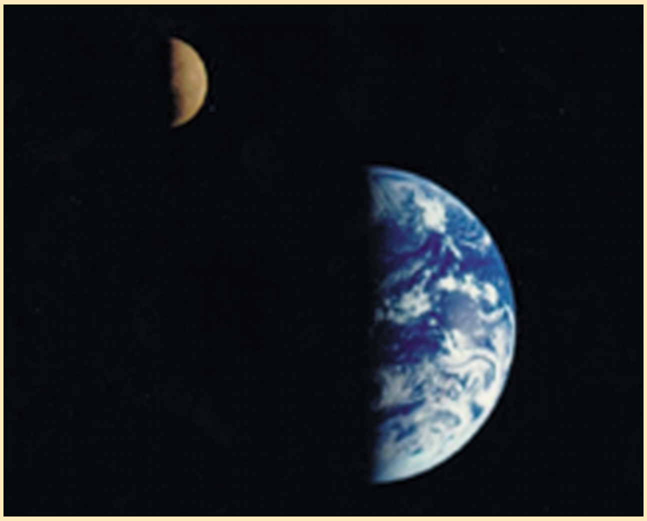
CHAPTER

4

# Newton's Laws: Explaining Motion



## Chapter Overview

The primary purpose of this chapter is to explain Newton's three laws of motion and how they apply in familiar situations. We begin with a historical sketch of their development and then proceed to a careful discussion of each law. The concepts of force, mass, and weight play critical roles in this discussion. We conclude the chapter by applying Newton's theory to several familiar examples.

## Chapter Outline

1 **A brief history.** Where do our ideas and theories about motion come from? What roles were played by Aristotle, Galileo, and Newton?

2 **The first and second laws of motion.** How do forces affect the motion of an object? What do Newton's first and second laws of motion tell us, and how are they related to one another?

3 **Mass and weight.** How can we define mass? What is the distinction between mass and weight?

4 **The third law of motion.** Where do forces come from? How does Newton's third law of motion help us to define force, and how is it applied?

5 **Applications of Newton's laws.** How can Newton's laws be applied in different situations such as pushing a chair, sky diving, throwing a ball, and pulling two connected carts across the floor?

A large person gives you a shove, and you move in the direction of that push. A child pulls a toy wagon with a string, and the wagon lurches along. An athlete kicks a football or a soccer ball, and the ball is launched toward the goal. These are familiar examples involving forces in the form of pushes or pulls that cause changes in motion.

To pick a less complex example, imagine yourself pushing a chair across a wood or tile floor (fig. 4.1). Why does the chair move? Will it continue its motion if you stop pushing? What factors determine the velocity of the chair? If you push harder, will the chair's velocity increase? Up to this point, we have introduced ideas useful in describing motion, but we have not talked much about what causes changes in motion. Explaining motion is more challenging than describing it.

You already have some intuitive notions about what causes the chair to move. Certainly, the push that you exert on the chair has something to do with it. But is the strength of that push more directly related to the velocity of the chair or to its acceleration? At this point, intuition often serves us poorly.

Over two thousand years ago, the Greek philosopher Aristotle (384–322 B.C.) attempted to provide answers to some of these questions. Many of us would find that his explanations match our intuition for the case of the moving chair, but they are less satisfactory in the case of a thrown object where the push is not sustained. Aristotle's ideas were widely accepted until they were replaced by a theory introduced by Isaac Newton in the seventeenth century. Newton's theory of motion has proved to be a much more complete and satisfactory explanation of motion, and it permits quantitative predictions that were largely lacking in Aristotle's ideas.

***Figure 4.1*** Moving a chair. Will the chair continue to move when the person stops pushing?

Newton's three laws of motion form the foundation of his theory. What are these laws and how are they used in explaining motion? How do Newton's ideas differ from those of Aristotle, and why do Aristotle's ideas often seem to fit our commonsense notions of what is happening? A good understanding of Newton's laws will permit you to analyze and explain almost any simple motion. This understanding will provide you with insights useful in driving a car, moving heavy objects, and many other everyday activities.

## ■ 4.1 A BRIEF HISTORY

Did some genius, sitting under an apple tree, concoct a full-blown theory of motion in a sudden, blinding flash of inspiration? Not quite. The story of how theories are developed and gain acceptance involves many players over long periods of time.

Let's highlight the roles of a few key people whose insights produced major advances. A glimpse of this history can help you appreciate the physical concepts we will discuss by showing when and how the theories emerged. It is important, for example, to know whether a theory was just proposed yesterday or has been tried and tested over a long time. Not all theories carry equal weight in their acceptance and use by scientists. Aristotle, Galileo, and Newton were major players in shaping our views of the causes of motion.

### *Aristotle's view of the cause of motion*

Questions about the causes of motion and changes in motion had perplexed philosophers and other observers of nature for centuries. For over a thousand years, Aristotle's views prevailed. Aristotle was an astute and careful observer of nature. Aristotle investigated an incredible range of subjects, and he (or perhaps his students) produced extensive writings on topics such as logic, metaphysics, politics, literary criticism, rhetoric, psychology, biology, and physics.

In his discussions of motion, Aristotle conceived of force much as we have talked about it to this point: as a push or pull acting on an object. He believed that a force had to act for an object to move and that the velocity of the object was proportional to the strength of the force. A heavy object would fall more quickly toward the earth than a lighter object, because there was a larger force pulling the object to the earth. The strength of this force could be appreciated simply by holding the object in your hand.

Aristotle was also aware of the resistance that a medium offers the motion of an object. A rock falls more rapidly through air than through water. Water provides greater resistance to motion than air, as you surely know from trying to walk through waist-deep water at the beach. Aristotle thus saw the velocity of the object as being proportional to the force acting on it and inversely related to the resistance, but he never defined the concept of resistance quantitatively. He did not distinguish acceleration from velocity, and he spoke of velocity by stating the time required to cover a fixed distance.

Aristotle was an observer of nature rather than an experimenter. He did not make quantitative predictions that he checked by experiment. Even without such tests, however, some problems with his basic ideas of motion troubled Aristotle himself, as well as later thinkers. For example, in the case of a thrown ball or rock, the force that initially propels the object no longer acts once the ball leaves the hand. What keeps the ball moving?

Since the ball does keep moving for some time after leaving the hand that throws it, a force was necessary, according to Aristotle's theory. He suggested that the force that maintains the motion once the ball leaves the hand is provided by air rushing around to fill the vacuum in the spot where the ball has just been (fig. 4.2). This flow of air then pushes the ball from behind. Does this seem reasonable?

Following the decline of the Roman Empire, only fragments of Aristotle's writings were known to European thinkers for several centuries. His complete works, which had been preserved by Arab scholars, did not resurface in Europe until the twelfth century. Along with the work of other Greek thinkers, Aristotle's works were translated into Latin during the twelfth and thirteenth centuries.

### How did Galileo challenge Aristotle's views?

By the time that the Italian scientist Galileo Galilei (1564–1642) came on the scene, Aristotle's ideas were well established at European universities, including the universities of Pisa and Padua where Galileo studied and taught. In fact, education at the universities was organized around the disciplines defined by Aristotle, and much of Aristotle's natural philosophy had been incorporated into the teaching of the Roman Catholic Church. The Italian theologian Thomas Aquinas had carefully interwoven Aristotle's thinking with the theology of the church.

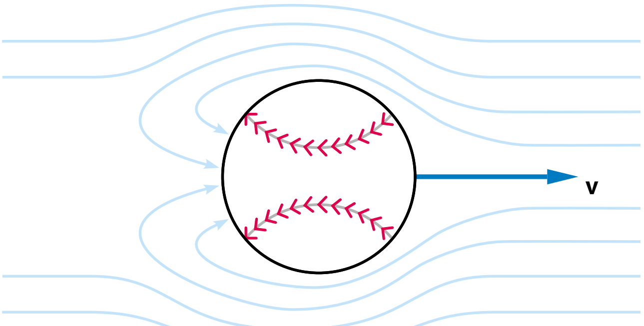



*Figure 4.2* Aristotle pictured air rushing around a thrown object to continue pushing the object forward. Does this picture seem reasonable?

To challenge Aristotle was equivalent to challenging the authority of the church and could carry heavy consequences. Galileo was not alone in questioning Aristotle's ideas on motion; others had noted that dropped objects of similar form but radically different weights fall at virtually the same rate, contrary to Aristotle's theory. Although Galileo may never have dropped objects from the Leaning Tower of Pisa, he did perform careful experiments with dropped objects and actively publicized his results.

Galileo's primary problems with the church came from advocating the ideas of Copernicus. Copernicus had proposed a sun-centered (*heliocentric*) model of the solar system (discussed in chapter 5), which opposed the prevailing earth-centered models of Aristotle and others. Galileo was an activist on several fronts in challenging Aristotle and the traditional thinking. This placed him in conflict with many of his university colleagues and with members of the church hierarchy. He was eventually tried by the Inquisition and found guilty of heresy. He was placed under house arrest and forced to retract some of his teachings.

In addition to his work on falling objects, Galileo developed new ideas on motion that contradicted Aristotle's theory. Galileo argued that the natural tendency of a moving object is to continue moving: no force is required to maintain this motion. (Think about the pushed chair again. Does this statement make sense in that situation?) Building on the work of others, Galileo also developed a mathematical description of motion that included acceleration. The relationship $d = \frac{1}{2}at^2$ for the distance covered by a uniformly accelerating object was carefully demonstrated by Galileo. He published many of these ideas near the end of his life in his famous *Dialogues Concerning Two New Sciences.*

### What did Newton accomplish?

Isaac Newton (1642–1727; fig. 4.3) was born in England the same year that Galileo died in Italy. Building on the work of Galileo, he proposed a theory of the causes of motion that could explain the motion of any object—the motion of ordinary objects such as a ball or chair as well as the motion of heavenly bodies such as the moon and the planets. In the Greek tradition, celestial motions were thought of as an entirely different realm from earthbound motions, thus requiring different explanations. Newton abolished this distinction by explaining both terrestrial and celestial mechanics with one theory.

