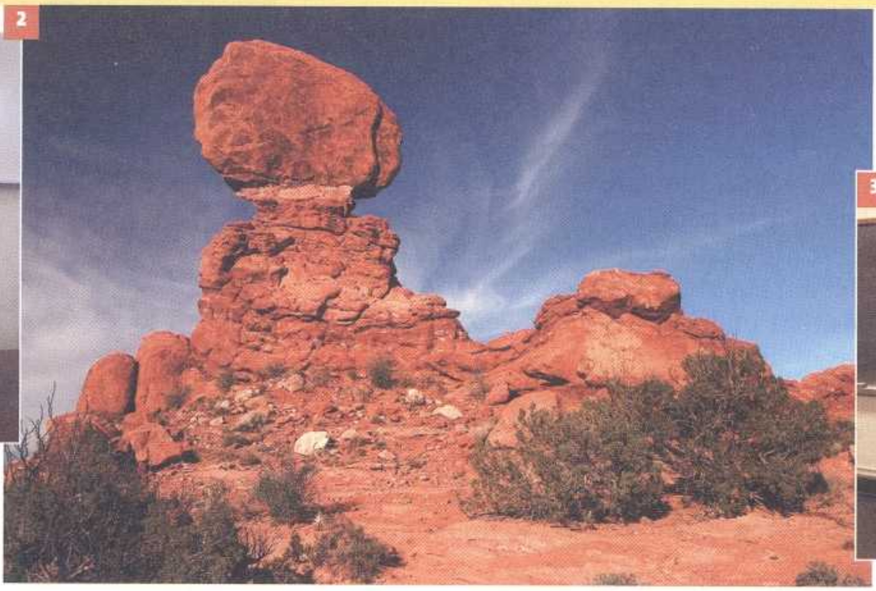
Part One
Mechanics

Like everyone, I'm made of atoms. They're so small and numerous that I inhale billions of trillions of atoms with each breath of air. I exhale some of them right away, but other atoms stay for awhile and become part of me, which I may exhale later. Other people breathe some of these, so they become a part of me. And vice versa. Although I am Egyptian and was born in Cairo, the atoms that make up my body were once in the bodies of people from every country in the world. Furthermore, since there are more atoms in a breath of air than the total number of humans since time zero, in each breath you inhale you recycle atoms that were once a part of every person who ever lived. Hey, in this sense, we're all one!

2 Newton's First Law of Motion—Inertia



1 Theoretical physicist Toby Jacobson, my protégé since age 13, shows a simple demonstration of inertia. 2 The balanced rock more strikingly illustrates inertia. 3 David Yee asks his students which string, the lower or the upper, will break when he suddenly yanks downward on the lower string.

"God said, Let Newton be! and all was light!" *Alexander Pope.*

In this and many other chapters we will study the ideas of Isaac Newton, one of the greatest minds of all time. Newton was born prematurely on Christmas Day, 1642, and barely survived in his mother's farmhouse in England. His father died several months before his birth, and he grew up under the care of his mother and grandmother. As a child, he showed no particular signs of brightness, and, as a young teen, he was taken out of school to help manage his mother's farm. He had little interest in this, preferring to read books he borrowed from a neighbor. An uncle, who sensed the scholarly potential in young Isaac, arranged for him to go back to school for a year and then on to the University of Cambridge, where he stayed for 5 years, graduating without particular distinction.

Isaac Newton (1642–1727)

When a plague swept through England, Newton retreated to his mother's farm—this time to continue his studies. There, at the age of 22 and 23, he laid the foundations for the work that was to make him immortal. Seeing an apple fall to the ground led him to consider the force of gravity extending to the Moon and beyond. He formulated the law of universal gravitation and applied it to solving the centuries-old mysteries of planetary motion and ocean tides; he invented the calculus, an indispensable mathematical tool in science. He extended the work of Italian scientist Galileo, and formulated the three fundamental laws of motion. The first of these laws is the law of inertia, which is the subject of this chapter.

As background to the physics that Newton so clearly presented, we go back to the 3rd century BC to Aristotle, the most outstanding philosopher-scientist of his time in ancient Greece. Aristotle attempted to clarify motion by classification.

