable of producing an acceleration in accord with the second law of motion.

Momentum is the product of the mass of an object and its velocity. In the absence of external forces, the momentum of a group of interacting objects always remains the same. This relationship is the *law of conservation of momentum.*

An object moving in a circular path must have a force acting on it, since it does not move off in a straight line. The force that pulls an object out of its straight-line path is called a *centripetal force.* The centripetal force needed to keep an object in a circular path depends on the mass (m) of the object, its velocity (v), and the radius of the circle (r), or

$$F = \frac{mv^2}{r}$$

The *universal law of gravitation* is a relationship between the masses of two objects, the distance between the objects, and a proportionality constant. The relationship is

$$F = G\frac{m_1 m_2}{d^2}$$

Newton was able to use this relationship to show that gravitational attraction provides the centripetal force that keeps the Moon in its orbit. This relationship was found to explain the relationship between all parts of the Solar System.

Summary of Equations

3.1

$$\text{force} = \text{mass} \times \text{acceleration}$$

$$F = ma$$

3.2

$$\text{weight} = \text{mass} \times \text{acceleration due to gravity}$$

$$w = mg$$

3.3

$$\text{force on object A} = \text{force on object B}$$

$$F_{\text{A due to B}} = F_{\text{B due to A}}$$

3.4

$$\text{momentum} = \text{mass} \times \text{velocity}$$

$$p = mv$$

3.5

$$\text{centripetal acceleration} = \frac{\text{velocity squared}}{\text{radius of circle}}$$

$$a_c = \frac{v^2}{r}$$

3.6

$$\text{centripetal force} = \frac{\text{mass} \times \text{velocity squared}}{\text{radius of circle}}$$

$$F = \frac{mv^2}{r}$$

3.7

$$\text{gravitational force} = \text{constant} \times \frac{\text{one mass} \times \text{another mass}}{\text{distance squared}}$$

$$F = G\frac{m_1 m_2}{d^2}$$

KEY TERMS

centrifugal force (p. **57**)
centripetal force (p. **57**)
first law of motion (p. **48**)
law of conservation of momentum (p. **56**)
mass (p. **49**)
momentum (p. **55**)
newton (p. **51**)
second law of motion (p. **51**)
third law of motion (p. **54**)
universal law of gravitation (p. **59**)

APPLYING THE CONCEPTS

1. The law of inertia is another name for Newton's
- **a.** first law of motion.
- **b.** second law of motion.
- **c.** third law of motion.
- **d.** None of the above are correct.

2. The extent of resistance to a change of motion is determined by an object's
- **a.** weight.
- **b.** mass.
- **c.** density.
- **d.** All of the above are correct.

3. Mass is
- **a.** a measure of inertia.
- **b.** a measure of how difficult it is to stop a moving object.
- **c.** a measure of how difficult it is to change the direction of travel of a moving object.
- **d.** All of the above are correct.

4. A change in the state of motion is evidence of
- **a.** a force.
- **b.** an unbalanced force.
- **c.** a force that has been worn out after an earlier application.
- **d.** Any of the above are correct.

5. Considering the forces on the system of you and a bicycle as you pedal the bike at a constant velocity in a horizontal straight line,
- **a.** the force you are exerting on the pedal is greater than the resisting forces.
- **b.** all forces are in balance, with the net force equal to zero.
- **c.** the resisting forces of air and tire friction are less than the force you are exerting.
- **d.** the resisting forces are greater than the force you are exerting.

6. If you double the unbalanced force on an object of a given mass, the acceleration will be
- **a.** doubled.
- **b.** increased fourfold.
- **c.** increased by one-half.
- **d.** increased by one-fourth.

7. If you double the mass of a cart while it is undergoing a constant unbalanced force, the acceleration will be
- **a.** doubled.
- **b.** increased fourfold.
- **c.** half as much.
- **d.** one-fourth as much.