The central ideas in Newton's theory are his three laws of motion (discussed in this chapter) and his law of universal gravitation (discussed in chapter 5). Newton's theory provided successful explanations of aspects of motion already known and offered a framework for many new studies in physics and astronomy. Some of these studies led to predictions of phenomena not previously observed. For example,

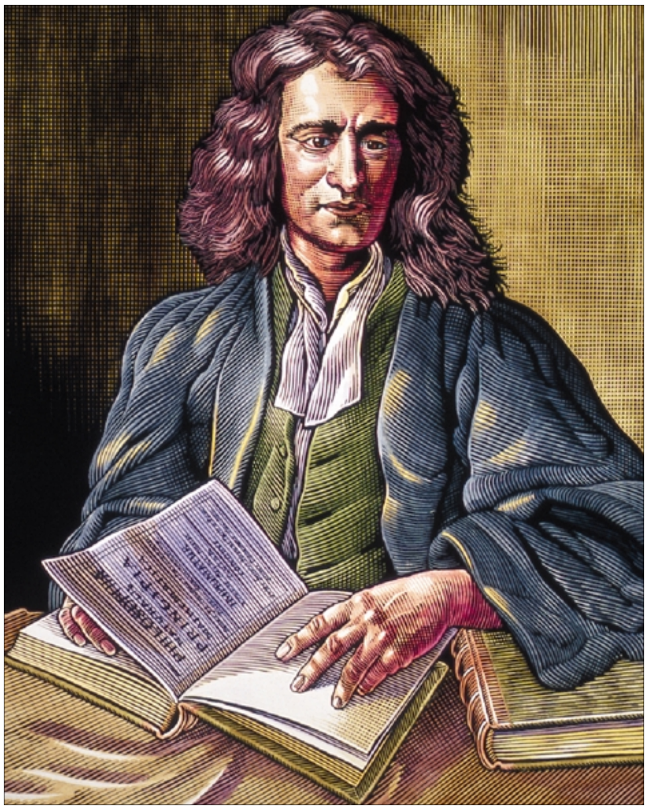


***Figure 4.3*** A portrait of Isaac Newton.

calculations applying Newton's theory to irregularities in the orbits of the known planets led to the prediction of the existence of Neptune, which was quickly confirmed by observation. Confirmed predictions are one of the marks of a successful theory. Newton's theory served as the basic theory of mechanics for over two hundred years and is still used extensively in physics and engineering.

Newton developed the basic ideas of his theory around 1665, when he was still a young man. To avoid the plague, he had returned to his family's farm in the countryside where he had time to engage in serious thought with little interruption. He may have spent some time sitting under apple trees. The story has it that seeing an apple fall led to his insight that the moon also falls toward the earth and that the force of gravity is involved in both cases. (See chapter 5.) Flashes of insight or inspiration were surely a part of the process.

Although Newton developed much of his theory and its details in 1665, he did not formally publish his ideas until 1687. One reason for this delay was his need to develop some of the mathematical techniques required to calculate the effects of the proposed gravitational force on objects such as planets. (He is generally credited with being the coinventor of what we now call *calculus*.) The English title of Newton's 1687 treatise is *The Mathematical Principles of Natural Philosophy* (*Philosophiae Naturalis Principia Mathematica* in Latin), which is often referred to as Newton's *Principia.*

Scientific theories like Newton's do not just emerge in an intellectual vacuum. They are products of their time and the state of knowledge and worldview current then. They usually replace earlier and often cruder theories. The accepted theory of motion in Newton's day was still that of Aristotle, although it had come under attack by Galileo and others. Its shortcomings were generally recognized. Newton provided the capstone for a revolution in thought that was already well underway.

Although Aristotle's ideas on motion are now considered unsatisfactory and are worthless for making quantitative predictions, they do have an intuitive appeal much like our own untrained thinking about motion. For this reason, we often speak of the need to replace Aristotelian ideas about motion with Newtonian concepts as we learn mechanics. Even though our own naive ideas about motion are not usually as fully developed as those of Aristotle, you may find that some of your commonsense notions will require modification.

Newton's theory, in turn, has been partially superseded by more sophisticated theories that provide more accurate descriptions of motion. These include Einstein's theory of relativity as well as the theory of quantum mechanics, both of which arose early in the twentieth century. Although the predictions of these theories differ substantially from Newton's theory in the realm of the very fast (in the case of relativity) and the very small (quantum mechanics), they differ insignificantly for the motion of ordinary objects traveling at speeds much less than that of light. Newton's theory was a tremendous step forward and is still used extensively to analyze motion of ordinary objects.

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*Aristotle's ideas on motion, although not capable of making quantitative predictions, provided explanations that were widely accepted for many centuries and that fit well with some of our own commonsense thinking. Galileo challenged Aristotle's ideas on free fall as well as his general assumption that a force was required to keep an object in motion. Building on Galileo's work, Newton developed a more comprehensive theory of motion that replaced Aristotle's ideas. Newton's theory is still widely used to explain ordinary motions.*

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## ■ 4.2 NEWTON'S FIRST AND SECOND LAWS

If we push a chair across the floor, what causes the chair to move or to stop moving? Newton's first two laws of motion address these questions and, in the process, provide part of a definition of **force.** The first law tells us what happens in the absence of a force, and the second describes the effects of applying a force to an object.

We discuss the first and second laws of motion together because the first law is actually a special case of the more general second law. Newton felt the need to state the first law separately, however, to counter strongly held Aristotelian ideas about motion. In doing so, Newton was following the lead of Galileo, who had stated a principle similar to Newton's first law several years earlier.

### Newton's first law of motion

In language not too different from his own, **Newton's first law of motion** can be stated as follows:

> An object remains at rest, or in uniform motion in a straight line, unless it is compelled to change by an externally imposed force.

In other words, unless there is a force acting on the object, its *velocity* will not change. If it is initially at rest, it will remain at rest; if it is moving, it will continue to do so with constant velocity (fig 4.4).

Notice that, in paraphrasing Newton's first law, we have used the term *velocity* rather than the term *speed.* Constant velocity implies that neither the direction nor the magnitude of the velocity changes. When the object is at rest, its velocity is zero, and that value remains constant in the absence of a force. If there is no force, the acceleration of the object is zero. The velocity does not change.

Although this law seems simple enough, it directly contradicts Aristotle's ideas (and perhaps your own intuition as well). Aristotle believed that a force is required to keep an object moving. His views make intuitive sense if we are talking about moving a heavy object such as the chair mentioned in our introduction. If you stop pushing, the chair stops moving. This view encounters problems, however, if we consider the motion of a thrown ball, or even a chair moving on a slippery surface. These objects continue to move after the initial push. Newton (and Galileo) made the strong statement that no force is needed to keep an object moving.

How can Aristotle's ideas be so different from those of Newton and Galileo and yet seem so reasonable in some situations? The key to answering that question involves the existence of resistive or **frictional forces.** The chair does not move far after you stop pushing because the frictional forces of the floor acting on the chair cause the velocity to quickly decrease to zero. A thrown ball would eventually stop moving, even if it did not fall to the ground, because the force of air resistance is pushing against it. It is really quite difficult to find a situation in which there are *no* forces acting upon an object. Aristotle recognized the presence of air resistance and similar effects but did not treat them as forces in his theory.

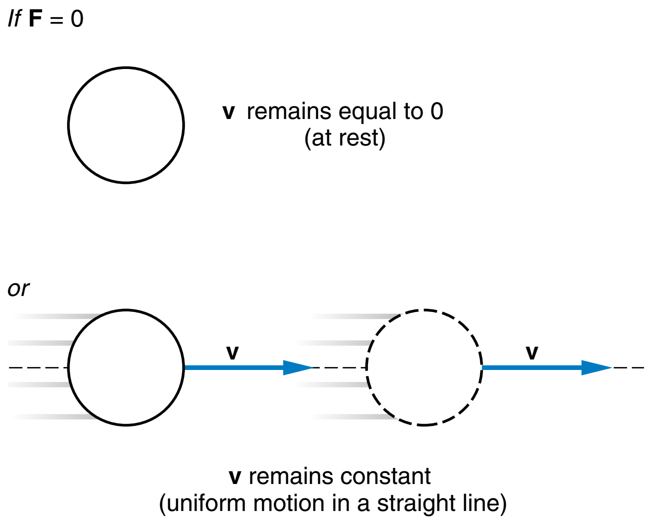



*Figure 4.4* Newton's first law: In the absence of a force, an object remains at rest or moves with constant velocity.

### How is force related to acceleration?

**Newton's second law of motion** is a more complete statement about the effect of an imposed force on the motion of an object. Stated in terms of acceleration, it says the following:

> The acceleration of an object is directly proportional to the magnitude of the imposed force and inversely proportional to the mass of the object. The acceleration is in the same direction as that of the imposed force.

This statement is most easily grasped in symbolic form. By choosing appropriate units for force, we can state the proportionality of Newton's second law as the equation:

$$\mathbf{a} = \frac{\mathbf{F}}{m},$$

where **a** is the acceleration, **F** is the total force acting on the object, and $m$ is the mass of the object. Since the acceleration is directly proportional to the imposed force, if we double the force acting on the object, we double the acceleration of the object. The same force acting on an object with a larger mass, however, will produce a smaller acceleration (fig. 4.5).

Note that the *acceleration* is directly related to the imposed force, not the velocity. Aristotle did not make a clear distinction between acceleration and velocity. Many of us also fail to make the distinction when we think informally about motion. In Newton's theory, this distinction is critical.

Newton's second law is *the* central idea of his theory of motion. According to this law, the acceleration of an object is determined by two quantities: the total force acting on the object and the mass of the object. In fact, the concepts of

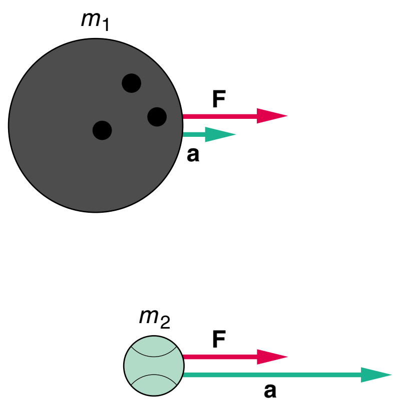



*Figure 4.5* The smaller-mass object experiences a larger acceleration than the larger-mass object when identical forces are applied to the two objects.

force and mass are, in part, defined by the second law. The total force acting on the object is the cause of its acceleration, and the magnitude of the force is defined by the size of the acceleration that it produces. Newton's third law, discussed in section 4.4, completes the definition of force by noting that forces result from interaction of the object with other objects.