Aristotle on Motion

Aristotle divided motion into two main classes: *natural motion* and *violent motion.* We briefly consider each, not as study material, but as a background to present-day ideas about motion.

Aristotle asserted that natural motion proceeds from the "nature" of an object, dependent on the combination of the four elements (earth, water, air, and fire) the object contains. In his view, every object in the universe has a proper place, determined by its "nature"; any object not in its proper place will "strive" to get there. Being of the earth, an unsupported lump of clay will fall to the ground; being of the air, an unimpeded puff of smoke will rise; being a mixture of earth and air but predominantly earth, a feather falls to the ground, but not as rapidly as a lump of clay. He stated that heavier objects would strive harder and argued that objects should fall at speeds proportional to their weights: The heavier the object, the faster it should fall.

Natural motion could be either straight up or straight down, as in the case of all things on Earth, or it could be circular, as in the case of celestial objects. Unlike up-and-down motion, circular motion has no beginning or end, repeating itself without deviation. Aristotle believed that different rules apply to the heavens and asserted that celestial bodies are perfect spheres made of a perfect and unchanging substance, which he called *quintessence.*[1] (The only celestial object with any detectable variation on its face was the Moon. Medieval Christians, still under the sway of Aristotle's teaching, ignorantly explained that lunar imperfections were due to the closeness of the Moon and contamination by human corruption on Earth.)

Violent motion, Aristotle's other class of motion, resulted from pushing or pulling forces. Violent motion was imposed motion. A person pushing a cart or lifting a heavy weight imposed motion, as did someone hurling a stone or winning a tug of war. The wind imposed motion on ships. Floodwaters imposed it on boulders and tree trunks. The essential thing about violent motion was that it was externally caused and was imparted to objects; they moved not of themselves, not by their "nature," but because of pushes or pulls.

The concept of violent motion had its difficulties, for the pushes and pulls responsible for it were not always evident. For example, a bowstring moved an arrow until the arrow left the bow; after that, further explanation of the arrow's motion seemed to require some other pushing agent. Aristotle imagined, therefore, that a parting of the air by the moving arrow resulted in a squeezing effect on the rear of the arrow as the air rushed back to prevent a vacuum from forming. The arrow was propelled through the air as a bar of soap is propelled in the bathtub when you squeeze one end of it.

To sum up, Aristotle taught that all motions are due to the nature of the moving object, or due to a sustained push or pull. Provided that an object is in its proper place, it will not move unless subjected to a force. Except for celestial objects, the normal state is one of rest.

Aristotle's statements about motion were a beginning in scientific thought, and, although he did not consider them to be the final words on the subject, his followers for nearly 2000 years regarded his views as beyond question. Implicit in the thinking of ancient, medieval, and early Renaissance times was the notion that the normal state of objects is one of rest. Since it was evident to most thinkers until the 16th century that Earth must be in its proper place, and since a force capable of moving Earth was inconceivable, it seemed quite clear to them that Earth does not move.

[1]Quintessence is the *fifth* essence, the other four being earth, water, air, and fire.

CHECK POINT

Isn't it common sense to think of Earth in its proper place and that a force to move it *is* inconceivable, as Aristotle held, and that Earth *is* at rest in this universe?

Check Your Answer

Aristotle's views were logical and consistent with everyday observations. So, unless you become familiar with the physics to follow in this book, Aristotle's views about motion *do* make common sense. But, as you acquire new information about nature's rules, you'll likely find your common sense progressing beyond Aristotelian thinking.