8. The acceleration of any object depends on
- **a.** only the net force acting on the object.
- **b.** only the mass of the object.
- **c.** both the net force acting on the object and the mass of the object.
- **d.** neither the net force acting on the object nor the mass of the object.

9. Which of the following is a measure of mass?
- **a.** pound
- **b.** newton
- **c.** kilogram
- **d.** All of the above are correct.

10. Which of the following is a correct unit for a measure of weight?
- **a.** kilogram
- **b.** newton
- **c.** kg·m/s
- **d.** None of the above are correct.

11. From the equation of $F = ma$, you know that m is equal to
- **a.** a/F
- **b.** Fa
- **c.** F/a
- **d.** $F - a$

12. A newton of force has what combination of units?
- **a.** kg·m/s
- **b.** kg/m^2
- **c.** $kg/m^2/s^2$
- **d.** $kg{\cdot}m/s^2$

13. Which of the following is *not* a unit or combination of units for a downward force?
- **a.** lb
- **b.** kg
- **c.** N
- **d.** $kg{\cdot}m/s^2$

14. Which of the following is a unit for a measure of resistance to a change of motion?
- **a.** lb
- **b.** kg
- **c.** N
- **d.** All of the above are correct.

15. Which of the following represents *mass* in the English system of measurement?
- **a.** lb
- **b.** $lb/ft/s^2$
- **c.** kg
- **d.** None of the above are correct.

16. The force that accelerates a car over a road comes from
    a. the engine.
    b. the tires.
    c. the road.
    d. All of the above are correct.
17. Ignoring all external forces, the momentum of the exhaust gases from a flying jet airplane that was initially at rest is
    a. much less than the momentum of the airplane.
    b. equal to the momentum of the airplane.
    c. somewhat greater than the momentum of the airplane.
    d. greater than the momentum of the airplane when the aircraft is accelerating.
18. Doubling the distance between the center of an orbiting satellite and the center of the earth will result in what change in the gravitational attraction of the earth for the satellite?
    a. one-half as much
    b. one-fourth as much
    c. twice as much
    d. four times as much
19. If a ball swinging in a circle on a string is moved twice as fast, the force on the string will be
    a. twice as great.
    b. four times as great.
    c. one-half as much.
    d. one-fourth as much.
20. A ball is swinging in a circle on a string when the string length is doubled. At the same velocity, the force on the string will be
    a. twice as great.
    b. four times as great.
    c. one-half as much.
    d. one-fourth as much.

Answers

1. a **2.** b **3.** d **4.** b **5.** b **6.** a **7.** c **8.** c **9.** c **10.** b **11.** c **12.** d **13.** b **14.** b **15.** b **16.** c **17.** b **18.** b **19.** b **20.** c

QUESTIONS FOR THOUGHT

1. Is it possible for a small car to have the same momentum as a large truck? Explain.
2. What net force is needed to maintain the constant velocity of a car moving in a straight line? Explain.
3. How can there ever be an unbalanced force on an object if every action has an equal and opposite reaction?
4. Compare the force of gravity on an object at rest, the same object in free fall, and the same object moving horizontally to the surface of the earth.
5. Is it possible for your weight to change as your mass remains constant? Explain.
6. What maintains the *speed* of Earth as it moves in its orbit around the Sun?
7. Suppose you are standing on the ice of a frozen lake and there is no friction whatsoever. How can you get off the ice? (HINT: Friction is necessary to crawl or walk, so that will not get you off the ice.)
8. A rocket blasts off from a platform on a space station. An identical rocket blasts off from free space. Considering everything else to be equal, and the space station to have negligible mass, will the two rockets have the same acceleration? Explain.
9. An astronaut leaves a spaceship, moving through free space to adjust an antenna. Will the spaceship move off and leave the astronaut behind? Explain.
10. Is a constant force necessary for a constant acceleration? Explain.
11. Is an unbalanced force necessary to maintain a constant speed? Explain.
12. Use Newton's laws of motion to explain why water leaves the wet clothes when a washer is in the spin cycle.