The **mass** of an object is a quantity that tells us how much resistance an object has to a change in its motion, as indicated by the second law. We call this resistance to a change in motion **inertia,** following Galileo. We can define mass as follows:

> Mass is a measure of an object's inertia, the property that causes it to resist a change in its motion.

The standard metric unit for mass is the kilogram (kg). We will say more about the determination of mass and its relationship to the weight of an object shortly (section 4.3).

Units of force can also be derived from Newton's second law. If we multiply both sides of the second-law equation by the mass, it can be expressed as

$$\mathbf{F} = m\mathbf{a}.$$

The appropriate unit for force must therefore be the product of a unit of mass and a unit of acceleration, or in the metric system, kilograms times meters per second squared. This frequently used unit is called the **newton** (N). Accordingly,

$$1 \text{ newton} = 1 \text{ N} = 1 \text{ kg·m/s}^2.$$

### *How do forces add?*

Our version of the second law implies that the imposed force is the *total* or **net force** acting on the object. Force is a vector quantity whose direction is clearly important. If there is more than one force acting on an object, as there often is, we must then add these forces as vectors, taking into account their directions.

This process is illustrated in figure 4.6 and the sample exercise in Try This Box 4.1. A block is being pulled across a table by a force of 10 N applied through a string attached to the block. A frictional force of 2 N acts on the block, a result of contact with the table. What is the total force acting on the block?

Is the total force the numerical sum of the two forces, 10 N plus 2 N or 12 N? Looking at the diagram in figure 4.6 should convince you that this cannot be true. The two forces oppose one another. Because the forces are in opposite directions, the total force is found by subtracting the frictional force from the force applied by the string, resulting in a net force of 8 N. We cannot ignore the directions of the forces involved.

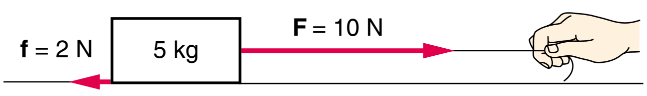



*Figure 4.6* A block being pulled across a table. Two horizontal forces are involved.

**Try This Box 4.1**

#### Sample Exercise: Finding the Net Force

A block with a mass of 5 kg is being pulled across a tabletop by a force of 10 N applied by a string tied to the front end of the block (fig 4.6). The table exerts a 2-N frictional force on the block. What is the acceleration of the block?

$\mathbf{F}_{\text{string}} = 10$ N (to the right)
$\mathbf{f}_{\text{table}} = 2$ N (to the left)
$m = 5$ kg
$\mathbf{a} = ?$

$F = F_{\text{string}} - f_{\text{table}}$
$= 10 \text{ N} - 2 \text{ N} = 8 \text{ N}$
$\mathbf{F} = 8$ N (to the right)

$$a = \frac{F}{m} = \frac{8 \text{ N}}{5 \text{ kg}} = \mathbf{1.6\ m/s^2}$$

**($\mathbf{a}$ = 1.6 m/s² to the right)**

That forces are vectors whose directions must be taken into account when finding the net force is an important aspect of the second law. For forces restricted to one dimension, as in box 4.1, finding the total force is not difficult. In problems involving forces in two or three dimensions, addition is more complex but can be accomplished using techniques described in appendix C. In this chapter we will only consider one-dimensional cases.

A final point about Newton's first and second laws bears repeating: the first law is a special case of the second law. This can be seen by asking what happens, according to the second law, when the total force acting on an object is zero. In this case, the acceleration $\mathbf{a} = \mathbf{F}/m$ must also be zero. If the acceleration is zero, the velocity must be constant. The first law tells us that if the total force is zero, the object moves with constant velocity (or remains at rest). Newton's first law addresses the special case of the second law in which the total force acting on an object is zero.

*The central principle in Newton's theory of motion is his second law of motion. This law states that the acceleration of an object is proportional to total force applied to the object and inversely proportional to the mass of the object. The mass of an object is its inertia or resistance to change in motion. Newton's first law is a special case of the second law when the total force acting on the object is zero. To find the total force acting on the object, we take into account the directions of the individual forces and add them as vectors.*

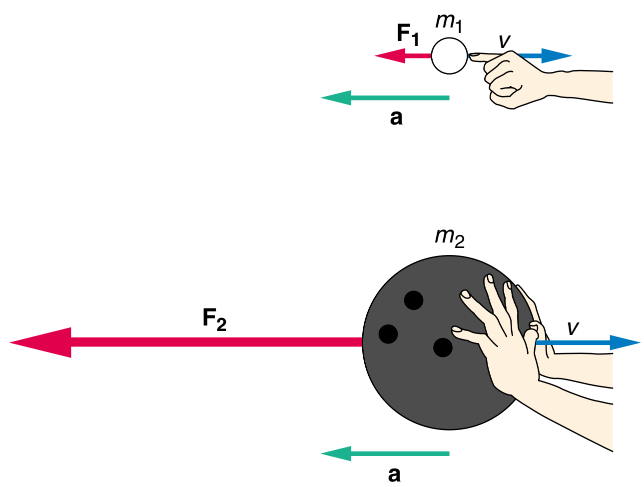



*Figure 4.7* Stopping a bowling ball and a ping-pong ball. A much larger force is required to produce the same *rate* of change in velocity for the larger mass.

## ■ 4.3 MASS AND WEIGHT

What exactly is **weight**? Is your *weight* the same as your *mass,* or is there a difference in the meaning of these two terms? Clearly, mass plays an important role in Newton's second law. *Weight* is a familiar term often used interchangeably with *mass* in everyday language. Here again, physicists make a distinction between mass and weight that is important to Newton's theory.

### *How can masses be compared?*

From the role that mass plays in Newton's second law, we can devise experimental methods of comparing masses. Mass is defined as the property of matter that determines how much an object resists a change in its motion. The greater the mass, the greater the *inertia* or resistance to change, and the smaller the acceleration provided by a given force. Imagine, for example, trying to decelerate a bowling ball and a ping-pong ball that are moving initially with equal velocities (fig. 4.7). A much greater force is required to decelerate the bowling ball than the ping-pong ball because of the difference in mass. According to the second law, the force required is proportional to the mass.

In effect, we are using Newton's second law to define mass. If we used the same force to accelerate different masses, the different accelerations could be used to compare the masses involved. If we choose one mass as a standard, any other mass can be measured against the standard mass by comparing the accelerations produced by equal forces. We could, in principle, determine the mass of any object this way.

### *How do we define weight?*

In practice, the method just described is not convenient for comparing masses because of the difficulty of measuring acceleration. The more common method of comparing masses is to "weigh" the objects on a balance or scale (fig. 4.8). What we actually do in weighing is to compare the gravitational force acting on the mass we wish to measure with that acting on some standard mass. The gravitational force acting on an object is the **weight** of the object. As a force, weight has different units (newtons) than mass (kilograms).

How is weight related to mass? From our discussion of gravitational acceleration in the previous chapter, we know that objects of different mass experience the same gravitational acceleration near the earth's surface ($g$ = 9.8 m/s$^2$). This acceleration is caused by the gravitational force exerted by the earth on the object, which is the weight of the object. By Newton's second law, the force (the weight) is equal to the mass times the acceleration or

$$\mathbf{W} = m\mathbf{g}.$$

The symbol $\mathbf{W}$ represents the weight. It is a vector whose direction is straight down toward the center of the earth.

If we know the mass of an object, we can then compute its weight. An example is provided in Try This Box 4.2, where we show that a woman with a mass of 50 kg has a weight of 490 N. Since we are more used to expressing weights in the English system, we also convert her weight in newtons to pounds (lb), which yields a weight of 110 lb. The pound is most commonly used as a unit of *force,* not mass, in the English system. A mass of 1 kg weighs approximately 2.2 lb near the surface of the earth.

Although weight is proportional to mass, it also depends on the gravitational acceleration $g$. Since $g$ varies slightly from place to place on the surface of the earth—and has a much smaller value on the moon or the smaller planets—the weight of an object clearly depends on where that object is. On the other hand, the mass of an object is a property of the object related to the quantity of matter making up that object and does not depend on the location of the object.

If we transported the woman whose weight we have just determined to the moon, her weight would decrease to about 18 lb (or 82 N). The gravitational acceleration on the moon is approximately one-sixth that on the surface of the earth. The woman's mass would still be 50 kg, provided that the trip did not take too much out of her. The mass of an object changes only if we add or subtract matter from it.

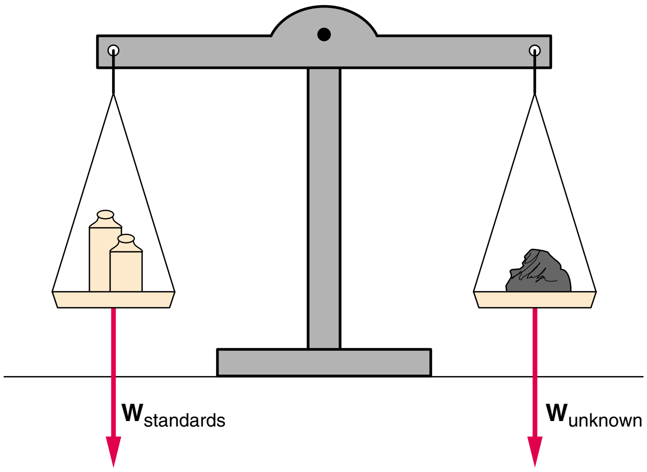



*Figure 4.8* Comparing an unknown mass to standard masses on a balance.

### *Try This Box 4.2*

**Sample Exercise: Computing Weights**

Suppose that a woman has a mass of 50 kg. What is her weight in

a. newtons?
b. pounds?

**a.** $m = 50$ kg  $W = mg$

$W = ?$  $= (50\text{ kg})(9.8\text{ m/s}^2)$

$= \mathbf{490\ N}$

**b.** $W = ?$ in pounds

1 lb = 4.45 N  $W = \dfrac{490\text{ N}}{4.45\text{ N/lb}}$

$= \mathbf{110\ lb}$

### *Why is the gravitational acceleration independent of mass?*

The distinction between weight and mass can provide insight into why the gravitational acceleration is independent of mass. Let's turn to the case of a falling object and consider its motion using Newton's second law. Reversing the argument that we used in defining weight, we use the gravitational force (the weight) to determine the acceleration. By Newton's second law, the acceleration can be found by dividing the force ($\mathbf{W} = m\mathbf{g}$) by the mass:

$$\mathbf{a} = \frac{m\mathbf{g}}{m} = \mathbf{g}.$$

Mass cancels out of the equation when we compute the acceleration for a falling object. The gravitational force is proportional to the mass, but by Newton's second law, the acceleration is inversely proportional to the mass: these two effects cancel one another. This only holds true for falling objects. In most other cases, the net force does not depend directly on the mass.