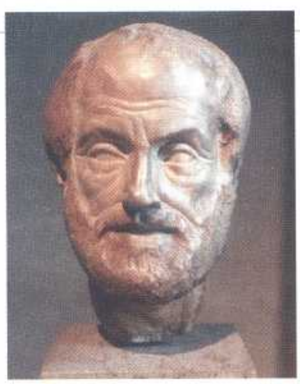
Copernicus and the Moving Earth

Nicolaus Copernicus (1473–1543)

It was in this intellectual climate that the Polish astronomer Nicolaus Copernicus (1473–1543) formulated his theory of the moving Earth. Copernicus reasoned that the simplest way to account for the observed motions of the Sun, Moon, and planets through the sky was to assume that Earth (and other planets) circle around the Sun. For years he worked without making his thoughts public—for two reasons. The first was that he feared persecution; a theory so completely different from common opinion would surely be taken as an attack on established order. The second reason was that he had grave doubts about it himself; he could not reconcile the idea of a moving Earth with the prevailing ideas of motion. Finally, in the last days of his life, at the urging of close friends, he sent his *De Revolutionibus* to the printer. The first copy of his famous exposition reached him on the day he died—May 24, 1543.

Most of us know about the reaction of the medieval Church to the idea that Earth travels around the Sun. Because Aristotle's views had become so formidably a part of Church doctrine, to contradict them was to question the Church itself. For many Church leaders, the idea of a moving Earth threatened not only their authority but the very foundations of faith and civilization as well. For better or for worse, this new idea was to overturn their conception of the cosmos—although eventually the Church embraced it.

Aristotle (384–322 BC)



Greek philosopher, scientist, and educator, Aristotle was the son of a physician who personally served the king of Macedonia. At 17, he entered the Academy of Plato, where he worked and studied for 20 years until Plato's death. He then became the tutor of young Alexander the Great. Eight years later, he formed his own school. Aristotle's aim was to systematize existing knowledge, just as Euclid had systematized geometry. Aristotle made critical observations, collected specimens, and gathered together, summarized, and classified almost all existing knowledge of the physical world. His systematic approach became the method from which Western science later arose. After his death, his voluminous notebooks were preserved in caves near his home and were later sold to the library at Alexandria. Scholarly activity ceased in most of Europe through the Dark Ages, and the works of Aristotle were forgotten and lost in the scholarship that continued in the Byzantine and Islamic empires. Various texts were reintroduced to Europe during the 11th and 12th centuries and translated into Latin. The Church, the dominant political and cultural force in Western Europe, first prohibited the works of Aristotle and then accepted and incorporated them into Christian doctrine.

Galileo and the Leaning Tower

It was Galileo, the foremost scientist of the early 17th century, who gave credence to the Copernican view of a moving Earth. He accomplished this by discrediting the Aristotelian ideas about motion. Although he was not the first to point out difficulties in Aristotle's views, Galileo was the first to provide conclusive refutation through observation and experiment.

Galileo easily demolished Aristotle's falling-body hypothesis. Galileo is said to have dropped objects of various weights from the top of the Leaning Tower of Pisa to compare their falls. Contrary to Aristotle's assertion, Galileo found that a stone twice as heavy as another did not fall twice as fast. Except for the small effect of air resistance, he found that objects of various weights, when released at the same time, fell together and hit the ground at the same time. On one occasion, Galileo allegedly attracted a large crowd to witness the dropping of two objects of different weight from the top of the tower. Legend has it that many observers of this demonstration who saw the objects hit the ground together scoffed at the young Galileo and continued to hold fast to their Aristotelian teachings.

FIGURE 2.1
Galileo's famous demonstration.

Galileo's Inclined Planes

Galileo was concerned with *how* things move rather than *why* they move. He showed that experiment rather than logic is the best test of knowledge. Aristotle was an astute observer of nature, and he dealt with problems around him rather than with abstract cases that did not occur in his environment. Motion always involved a resistive medium such as air or water. He believed a vacuum to be impossible and therefore did not give serious consideration to motion in the absence of an interacting medium. That's why it was basic to Aristotle that an object requires a push or pull to keep it moving. And it was this basic principle that Galileo rejected when he stated that, if there is no interference with a moving object, it will keep moving in a straight line forever; no push, pull, or force of any kind is necessary.