PARALLEL EXERCISES

The exercises in groups A and B cover the same concepts. Solutions to group A are located in appendix D.

NOTE: *Neglect all frictional forces in all exercises.*

Group A

1. What force is needed to give a 40.0 kg grocery cart an acceleration of 2.4 m/s^2?
2. What is the resulting acceleration when an unbalanced force of 100 N is applied to a 5 kg object?
3. What force is needed to accelerate a 1,000 kg car from 72 to 108 km/hr over a time period of 5 s?
4. An unbalanced force of 18 N is needed to give an object an acceleration of 3 m/s^2. What force is needed to give this very same object an acceleration of 10 m/s^2?
5. A rocket pack with a thrust of 100 N accelerates a weightless astronaut at 0.5 m/s^2 through free space. What is the mass of the astronaut and equipment?

Group B

1. What force would an asphalt road have to give a 6,000 kg truck in order to accelerate it at 2.2 m/s^2 over a level road?
2. Find the resulting acceleration from a 300 N force acting on an object with a mass of 3,000 kg.
3. How much time would be required to stop a 2,000 kg car that is moving at 80.0 km/hr if the braking force is 8,000 N?
4. If a space probe weighs 39,200 N on the surface of Earth, what will be the mass of the probe on the surface of Mars?
5. On the earth, an astronaut and equipment weigh 1,960 N. Weightless in space, the motionless astronaut and equipment are accelerated by a rocket pack with a 100 N thruster that fires for 2 s. What is the resulting final velocity?

6. A 1,500 kg car is to be pulled across level ground by a towline from another car. If the pulling car accelerates at 2 m/s^2, what force (tension) must the towline support without breaking?
7. What is the gravitational force the Earth exerts on the Moon if the Earth has a mass of 5.98×10^{24} kg, the Moon has a mass of 7.36×10^{22} kg, and the Moon is on the average a center-to-center distance of 3.84×10^{8} m from Earth?
8. What is the acceleration of gravity at an altitude of 500 kilometers above the earth's surface?
9. What would a student who weighs 591 N on the surface of the earth weigh at an altitude of 1,100 kilometers from the surface?
10. What is the momentum of a 100 kg football player who is moving at 6 m/s?
11. A car weighing 13,720 N is speeding down a highway with a velocity of 91 km/hr. What is the momentum of this car?
12. Car A has a mass of 1,200 kg and is driving north at 25 m/s when it collides head-on with car B, which has a 2,200 kg mass and is moving at 15 m/s. If the collision is exactly head-on and the cars lock together, which way will the wreckage move?
13. A 15 g bullet is fired with a velocity of 200 m/s from a 6 kg rifle. What is the recoil velocity of the rifle?
14. An astronaut and equipment weigh 2,156 N on earth. Weightless in space, the astronaut throws away a 5.0 kg wrench with a velocity of 5.0 m/s. What is the resulting velocity of the astronaut in the opposite direction?
15. A student and her boat have a combined mass of 100.0 kg. Standing in the motionless boat in calm water, she tosses a 5.0 kg rock out the back of the boat with a velocity of 5.0 m/s. What will be the resulting speed of the boat?
16. (a) What is the weight of a 1.25 kg book? (b) What is the acceleration when a net force of 10.0 N is applied to the book?
17. What net force is needed to accelerate a 1.25 kg book 5.00 m/s^2?
18. What net force does the road exert on a 70.0 kg bicycle and rider to give them an acceleration of 2.0 m/s^2?
19. A 1,500 kg car accelerates uniformly from 44.0 km/hr to 80.0 km/hr in 10.0 s. What was the net force exerted on the car?
20. A net force of 5,000.0 N accelerates a car from rest to 90.0 km/hr in 5.0 s. (a) What is the mass of the car? (b) What is the weight of the car?
21. What is the weight of a 70.0 kg person?
22. A 1,000.0 kg car at rest experiences a net force of 1,000.0 N for 10.0 s. What is the final speed of the car?
23. What is the momentum of a 50 kg person walking at a speed of 2 m/s?
24. How much centripetal force is needed to keep a 0.20 kg ball on a 1.50 m string moving in a circular path with a speed of 3.0 m/s?
25. What is the velocity of a 100.0 g ball on a 50.0 cm string moving in a horizontal circle that requires a centripetal force of 1.0 N?
26. A 1,000.0 kg car moves around a curve with a 20.0 m radius with a velocity of 10.0 m/s. (a) What centripetal force is required? (b) What is the source of this force?
27. On earth, an astronaut and equipment weigh 1,960.0 N. While weightless in space, the astronaut fires a 100 N rocket backpack for 2.0 s. What is the resulting velocity of the astronaut and equipment?