Force and acceleration are *not* the same, although they are closely related by Newton's second law. A heavy object experiences a larger gravitational force (its weight) than a lighter object, but the two objects will have the same gravitational acceleration (fig. 4.9). Because the gravitational force is proportional to mass, we find the same acceleration for different masses. The gravitational force will be discussed further in chapter 5 when we take up Newton's law of gravitation, a critical piece of his overall theory of motion.

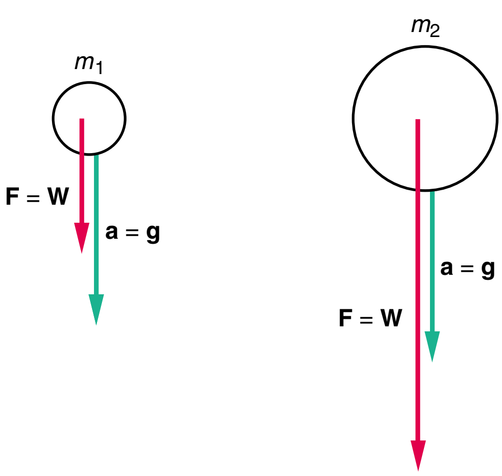



*Figure 4.9* Different gravitational forces (weights) act on falling objects of different masses, but because acceleration is inversely proportional to mass, the objects have the same acceleration.

*Weight and mass are not the same. Weight is the gravitational force acting on an object, and mass is an inherent property related to the amount of matter in the object. Near the surface of the earth, weight is equal to the mass multiplied by the gravitational acceleration ($\mathbf{W} = m\mathbf{g}$), but the weight would change if we took the object to another planet where* **g** *has a different value. The reason that all objects experience the same gravitational acceleration near the earth's surface is that the gravitational force is proportional to the mass of the object, but acceleration is equal to the force divided by the mass.*

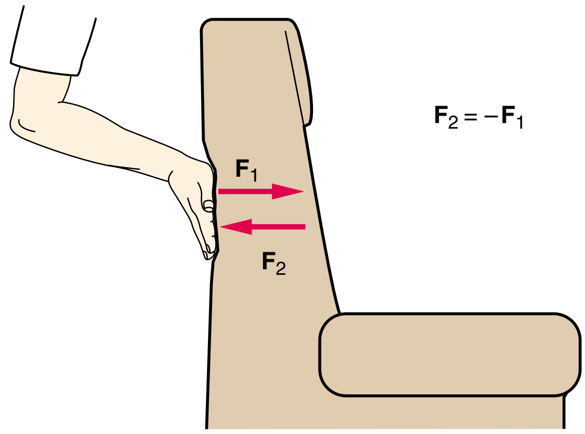



*Figure 4.10* The chair pushes back on the hand with a force $\mathbf{F}_2$ that is equal in size but opposite in direction to the force $\mathbf{F}_1$ exerted by the hand on the chair.

## ■ 4.4 NEWTON'S THIRD LAW

Where do forces come from? If you push on a chair to move it across the floor, does the chair also push back on you? If so, how does that push affect your own motion? Questions like these are important to what we mean by *force.* Newton's third law provides some answers.

**Newton's third law of motion** is an important part of his definition of force. It is an essential tool for analyzing the motion or lack of motion of real objects, but it is often misunderstood. For this reason, it is good to take a careful look at the statement and use of the third law.

### *How does the third law help us to define force?*

If you push with your hand against a large chair or any large object, such as the wall of your room, you will feel the object push back against your hand. A force is acting on your hand that you can sense as it compresses your hand. Your hand is interacting with the chair or wall, and that object pushes back against your hand as you push against the object.

Newton's third law contains the idea that forces are caused by such interactions of two objects, each exerting a force on the other. It can be stated as follows:

> If object A exerts a force on object B, object B exerts a force on object A that is equal in magnitude but opposite in direction to the force exerted on B.

The third law is sometimes referred to as the **action/reaction principle**—for every action there is an equal but opposite reaction. Note that the two forces always act on two *different* objects, never on the same object. Newton's definition of force includes the idea of an *interaction* between objects. The forces represent that interaction.

If you exert a force $\mathbf{F}_1$ on the chair with your hand, the chair pushes back on your hand with a force $\mathbf{F}_2$ that is equal in size, but opposite in direction (fig. 4.10). Using this notation, Newton's third law can be stated in symbolic form as follows:

$$\mathbf{F}_2 = -\mathbf{F}_1.$$

The minus sign indicates that the two forces have opposite directions. The force $\mathbf{F}_2$ acts on your hand and partly determines your own motion, but it has nothing to do with the motion of the chair. Of this pair of forces, the only one that affects the motion of the chair is the one acting on the chair, $\mathbf{F}_1$.

Our definition of force is now complete. Newton's second law tells us how the motion of an object is affected by a force, and his third law tells where forces come from. They come from interactions with other objects. With a suitable definition of mass, which also depends upon the second law, we know how to measure the size of forces by determining the acceleration that they produce ($\mathbf{F} = m\mathbf{a}$). Both the second and third laws are necessary to define what we mean by *force*.

### *How can we use the third law to identify forces?*

How do we identify the forces that act on an object to analyze how that object will move? First, we identify other objects that interact with the object of interest. Consider a book lying on a table (fig. 4.11). What objects are interacting with the book? Since it is in direct contact with the table, the book must be interacting with the table, but it also interacts with the earth through the gravitational attraction.

The downward pull of gravity that the earth exerts on the book is the book's weight **W**. The object interacting with the book to produce this force is the earth itself. The book and the earth are attracted to one another (through gravity) with equal and opposite forces that form a third-law pair. The

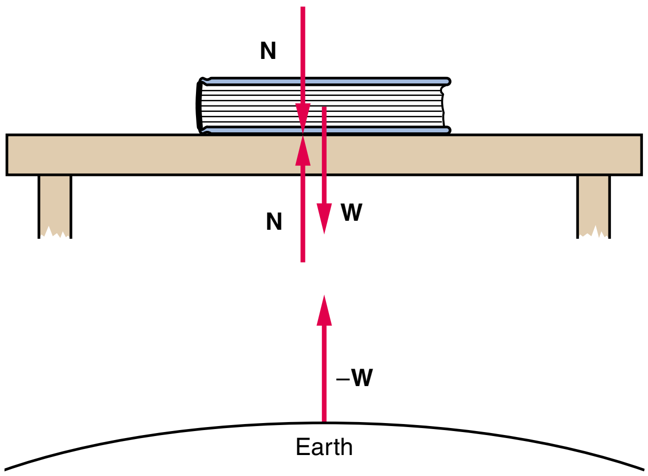



***Figure 4.11*** Two forces, **N** and **W**, act on a book resting on a table. The third-law reaction forces –**N** and –**W** act on different objects, the table and the earth.

earth pulls down on the book with the force **W**, and the book pulls upward on the earth with the force –**W**. Because of the enormous mass of the earth, the effect of this upward force on the earth is extremely small.

The second force acting on the book is an upward force exerted on the book by the table. This force is often called the **normal force,** where the word *normal* means "perpendicular" rather than "usual." The normal force **N** is always perpendicular to the surfaces of contact. The book, in turn, exerts an equal but oppositely directed downward force –**N** on the table. These two forces, **N** and –**N**, constitute another third-law pair. They result from the mutual compression of the book and table as they come into contact with one another. You could think of the table as a large and very stiff spring that compresses ever so slightly when the book is placed on it (fig. 4.12).

The two forces acting on the book, the force of gravity and the force that exerted by the table, also happen to be equal in size and opposite to one another, but this is *not* due to the third law. How do we know that they must be equal? Since the book's velocity is not changing, its acceleration must be zero. According to Newton's *second* law, the total force **F** acting on the book must then be zero, since $\mathbf{F} = m\mathbf{a}$ and the acceleration **a** is zero. The only way that the total force can be zero is for the two contributing forces, **W** and **N**, to cancel one another. They must be equal in magnitude and opposite in direction for their sum to be zero.

Even though equal in size and opposite in direction, these two forces do not constitute a third-law action/reaction pair. They both act on the *same* object, the book, and the third law always deals with interactions between *different* objects. So, **W** and **N** are equal in size and opposite in direction in this case as a consequence of the second law rather than the third law. If they did not cancel one another, the book would accelerate away from the table top. (Both the second and third laws are critical to the analysis of the elevator example in Everyday Phenomenon Box 4.1.)

### *Can a mule accelerate a cart?*

Consider the story of the stubborn mule who, having had a brief exposure to physics, argued to his handler that there was no point in pulling on the cart to which he was connected. According to Newton's third law, the mule argued, the harder he pulls on the cart, the harder the cart pulls back on him (fig. 4.13). The net result is, therefore, nothing. Is he right, or is there a fallacy in his argument?

The fallacy is simple but perhaps not obvious. The motion of the cart is affected by only one of the two forces that the mule is talking about, namely, the force that acts on the cart. The other force in this third-law pair acts on the mule and must be considered in conjunction with other forces that act on the mule to determine how he will move. The cart will accelerate if the force exerted by the mule on the cart is larger than the frictional forces acting on the cart. Try placing yourself in the role of the handler and explain the fallacy to the mule.

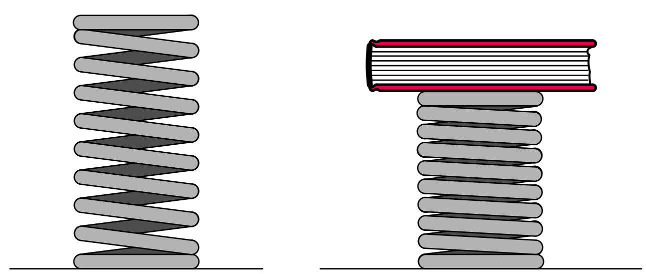


***Figure 4.12*** An uncompressed spring and the same spring supporting a book. The compressed spring exerts an upward force on the book.