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Galileo Galilei (1564–1642)

Galileo was born in Pisa, Italy, in the same year Shakespeare was born and Michelangelo died. He studied medicine at the University of Pisa and then changed to mathematics. He developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies. Galileo's experiments with falling bodies discredited Aristotle's assertion that the speed of a falling object was proportional to its weight, as discussed above. But quite importantly, Galileo's findings also threatened the authority of the Church, who held that the teachings of Aristotle were part of Church doctrine. Galileo went on to report his telescopic observations, which got him further in trouble with the Church. He told of his sightings of moons that orbited the planet Jupiter. The Church, however, taught that everything in the heavens revolved around Earth. Galileo also reported dark spots on the Sun, but according to Church doctrine, God created the Sun as a perfect source of light, without blemish. Under pressure, Galileo recanted his discoveries and

avoided the fate of Giordano Bruno, who held firm to his belief in the Copernican model of the solar system and was burned at the stake in 1600. Nevertheless, Galileo was sentenced to perpetual house arrest. Earlier, he had damaged his eyes while investigating the Sun in his telescopic studies, which led to blindness at the age of 74. He died 4 years later. Every age has intellectual rebels, some of whom push the frontiers of knowledge further. Among them is certainly Galileo.

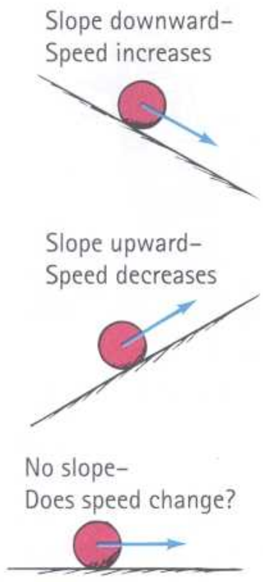

FIGURE 2.2
Motion of balls on various planes.

Galileo tested this hypothesis by experimenting with the motion of various objects on plane surfaces tilted at various angles. He noted that balls rolling on downward-sloping planes picked up speed, while balls rolling on upward-sloping planes lost speed. From this he reasoned that balls rolling along a horizontal plane would neither speed up nor slow down. The ball would finally come to rest not because of its "nature," but because of friction. This idea was supported by Galileo's observation of motion along smoother surfaces: When there was less friction, the motion of objects persisted for a longer time; the less the friction, the more the motion approached constant speed. He reasoned that, in the absence of friction or other opposing forces, a horizontally moving object would continue moving indefinitely.

This assertion was supported by a different experiment and another line of reasoning. Galileo placed two of his inclined planes facing each other. He observed that a ball released from a position of rest at the top of a downward-sloping plane rolled down and then up the slope of the upward-sloping plane until it almost reached its initial height. He reasoned that only friction prevented it from rising to exactly the same height, for the smoother the planes, the closer the ball rose to the same height. Then he reduced the angle of the upward-sloping plane. Again the ball rose to the same height, but it had to go farther. Additional reductions of the angle yielded similar results; to reach the same height, the ball had to go farther each time. He then asked the question, "If I have a long horizontal plane, how far must the ball go to reach the same height?" The obvious answer is "Forever—it will never reach its initial height."[2]

Galileo analyzed this in still another way. Because the downward motion of the ball from the first plane is the same for all cases, the speed of the ball when it begins moving up the second plane is the same for all cases. If it moves up a steep slope, it loses its speed rapidly. On a lesser slope, it loses its speed more slowly and rolls for a longer time. The less the upward slope, the more slowly it loses its speed. In the extreme case in which there is no slope at all—that is, when the plane is horizontal—the ball should not lose any speed. In the absence of retarding forces, the tendency of the ball is to move forever without slowing down. We call this property of an object to resist changes in motion **inertia.**

fyi

- Galileo published the first mathematical treatment of motion in 1632—12 years after the Pilgrims landed at Plymouth Rock.