6. What force is applied to the seatback of an 80.0 kg passenger on a jet plane that is accelerating at 5 m/s^2? How does this force compare to the weight of the person?
7. Calculations show that acceleration due to gravity is 1.63 m/s^2 at the surface of the moon, and the distance to the center of the moon is 1.74×10^{6} m. Use these figures to calculate the mass of the moon.
8. An astronaut and space suit weigh 1,960 N on the earth. What weight would they have on the moon, where gravity has a value of 1.63 m/s^2?
9. To what altitude above the earth's surface would you need to travel to have half your weight?
10. What is the momentum of a 30.0 kg shell fired from a cannon with a velocity of 500 m/s?
11. What is the momentum of a 39.2 N bowling ball with a velocity of 7.00 m/s?
12. A 39.2 N bowling ball moving at 7.00 m/s collides head on with a 29.4 N bowling ball that is moving at 9.33 m/s. Which way will the balls move after the impact?
13. A 30.0 kg shell is fired from a 2,000 kg cannon with a velocity of 500 m/s. What is the resulting velocity of the cannon?
14. An 80.0 kg man is standing on a frictionless ice surface when he throws a 4.00 kg book at 20.0 m/s. With what velocity does the man move across the ice?
15. A person with a mass of 70.0 kg steps horizontally from the side of a 300.0 kg boat at 2.00 m/s. What happens to the boat?
16. (a) What is the weight of a 5.00 kg backpack? (b) What is the acceleration of the backpack if a net force of 10.0 N is applied?
17. What net force is required to accelerate a 20.0 kg object to 10.0 m/s^2?
18. What forward force must the ground apply to the foot of a 60.0 kg person to result in an acceleration of 1.00 m/s^2?
19. A 1,000.0 kg car accelerates uniformly to double its speed from 36.0 km/hr in 5.00 s. What net force acted on this car?
20. A net force of 3,000.0 N accelerates a car from rest to 36.0 km/hr in 5.00 s. (a) What is the mass of the car? (b) What is the weight of the car?
21. How much does a 60.0 kg person weigh?
22. A 60.0 gram tennis ball is struck by a racket with a force of 425.0 N for 0.01 s. What is the speed of the tennis ball in km/hr as a result?
23. Compare the momentum of (a) a 2,000.0 kg car moving at 25.0 m/s and (b) a 1,250 kg car moving at 40.0 m/s.
24. What tension must a 50.0 cm length of string support in order to whirl an attached 1,000.0 gram stone in a circular path at 5.00 m/s?
25. What is the maximum speed at which a 1,000.0 kg car can move around a curve with a radius of 30.0 m if the tires provide a maximum frictional force of 2,700.0 N?
26. How much centripetal force is needed to keep a 60.0 kg person and skateboard moving at 6.0 m/s in a circle with a 10.0 m radius?
27. A 200.0 kg astronaut and equipment move with a velocity of 2.00 m/s toward an orbiting spacecraft. How long will the astronaut need to fire a 100.0 N rocket backpack to stop the motion relative to the spacecraft?