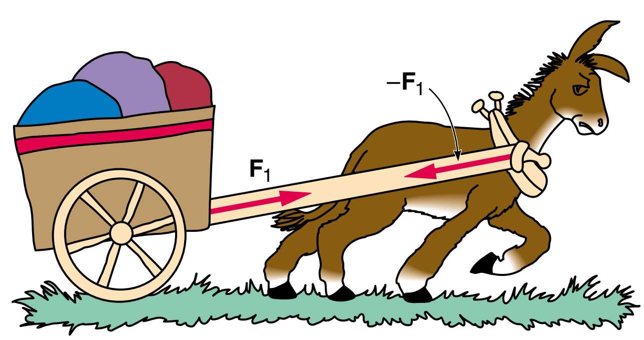


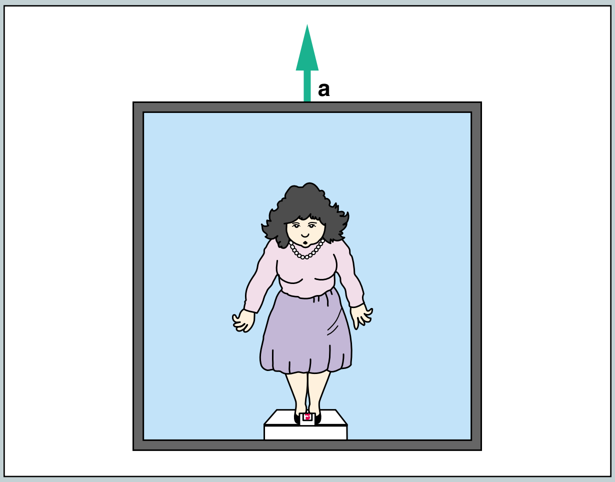

***Figure 4.13*** A mule and a cart. Does Newton's third law prevent the mule from moving the cart?

**Everyday Phenomenon Box 4.1**

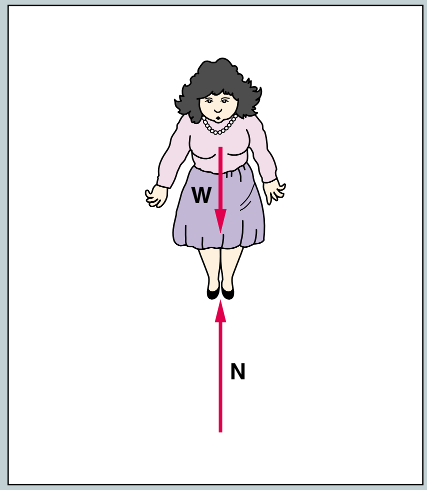
## Riding an Elevator

**The Situation.** We have all had the experience of riding an elevator and feeling sensations of heaviness or lightness as the elevator accelerates up or down. The feeling of lightness as the elevator accelerates downward is generally more striking, particularly if the acceleration is not smooth.

Do we really weigh more or less than usual in these situations? If you took a bathroom scale into the elevator, would it read your true weight when the elevator is accelerating? How can we apply Newton's laws of motion to explore these questions?




A woman standing on a bathroom scale inside an accelerating elevator. Will she read her true weight on the scale?




A free-body diagram of the woman in the elevator. Why is the normal force **N** larger than the weight **W**?

**The Analysis.** The first step in analyzing any situation using Newton's laws is to isolate the body of interest and carefully identify the forces that act on just that body. Different choices are possible for which objects to isolate, but some choices will be more productive than others. In this case, it makes sense to isolate the person standing on the scale, since her weight is the focus of our questions. The second drawing shows a **free-body diagram** of the woman indicating just those forces that act on her.

In this case, just two other objects interact with the woman, resulting in two forces. The earth pulls downward on the woman through the force of gravity **W**. The scale pushes upward on her feet with a force **N**, the normal force. The vector sum of these two forces determines her acceleration. If the elevator is accelerating upward with an acceleration **a**, the woman must also be accelerating upward at that rate. The total force must also be upward, which implies that the normal force **N** is larger than the gravitational force **W**. Using signs to indicate direction, and letting the positive direction be upward, Newton's second law requires that

$$\mathbf{F} = \mathbf{N} - \mathbf{W} = m\mathbf{a}.$$

What about the scale reading? By Newton's third law, the woman exerts a downward force on the scale equal in size to the normal force **N**, but opposite in direction. Since this is the force pushing down on the scale, the scale should read the value *N*, the magnitude of the normal force. The woman's true weight has not changed, but her apparent weight as measured by the scale has increased by an amount equal to $m\mathbf{a}$. (Rearranging the second-law equation yields $\mathbf{N} = \mathbf{W} + m\mathbf{a}$.)

What happens when the elevator is accelerating downward? In that case, the total force acting upon the woman must be downward, and the normal force must be less than her weight. The scale reading *N* will then be less than the woman's true weight by the amount *ma*, perhaps producing a smile rather than a scowl.

If the elevator cable breaks, we have a particularly interesting special case. Both the woman and the elevator will accelerate downward with the gravitational acceleration **g**. Since the woman's weight is all that is required to give her that acceleration, the normal force acting on her feet must then be zero. The scale reading will likewise be zero, and the woman is apparently weightless!

The sensation of our own weight is produced in part by the pressure on our feet and forces in our leg muscles needed to maintain our posture. The woman will feel weightless in this situation even though her true weight (the gravitational force acting on her) has not changed. In fact, she would be able to float around in the elevator as the astronauts do in the orbiting space shuttle. (The space shuttle is also falling toward the earth as it moves laterally in its orbit.) This happy scenario will come to a crashing halt for the woman, however, when the elevator reaches the bottom of the shaft.

### *What force causes a car to accelerate?*

As with the mule, the **reaction force** to a push or pull exerted by an object is often extremely important in describing the motion of the object itself. Consider the acceleration of a car. The engine cannot push the car because it is part of the car. The engine drives either the rear or front axle of the car, which causes the tires to rotate. The tires in turn push against the road surface through the force of friction **f** between the tires and the road (fig. 4.14).

According to Newton's third law, the road must then push against the tires with an equal but oppositely directed force –**f**. This external force causes the car to accelerate. Obviously, friction is desirable in this case. Without friction, the tires would spin, and the car would go nowhere. The case of the mule is similar. The frictional force exerted by the ground on his hooves causes him to accelerate forward. This frictional force is the reaction to his pushing against the ground.

Think about this next time you find yourself walking. What external force causes you to accelerate as you start out? What is your role and that of friction in producing this force? How would you walk on an icy or slippery surface?

To figure out what forces are acting on any object, we need first to identify the other objects with which it is interacting. Some of these will be obvious. Any object in direct contact with the object of interest will presumably contribute a force. Interactions producing other forces, such as air resistance or gravity, may be less obvious but still recognizable with a little thought. The third law is the principle we use to identify any of these forces.

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*Newton's third law of motion completes his definition of force. The third law notes that forces arise from interactions between different objects. If object A exerts a force on object B, object B exerts an equal-size but oppositely directed force on A. We use the third law to identify the external forces that act on an object in order to apply the second law of motion.*

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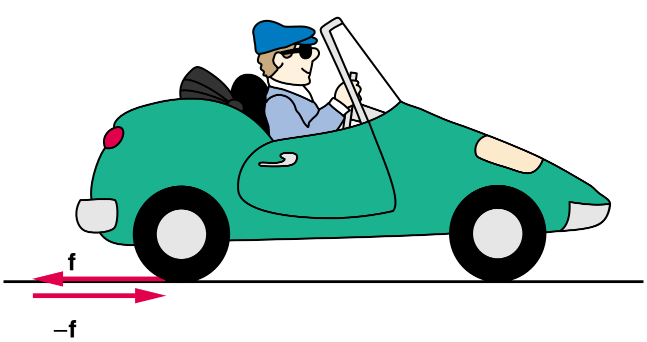



*Figure 4.14* The car pushes against the road, and the road, in turn, pushes against the car.

## ■ 4.5 APPLICATIONS OF NEWTON'S LAWS

We have now introduced Newton's laws of motion and discussed the definitions of force and mass within these laws. To appreciate their usefulness, however, we must be able to apply them to some familiar examples such as pushing a chair or throwing a ball. How do Newton's laws help us make sense of these motions? Do they provide a satisfactory picture of what is going on?

### *What forces are involved in moving a chair?*

We have returned from time to time to the example of a chair being pushed but have not yet analyzed how and why it moves. As we indicated in the previous section, the first step in any analysis is to identify the forces that act on the chair. As shown in figure 4.15, four forces act on the chair from four separate interactions:

1. The force of gravity (the weight) **W** due to interaction with the earth.
2. The upward (normal) force **N** exerted by the floor due to compression of the floor.
3. The force exerted by the hand of the person pushing, **P**.
4. The frictional force **f** exerted by the floor.

Two of these forces, the normal force **N** and the frictional force **f**, are actually due to interactions with a single object, the floor. Since they are due to different effects and are perpendicular to one another, they are usually treated separately.

The effects of the two vertical forces acting on the chair, the weight **W** and the normal force **N**, cancel one another. Like the book on the table in section 4.4, this results because

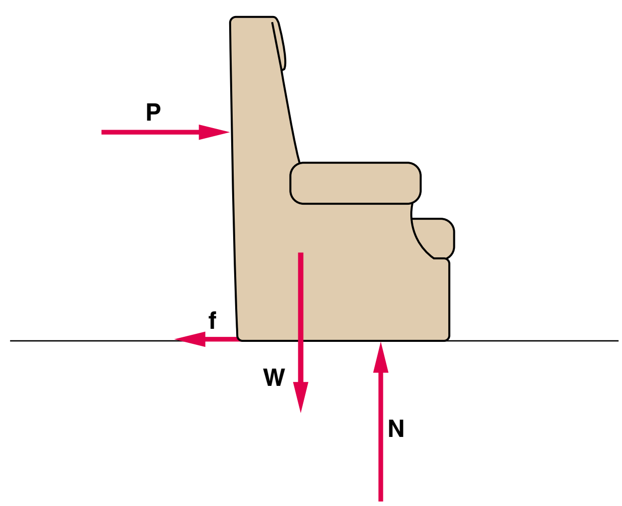



*Figure 4.15* Four forces act on a chair being pushed across the floor, the weight **W**, the normal force **N**, the force **P** exerted by the person pushing, and the frictional force **f**.

there is no acceleration of the chair in the vertical direction. By Newton's second law, the sum of the vertical forces must then be zero, which implies that the weight **W** and the normal force **N** are equal in size but opposite in direction. They play no direct role in the horizontal motion of the chair.