Galileo's concept of inertia discredited the Aristotelian theory of motion. Aristotle did not recognize the idea of inertia because he failed to imagine what motion would be like without friction. In his experience, all motion was subject to

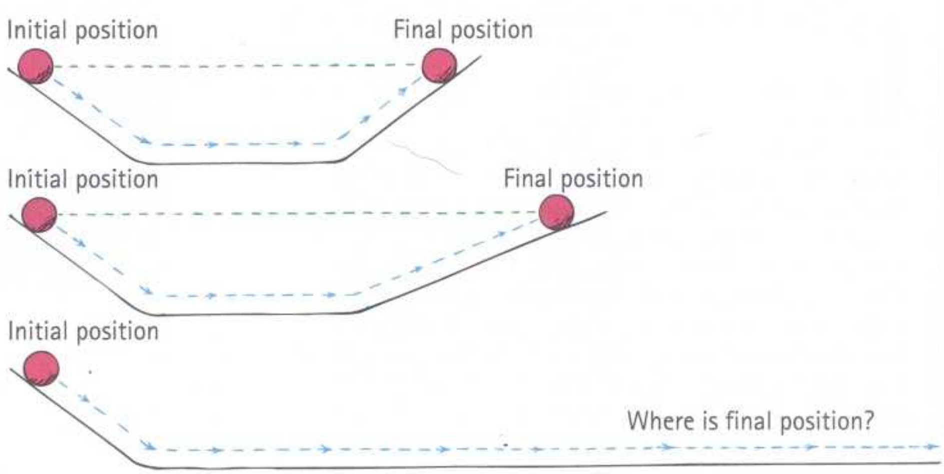

FIGURE 2.3
A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

[2]From Galileo's *Dialogues Concerning the Two New Sciences.*

resistance, and he made this fact central to his theory of motion. Aristotle's failure to recognize friction for what it is—namely, a force like any other—impeded the progress of physics for nearly 2000 years, until the time of Galileo. An application of Galileo's concept of inertia would show that no force is required to keep Earth moving forward. The way was open for Isaac Newton to synthesize a new vision of the universe.

CHECK POINT

Would it be correct to say that inertia is the *reason* a moving object continues in motion when no force acts upon it?

Check Your Answer

In the strict sense, no. We don't know the reason for objects persisting in their motion when no forces act upon them. We refer to the property of material objects to behave in this predictable way as *inertia.* We understand many things and have labels and names for these things. There are many things we do not understand, and we have labels and names for these things also. Education consists not so much in acquiring new names and labels, but in learning which phenomena we understand and which we don't.

In 1642, several months after Galileo died, Isaac Newton was born. By the time Newton was 23, he developed his famous laws of motion, which completed the overthrow of the Aristotelian ideas that had dominated the thinking of the best minds for nearly two millennia. In this chapter, we will consider the first of Newton's laws. It is a restatement of the concept of inertia as proposed earlier by Galileo. (Newton's three laws of motion first appeared in one of the most important books of all time, Newton's *Principia.*)

Inertia isn't a kind of force; it's a property of all matter to resist changes in motion.

Newton's First Law of Motion

Aristotle's idea that a moving object must be propelled by a steady force was completely turned around by Galileo, who stated that, in the *absence* of a force, a moving object will continue moving. The tendency of things to resist changes in motion was what Galileo called *inertia.* Newton refined Galileo's idea and made it his first law, appropriately called the **law of inertia.** From Newton's *Principia* (translated from the original Latin):

Every object continues in a state of rest or of uniform speed in a straight line unless acted on by a nonzero net force.

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The Old Tablecloth Trick
Toilet Paper Roll
Inertia of a Cylinder
Inertia of an Anvil

The key word in this law is *continues:* An object *continues* to do whatever it happens to be doing unless a force is exerted upon it. If it is at rest, it *continues* in a state of rest. This is nicely demonstrated when a tablecloth is skillfully whipped from under dishes on a tabletop, leaving the dishes in their initial state of rest. This property of objects to resist changes in motion is called inertia.

If an object is moving, it *continues* to move without turning or changing its speed. This is evident in space probes that continually move in outer space. Changes in motion must be imposed against the tendency of an object to retain its state of motion. In the absence of net forces, a moving object tends to move along a straight-line path indefinitely.

FIGURE 2.4
Inertia in action.