The other two forces, the push of the hand **P** and the frictional force **f**, do not necessarily cancel. These two forces together determine the horizontal acceleration of the chair. The push **P** must be larger than the frictional force **f** for the chair to accelerate. In the most likely scenario for moving the chair, you first give a push with your hand that is larger than the frictional force. This produces a total force, with magnitude $P - f$, in the forward direction, causing the chair to accelerate.

Once you have accelerated the chair to a reasonable velocity, you reduce the strength of your push **P** so that it is equal in size to the frictional force. The net horizontal force becomes equal to zero, and the horizontal acceleration is also zero by Newton's second law. If you sustain the push at this level, the chair moves across the floor with constant velocity.

Finally, you remove your hand and its push **P**, and the chair quickly decelerates to zero velocity under the influence of the frictional force **f**. If you happen to have a chair and a smooth floor handy, try to produce the motion that we have just been describing. See if you can feel differences in the force that you are exerting with your hand at various points in the motion. The force should be largest at the beginning of the motion.

The size of the force, needed to keep the chair moving with constant velocity is determined by the strength of the frictional force, which, in turn, is influenced by the weight of the chair and the condition of the floor surface. If you fail to recognize the importance of the frictional force, you may be led, like Aristotle, to think that a force is always needed to keep an object moving. Frictional forces are almost always present, but they are not as obvious as the forces applied directly.

### *Does a sky diver continue to accelerate?*

In chapter 3, we considered the fact that an object falls with constant acceleration **g** if air resistance is not a significant factor. What about objects such as sky divers who fall for large distances? Do they continue to accelerate at this rate gaining larger and larger downward velocities? Any person with experience in sky diving knows that this does not happen. Why not?

If air resistance were not a factor, a falling object would experience only the gravitational force (its weight) and would indeed continue to accelerate. In sky diving, air resistance is an important factor, and its effects get larger as the velocity of the sky diver (or any object) increases. The sky diver has an initial acceleration of **g**, but as her velocity increases, the force of air resistance becomes significant. Her acceleration decreases (fig. 4.16).

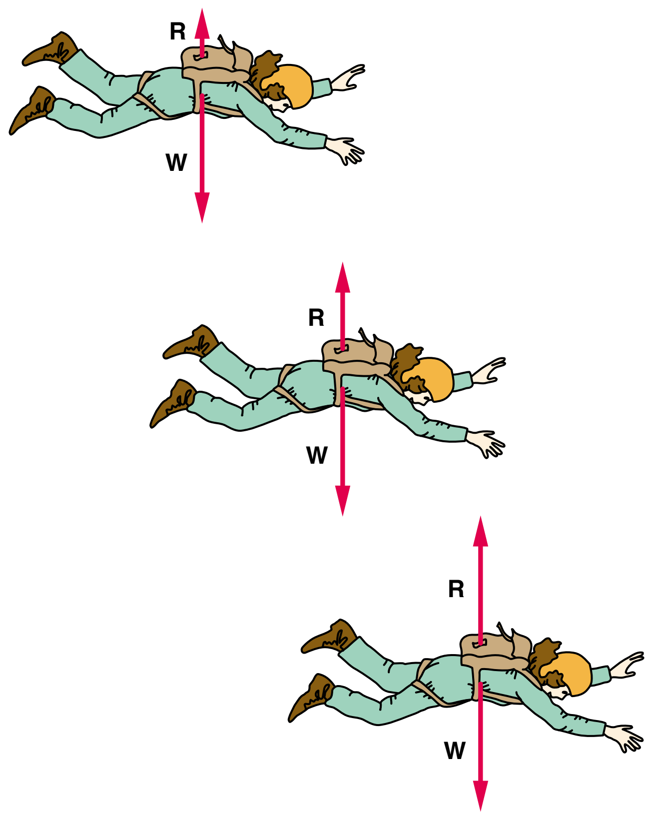



*Figure 4.16* The force of air resistance **R** acting on a sky diver increases as the velocity increases.

For small velocities, the air-resistive force **R** is small, and the weight is the dominant force. As the velocity increases, the air-resistive force gets larger, causing the total magnitude of the downward force, $W - R$, to decrease. Since the total force is responsible for the acceleration, the acceleration will also decrease. Ultimately, as the velocity continues to increase, the air-resistive force reaches a value equal in size to the gravitational force. The net force is then zero, and the sky diver stops accelerating. We say that she has reached **terminal velocity,** and from there on, she moves downward with constant velocity. This terminal velocity is usually between 100 and 120 MPH.

Frictional or resistive forces play a critical role in analyzing the motion. Aristotle did not have the opportunity to try sky diving (nor have many of us), so this example was not a part of his experience. He did observe the terminal velocity, however, of very light objects such as feathers or leaves. The weight of such objects is small and the surface area is large relative to the weight, so the air-resistive force **R** becomes equal in size to the weight much sooner than for a heavier object.

Try tearing a small corner from a piece of paper and watching it fall. Does it appear to reach a constant (terminal) velocity? It will flutter as it falls, but it does not seem to accelerate much for most of its downward motion. You can see why Aristotle concluded that heavier objects fall faster than lighter objects. Dropping heavier objects through water can also show the terminal velocity. Water exerts a larger resistive force at lower velocities than air.

### *What happens when a ball is thrown?*

Aristotle had trouble explaining the motion of a thrown object such as a ball, once it had left the thrower's hand. Let's reconsider this example from a Newtonian perspective. Do we need a force to keep the ball moving? Not according to Newton's first law. Three forces, however, are involved in the flight of the ball: the initial push by the thrower, the downward pull of gravity, and (once again) air resistance (fig 4.17).

To highlight Newton's approach, it is best to break the motion down into two different spans of time. The first is the process of throwing, when the hand is in contact with the ball. During this interval, the force **P** exerted by the hand dominates the motion. The combined effects of the other forces (gravity and air resistance) must be smaller than the force **P** if the ball is to accelerate. Thus **P** accelerates the ball to a velocity that we often refer to as the *initial* velocity. The magnitude and direction of the initial velocity are determined by the strength and direction of the force **P** and the length of time that it acts on the ball. Since this force usually varies with time, a full analysis of the process of throwing gets quite complex.

Once the ball leaves the hand, however, we are in the second time period, where **P** is no longer a consideration. During this interval, the gravitational force **W** and the air-resistive force **R** produce changes in the ball's velocity. From this point on, the problem becomes one of projectile motion (section 3.4). The gravitational force accelerates the ball downward, and the air-resistive force acts in a direction opposite to the velocity, gradually reducing the ball's velocity.

Contrary to Aristotle's view, no forces are needed to keep the ball moving once it has been thrown. In fact, if an object is thrown in deep space, where air resistance is negligible and gravitational forces are very weak, it would keep moving with constant velocity, as stated in Newton's first law. So, be careful with your tools when you are working in space outside of your spacecraft.

Because the air-resistive force or the push exerted by a person throwing a ball varies with time, we have avoided working out numerical examples for these situations. Just identifying the forces involved and their causes due to third-law interactions with other objects provides a useful description of what is happening.

### *How do we analyze the motion of connected objects?*

Verification of Newton's laws of motion came initially from simpler examples that can be easily set up in the laboratory. One example not difficult to picture and set up in a physics laboratory (or even at home if suitable toys are available) is two connected carts accelerated by the pull of a string (fig. 4.18). To keep things simple, we will assume that the carts have excellent wheel bearings, so that they roll with very little friction. We will also assume that a scale is available to determine the masses of the carts and their contents.

To measure the magnitude of the force applied by the string, we would have to insert a small spring balance somewhere between the hand and the carts. The trickiest part of the entire experiment is applying a steady force with this arrangement while the carts are accelerating.

If we know the masses of the carts and their contents, and the magnitude of the force applied by the string, we should be able to predict the value of the acceleration of the system from Newton's second law. (See Try This Box 4.3.) For the masses given, and an applied force of 36 N, we find an acceleration of 2.0 m/s$^2$ for the two carts. The acceleration could be verified experimentally by measuring the time required for the carts to travel a fixed distance and using the equations developed for constant acceleration in chapter 2 to calculate an experimentally determined value.

In box 4.3, we first treated the two carts as a single system to find the acceleration. Suppose, however, that we wanted to know the magnitude of the force exerted by the hooks connecting the two carts. In this case, it makes sense to treat the motion of the individual carts separately. Once we know the acceleration, we again apply Newton's second law to find the total force acting on each cart. This computation is done in the second part of box 4.4 and is illustrated in figure 4.19.

For the second cart, a force of 16 N is required to produce the acceleration of 2 m/s$^2$. By Newton's third law, there should then be a force of 16 N pulling back on the first cart. Combined with the forward force of 36 N applied by the string, this results in a total force of 20 N acting on the

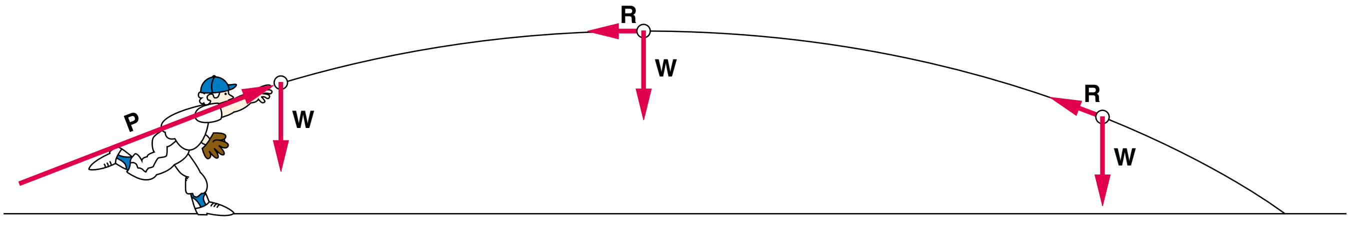



*Figure 4.17* Three forces act on a thrown ball, the initial push **P**, the weight **W**, and air resistance **R**.

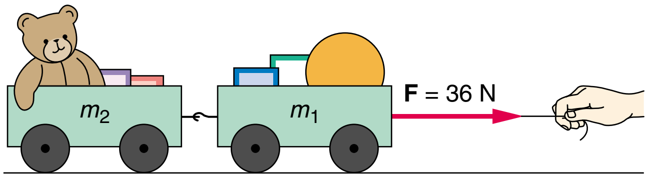



*Figure 4.18* Two connected carts being accelerated by a force **F** applied by a string.

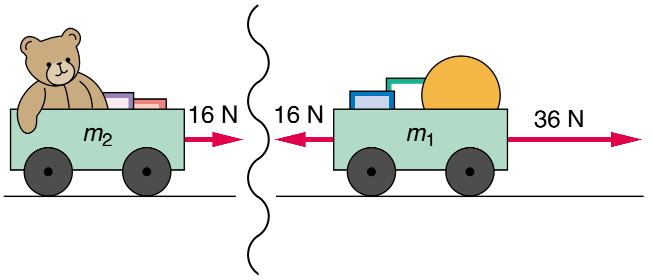



*Figure 4.19* The interaction between the two carts illustrates Newton's third law.

**Try This Box 4.3**

### Sample Exercise: Connected Objects

Two connected carts are pulled across the floor under the influence of a force of 36 N applied by a string (fig. 4.18). The forward cart and its contents have a mass of 10 kg, and the second cart and contents have a mass of 8 kg. Assuming that frictional forces are negligible:

a. What is the acceleration of the two carts?
b. What is the total force acting on each cart?

**a.** $m_1 = 10\text{ kg}$ $\quad F = ma$

$m_2 = 8\text{ kg}$

$F = 36\text{ N}$ $\quad$ or: $a = \dfrac{F}{m} = \dfrac{36\text{ N}}{10\text{ kg} + 8\text{ kg}}$

$\mathbf{a} = ?$ $\quad = \dfrac{36\text{ N}}{18\text{ kg}} = \mathbf{2.0\ m/s^2}$

$\mathbf{a} = 2.0\text{ m/s}^2$ in the forward direction

**b.** $F = ?$ (for each cart)

first cart

$F = ma$

$= (10\text{ kg})(2\text{ m/s}^2)$

$= \mathbf{20\ N}$

second cart

$F = ma$

$= (8\text{ kg})(2\text{ m/s}^2)$

$= \mathbf{16\ N}$

first cart (36 N – 16 N). This is exactly the value required to give the first cart an acceleration of 2 m/s$^2$.

From this example, we see that Newton's laws provide a completely consistent picture of the forces and accelerations of the different parts of the connected-cart system. This is a necessary condition for us to accept the laws as valid. Obviously, another condition is that any predictions be confirmed by experimental measurements. This has been done many times over by experiments similar to the one we have dealt with here.

We could try many variations on this experiment in the laboratory to see if the results agree with predictions derived from Newton's laws. Even with careful experimental technique using accurate stopwatches and balances, however, our results are unlikely to agree exactly with our predictions. It is impossible to eliminate the effects of friction completely, and none of our measurements can be made with infinite precision. The art of the experimentalist is to reduce these inaccuracies to a minimum as well as to predict how they affect our results.

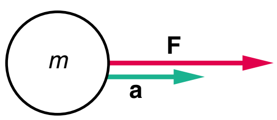
*Newton's laws of motion provide both qualitative and quantitative explanations of any familiar motion. First, we identify the forces acting on the object by examining interactions with other objects. The relative sizes of these forces, when added together, give the acceleration of the object. The acceleration may change as the forces change with time, as in the case of a sky diver. Newton's laws have been verified many times over by experimental tests of their quantitative predictions. They are a much more consistent theory of the causes of motion than the older Aristotelian view.*

## SUMMARY

In 1685, Newton published his *Principia,* in which he introduced three laws of motion as the foundation of his theory of mechanics. These laws continue to serve as an extremely useful model for explaining the causes of motion and for predicting how objects will move in many familiar situations.

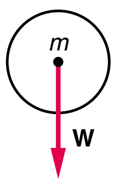
**A brief history.** Newton's theory was constructed on groundwork laid by Galileo and replaced a much earlier and less quantitative model developed by Aristotle to explain motion. Newton's theory had much greater predictive power than Aristotle's ideas. Although we now recognize its limitations, Newton's theory is still used extensively to explain the motion of ordinary objects.

**The first and second laws of motion.** Newton's second law states that the acceleration of an object is proportional to the total external force acting on that object and inversely proportional to the mass of the object. The first law, a *special case* of the second law, describes what happens when the total force is zero. The acceleration must then be zero, and the object moves with constant velocity.



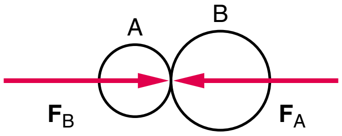

$$\mathbf{a} = \frac{\mathbf{F}}{m}$$

**Mass and weight.** Newton's second law defines the inertial mass of an object as the property that causes the object to resist a change in its motion. The weight of an object is the gravitational force acting on the object and is equal to the mass multiplied by the gravitational acceleration $\mathbf{g}$. The weight of an object may vary as $\mathbf{g}$ varies, but mass is an inherent property of the object related to its quantity of matter.



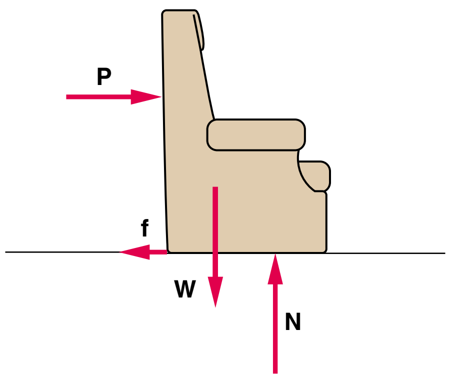

$$\mathbf{W} = m\mathbf{g}$$

**The third law of motion.** Newton's third law completes the definition of force by showing that forces result from interactions between objects. If object A exerts a force on object B, then object B exerts an equal-size but oppositely directed force on object A.




$$\mathbf{F}_A = -\mathbf{F}_B$$

**Applications of Newton's laws.** In analyzing the motion of an object using Newton's laws, the first step is to identify the forces that act on the object due to interactions with other objects. The strength and direction of the total force then determine how the object's motion will change.




## KEY TERMS

Force, 57
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## QUESTIONS

Q1. Did Galileo's work on motion precede in time that of Aristotle or Newton? Explain.

Q2. Why did Aristotle believe that heavier objects fall faster than lighter objects? Explain.

Q3. Aristotle believed that a force was necessary to keep an object moving. Where, in his view, did this force come from in the case of a ball moving through the air? Explain.

Q4. Did Galileo accept Aristotle's basic theory of motion? Explain.

Q5. Did Galileo develop a more complete theory of motion than that of Newton? Explain.

Q6. Two equal forces act on two different objects, one of which has a mass ten times as large as the other. Will the more massive object have a larger acceleration, an equal acceleration, or a smaller acceleration than the less massive object? Explain.

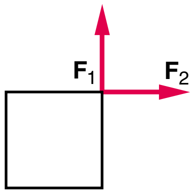
Q7. A 3-kg block is observed to accelerate at a rate twice that of a 6-kg block. Is the net force acting on the 3-kg block therefore twice as large as that acting on the 6-kg block? Explain.

Q8. Two equal-magnitude horizontal forces act on a box as shown in the diagram below. Is the object accelerated horizontally? Explain.


Q9. Is it possible that the object pictured in question 8 is moving, given the fact that the two forces acting on it are equal in size but opposite in direction? Explain.

Q10. Suppose that a bullet is fired from a rifle in outer space where there are no appreciable forces due to gravity or air resistance acting on the bullet. Will the bullet slow down as it travels away from the rifle? Explain.

Q11. Two equal forces act on an object in the directions pictured in the diagram below. If these are the only forces involved, will the object be accelerated? Explain, using a diagram.




Q12. An object moving horizontally across a table is observed to slow down. Is there a non-zero total force acting on the object? Explain.

Q13. A car goes around a curve traveling at constant speed.
a. Is the acceleration of the car zero in this process? Explain.
b. Is there a non-zero total force acting on the car? Explain.

Q14. Is the mass of an object the same thing as its weight? Explain.

Q15. The gravitational force acting on a lead ball is much larger than that acting on a wooden ball of the same size. When both are dropped, does the lead ball accelerate at the same rate as the wooden ball? Explain, using Newton's second law of motion.

Q16. The acceleration due to gravity on the moon is approximately one-sixth the gravitational acceleration near the earth's surface. If a rock is transported from the earth to the moon, will either its mass or its weight change in the process? Explain.

Q17. Is either mass or weight a force? Explain.

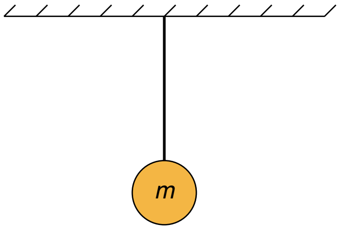
Q18. Two identical cans, one filled with lead shot and the other with feathers, are dropped from the same height by a student standing on a chair.
a. Which can, if either, experiences the greater force due to the gravitational attraction of the earth? Explain.
b. Which can, if either, experiences the greater acceleration due to gravity? Explain.

Q19. A boy sits at rest on the floor. What two vertical forces act upon the boy? Do these two forces constitute an action/reaction pair as defined by Newton's third law of motion? Explain.

Q20. The engine of a car is part of the car and cannot push directly on the car in order to accelerate it. What external force acting on the car is responsible for the acceleration of the car on a level road surface? Explain.

Q21. It is difficult to stop a car on an icy road surface. Is it also difficult to accelerate a car on this same icy road? Explain.

Q22. A ball hangs from a string attached to the ceiling, as shown in the diagram.
a. What forces act on the ball? How many are there?
b. What is the total (net) force acting on the ball? Explain.
c. For each force identified in part (a), what is the reaction force described by Newton's third law of motion?



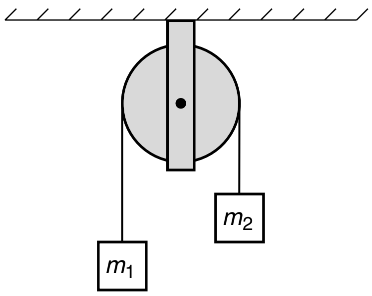

Q23. A sprinter accelerates at the beginning of a 100-meter race and then tries to maintain maximum speed throughout the rest of the race.
a. What external force is responsible for accelerating the runner at the beginning of the race? Explain carefully how this force is produced.
b. Once the runner reaches her maximum velocity, is it necessary to continue pushing against the track in order to maintain that velocity? Explain.