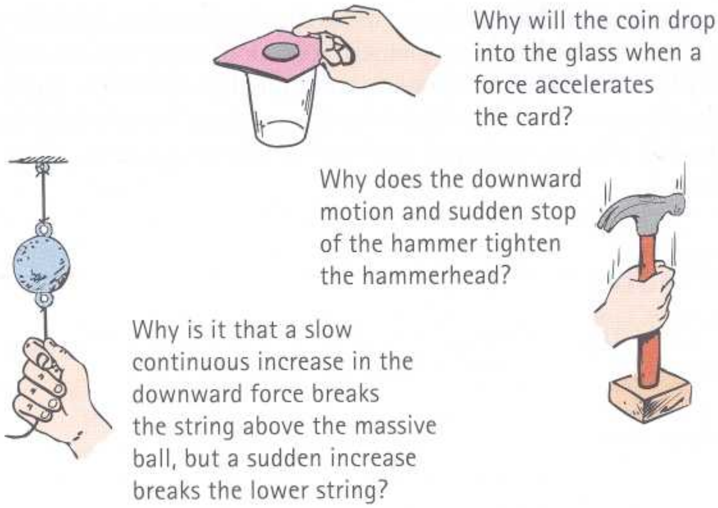

FIGURE 2.5
Examples of inertia.

You can think of inertia as another word for *laziness* (or resistance to change).

CHECK POINT

A hockey puck sliding across the ice finally comes to rest. How would Aristotle have interpreted this behavior? How would Galileo and Newton have interpreted it? How would you interpret it? *(Think before you read the answers below!)*

Check Your Answers

Aristotle would probably say that the puck slides to a stop because it seeks its proper and natural state, one of rest. Galileo and Newton would probably say that, once in motion, the puck would continue in motion and that what prevents continued motion is not its nature or its proper rest state, but the friction the puck encounters. This friction is small compared with the friction between the puck and a wooden floor, which is why the puck slides so much farther on ice. Only you can answer the last question.

Net Force

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Definition of a Newton

Changes in motion are produced by a force or combination of forces (in the next chapter we'll refer to changes in motion as *acceleration*). A **force,** in the simplest sense, is a push or a pull. Its source may be gravitational, electrical, magnetic, or simply muscular effort. When more than a single force acts on an object, we consider the ***net* force.** For example, if you and a friend pull in the same direction with equal forces on an object, the forces combine to produce a net force twice as great as your single force. If each of you pull with equal forces in *opposite* directions, the net force is zero. The equal but oppositely directed forces cancel each other. One of the forces can be considered to be the negative of the other, and they add algebraically to zero, with a resulting net force of zero.

Figure 2.6 shows how forces combine to produce a net force. A pair of 5-newton forces in the same direction produce a net force of 10 newtons (the newton, N, is the scientific unit of force). If the 5-newton forces are in opposite directions, the net force is zero. If 10 newtons of force is exerted to the right and 5 newtons to the left, the net force is 5 newtons to the right. The forces are shown by arrows. A quantity such as force that has both magnitude and direction is called a *vector quantity.* Vector quantities can be represented by arrows whose length and direction show the magnitude and direction of the quantity. (More about vectors in Chapter 4.)

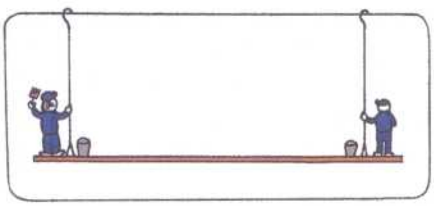
Personal Essay

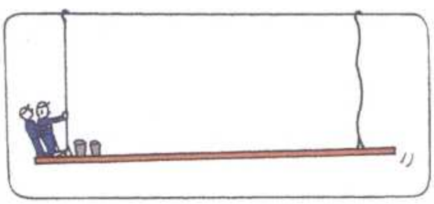
When I was in high school, my counselor advised me not to enroll in science and math classes and instead to focus on what seemed to be my gift for art. I took this advice. I was then interested in drawing comic strips and in boxing, neither of which earned me much success. After a stint in the Army, I tried my luck at sign painting, and the cold Boston winters drove me south to warmer Miami, Florida. There, at age 26, I got a job painting billboards and met a man who became a great intellectual influence on me, Burl Grey. Like me, Burl had never studied physics in high school. But he was passionate about science in general, and he shared his passion with many questions as we painted together. I remember Burl asking me about the tensions in the ropes that held up the scaffold we were on. The scaffold was simply a heavy horizontal plank suspended by a pair of ropes. Burl twanged the rope nearest his end of the scaffold and asked me to do the same with mine. He was comparing the tensions in both ropes—to determine which was greater. Burl was heavier than I was, and he reasoned that the tension in his rope was greater. Like a more tightly stretched guitar string, the rope with greater tension twangs at a higher pitch. The finding that Burl's rope had a higher pitch seemed reasonable because his rope supported more of the load.

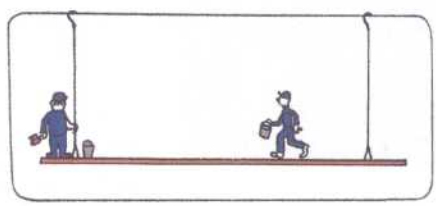
When I walked toward Burl to borrow one of his brushes, he asked if the tensions in the ropes had changed. Did tension in his rope increase as I moved closer? We agreed that it should have, because even more of the load was supported by Burl's rope. How about my rope? Would its tension decrease? We agreed that it would, for it would be supporting less of the total load. I was unaware at the time that I was discussing physics. Burl and I used exaggeration to bolster our reasoning (just as physicists do). If we both stood at an extreme end of the scaffold and leaned outward, it was easy to imagine the opposite end of the scaffold rising like the end of a seesaw—with the opposite rope going limp. Then there would be no tension in that rope. We then reasoned the tension in my rope would gradually decrease as I walked toward Burl. It was fun posing such questions and seeing if we could answer them.

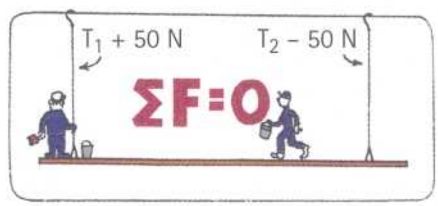
A question that we couldn't answer was whether or not the decrease in tension in my rope when I walked away from it would be *exactly* compensated by a tension increase in Burl's rope. For example, if my rope underwent a decrease of 50 newtons, would Burl's rope gain 50 newtons? (We talked pounds back then, but here we use the scientific unit of force, the *newton*—abbreviated N.) Would the gain be *exactly* 50 N? And, if so, would this be a grand coincidence? I didn't know the answer until more than a year later, when Burl's stimulation resulted in my leaving full-time painting and going to college to learn more about science.[3]

At college, I learned that any object at rest, such as the sign-painting scaffold that supported us, is said to be in equilibrium. That is, all the forces that act on it balance to zero. So the sums of the upward forces supplied by the supporting ropes indeed do add up to our weights plus the weight of the scaffold. A 50-N loss in one would be accompanied by a 50-N gain in the other.









I tell this true story to make the point that one's thinking is very different when there is a rule to guide it. Now when I look at any motionless object I know immediately that all the forces acting on it cancel out. We view nature differently when we know its rules. Without the rules of physics, we tend to be superstitious and to see magic where there is none. Quite wonderfully, everything is connected to everything else by a surprisingly small number of rules, and in a beautifully simple way. The rules of nature are what the study of physics is about.

[3] I am forever indebted to Burl Grey for the stimulation he provided, for when I continued with formal education, it was with enthusiasm. I lost touch with Burl for 40 years. A student in my class at the Exploratorium in San Francisco, Jayson Wechter, who was a private detective, located him in 1998 and put us in contact. Friendship renewed, we once again continue in spirited conversations.

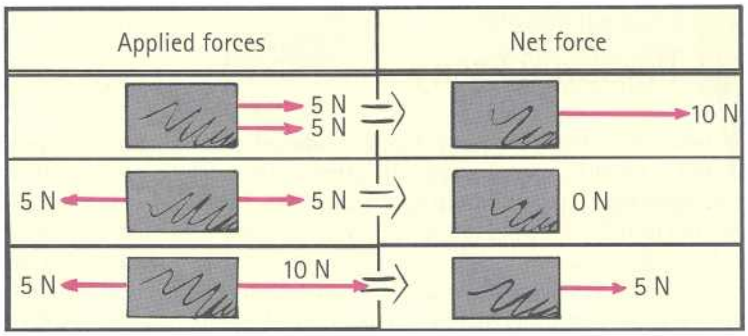


FIGURE 2.6
Net force (a force of 5 N is about 1.1 lb).