Q24. A mule is attempting to move a cart loaded with rock. Since the cart pulls back on the mule with a force equal in size to the force that the mule exerts on the cart (according to Newton's third law), is it possible for the mule to accelerate the cart? Explain.

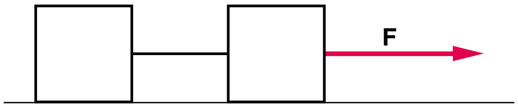
Q25. A toy battery-powered tractor pushes a book across a table. Draw separate diagrams of the book and the tractor identifying all of the forces that act upon each object. What is the reaction force described by Newton's third law of motion for each of the forces that you have drawn?

Q26. The upward normal force exerted by the floor on a chair is equal in size but opposite in direction to the weight of the chair. Is this equality an illustration of Newton's third law of motion? Explain.

Q27. Two masses, $m_1$ and $m_2$, connected by a string, are placed upon a fixed frictionless pulley as shown in the diagram. If $m_2$ is larger than $m_1$, will the two masses accelerate? Explain.




Q28. Two blocks with the same mass are connected by a string and are pulled across a frictionless surface by a constant force, **F**, exerted by a second string (see diagram).
a. Will the two blocks move with constant velocity? Explain.
b. Will the tension in the connecting string be greater than, less than, or equal to the force **F**? Explain.




Q29. Suppose that a sky diver wears a specially lubricated suit that reduces air resistance to a small constant force that does not increase as the diver's velocity increases. Will the sky diver ever reach a terminal velocity before opening her parachute? Explain.

Q30. If you get into an elevator on the top floor of a large building and the elevator begins to accelerate downward, will the normal force pushing up on your feet be greater than, equal to, or less than the force of gravity pulling downward on you? Explain.

Q31. If the elevator cable breaks and you find yourself in a condition of apparent weightlessness as the elevator falls, is the gravitational force acting upon you equal to zero? Explain.

## EXERCISES

E1. A single force of 30 N acts upon a 5-kg block. What is the magnitude of the acceleration of the block?

E2. A ball with a mass of 1.5 kg is observed to accelerate at a rate of 6.0 m/s$^2$. What is the size of the net force acting on this ball?

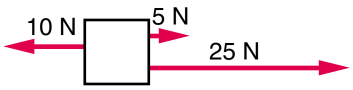
E3. A net force of 30 N acting on a wooden block produces an acceleration of 1.5 m/s$^2$ for the block. What is the mass of the block?

E4. A 3-kg block being pulled across a table by a horizontal force of 40 N also experiences a frictional force of 4 N. What is the acceleration of the block?

E5. A 5-kg block being pushed across a table by a force **P** has an acceleration of 3.0 m/s$^2$.
a. What is the net force acting upon the block?
b. If the magnitude of **P** is 22 N, what is the magnitude of the frictional force acting upon the block?

E6. Two forces, one of 50 N and the other of 30 N, act in opposite directions on a box as shown in the diagram. What is the mass of the box if its acceleration is 2.5 m/s$^2$?


E7. A 4-kg block is acted upon by three horizontal forces as shown in the diagram.
a. What is the net horizontal force acting on the block?
b. What is the horizontal acceleration of the block?




E8. What is the weight of a 60-kg mass?

E9. What is the mass of a 245-N weight?

E10. Jennifer has a weight of 120 lb.
a. What is her weight in newtons? (1 lb = 4.45 N)
b. What is her mass in kilograms?

E11. The author of this text has a weight of 600 N.
a. What is his mass in kilograms?
b. What is his weight in pounds? (1 lb = 4.45 N)

E12. Who has the larger mass, a man weighing 145 lb or one weighing 490 N?

E13. At a given instant in time, a 5-kg rock that has been dropped from a high cliff experiences a force of air resistance of 15 N. What are the magnitude and direction of the acceleration of the rock? (Do not forget the gravitational force!)

E14. At a given instant in time, an 8-kg rock is observed to be falling with an acceleration of 7.0 m/s$^2$. What is the magnitude of the force of air resistance acting upon the rock at this instant?

E15. A 0.5-kg book rests on a table. A downward force of 8 N is exerted on the top of the book by a hand pushing down on the book.
a. What is the magnitude of the gravitational force acting upon the book?
b. What is the magnitude of the upward (normal) force exerted by the table on the book? (Is the book accelerated?)

E16. An upward force of 18 N is applied via a string to lift a ball with a mass of 3.0 kg.
a. What is the net force acting upon the ball?
b. What is the acceleration of the ball?

E17. A 50-kg woman in an elevator is accelerating upward at a rate of 1.2 m/s$^2$.
a. What is the net force acting upon the woman?
b. What is the gravitational force acting upon the woman?
c. What is the normal force pushing upward on the woman's feet?

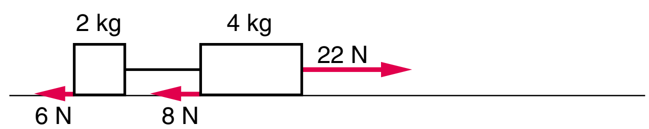
## CHALLENGE PROBLEMS

CP1. A constant horizontal force of 30 N is exerted by a string attached to a 5-kg block being pulled across a table top. The block also experiences a frictional force of 5 N due to contact with the table.
a. What is the horizontal acceleration of the block?
b. If the block starts from rest, what will its velocity be after 3 seconds?
c. How far will it travel in these 3 seconds?

CP2. A rope exerts a constant horizontal force of 250 N to pull a 60-kg crate across the floor. The velocity of the crate is observed to increase from 1 m/s to 3 m/s in a time of 2 seconds under the influence of this force and the frictional force exerted by the floor on the crate.
a. What is the acceleration of the crate?
b. What is the total force acting upon the crate?
c. What is the magnitude of the frictional force acting on the crate?
d. What force would have to be applied to the crate by the rope in order for the crate to move with constant velocity? Explain.

CP3. A 50-kg crate is lowered from a loading dock to the floor using a rope passing over a fixed support. The rope exerts a constant upward force on the crate of 400 N.
a. Will the crate accelerate? Explain.
b. What are the magnitude and direction of the acceleration of the crate?
c. How long will it take for the crate to reach the floor if the height of the loading dock is 1.4 m above the floor?
d. How fast is the crate traveling when it hits the floor?

CP4. Two blocks tied together by a horizontal string are being pulled across the table by a horizontal force of 22 N as shown. The 2-kg block has a 6-N frictional force exerted on it by the table, and the 4-kg block has an 8-N frictional force acting on it.
a. What is the net force acting on the entire two-block system?
b. What is the acceleration of this system?
c. What force is exerted on the 2-kg block by the connecting string? (Consider only the forces acting on this block. Its acceleration is the same as that of the entire system.)
d. Find the net force acting on the 4-kg block and calculate its acceleration. How does this value compare to that found in part b?




CP5. An 80-kg man is in an elevator that is accelerating downward at the rate of 1.2 m/s$^2$.
a. What is the true weight of the man in newtons?
b. What is the net force acting on the man required to produce the acceleration?
c. What is the force exerted on the man's feet by the floor of the elevator?
d. What is the apparent weight of the man in newtons? (This is the weight that would be read on the scale dial if the man were standing on a bathroom scale in the accelerating elevator.)
e. How would your answers to parts (b) through (d) change if the elevator were accelerating upward with an acceleration of 1.2 m/s$^2$?

CP6. A sky diver has a weight of 650 N. Suppose that the air-resistance force acting on the diver increases in direct proportion to his velocity such that for every 10 m/s that the diver's velocity increases, the force of air resistance increases by 100 N.
a. What is the net force acting on the sky diver when his velocity is 40 m/s?
b. What is the acceleration of the diver at this velocity?
c. What is the terminal velocity of the sky diver?
d. What would happen to the velocity of the sky diver if for some reason (perhaps a brief down draft) his velocity exceeded the terminal velocity? Explain.

## HOME EXPERIMENTS AND OBSERVATIONS

HE1. Collect a variety of small objects such as coins, pencils, keys, and bottle caps. Ice cubes, if they are available, also make excellent test objects. Try sliding these objects across a smooth surface such as a tabletop or floor, being as consistent as possible in the initial velocity that you give to them.

a. Do the objects slide the same distance after they leave your hand? What differences are apparent, and how are they related to the nature of the surface and size of the objects? Which objects come closest to demonstrating Newton's first law of motion?

b. What factors seem to be important in reducing the frictional force between the objects and the surface upon which they are sliding? If you see some general principle at work, test this idea by finding other objects that would support your hypothesis.

HE2. Place a sheet of paper under a medium-sized book lying on a smooth tabletop or desktop.

a. Try to accelerate the book smoothly by exerting a constant pull on the sheet of paper. What happens if you try to accelerate the book too rapidly? Can you pull the paper cleanly from underneath the book without moving the book? Explain your observations in terms of Newton's laws of motion.

b. Repeat these observations with larger books or with a few books in a stack. How does increasing the mass of the book or books affect the results?

HE3. Falling objects whose surface area is large relative to their weight will reach terminal velocity more readily than a ball or a rock. Test several objects, such as a balloon, small pieces of paper, plant parts (leaves, flowers, or seeds), or whatever you think might work. Do these objects reach a terminal velocity? How far does each object fall before reaching constant velocity? How does the rate of fall differ for different objects when dropped at the same time? Which of the objects tested produces the clearest demonstration of terminal velocity, showing first a brief acceleration followed by a constant velocity?

HE4. Using elevators in your dormitory or other campus buildings, observe the effects of the elevator's acceleration. Most elevators accelerate briefly as they start and again as they stop (deceleration). Express elevators in high-rise buildings are best for observing the effects of acceleration.

a. If you have a bathroom scale, see how much your apparent weight differs from your true weight when the elevator is stopping or starting. Can you estimate the rate of acceleration from this information? (See Everyday Phenomenon Box 4.1 and challenge problem 5.)

b. Try holding your arm away from your body and maintaining it in this position as the elevator accelerates. How difficult is this to do for different conditions during the motion of the elevator? Explain your observations.