The Equilibrium Rule

If you tie a string around a 2-pound bag of flour and hang it on a weighing scale (Figure 2.7), a spring in the scale stretches until the scale reads 2 pounds. The stretched spring is under a "stretching force" called *tension.* The same scale in a science lab is likely calibrated to read the same force as 9 newtons. Both pounds and newtons are units of weight, which in turn are units of *force.* The bag of flour is attracted to Earth with a gravitational force of 2 pounds—or, equivalently, 9 newtons. Hang twice as much flour from the scale and the reading will be 18 newtons.

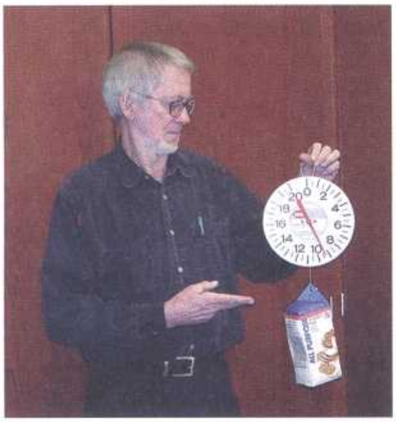


FIGURE 2.7
Burl Grey, who first introduced the author to tension forces, suspends a 2-lb bag of flour from a spring scale, showing its weight and the tension in the string of about 9 N.

Note that there are two forces acting on the bag of flour—tension force acting upward and weight acting downward. The two forces on the bag are equal and opposite, and they cancel to zero. Hence, the bag remains at rest. In accord with Newton's first law, no net force acts on the bag. We can look at Newton's first law in a different light—*mechanical equilibrium.*

When the net force on something is zero, we say that something is in **mechanical equilibrium.**[4] In mathematical notation, the **equilibrium rule** is

$$\Sigma \mathbf{F} = 0$$

The symbol Σ stands for "the vector sum of" and **F** stands for "forces." For a suspended object at rest, like the bag of flour, the rule says that the forces acting upward on the object must be balanced by other forces acting downward to make the vector sum equal zero. (Vector quantities take direction into account, so if upward forces are $+$, downward ones are $-$, and, when added, they actually subtract.)

Everything not undergoing changes in motion is in mechanical equilibrium. That's when $\Sigma \mathbf{F} = 0$.

In Figure 2.8, we see the forces involved for Burl and Hewitt on their sign-painting scaffold. The sum of the upward tensions is equal to the sum of their weights plus the weight of the scaffold. Note how the magnitudes of the two upward vectors equal the magnitude of the three downward vectors. Net force on the scaffold is zero, so we say it is in mechanical equilibrium.

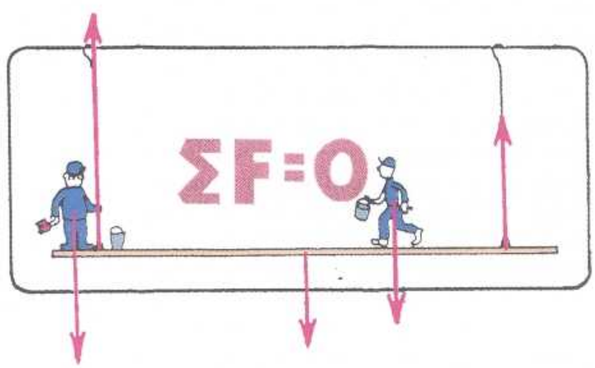
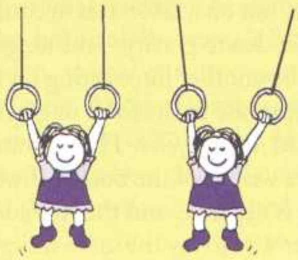


FIGURE 2.8
The sum of the upward vectors equals the sum of the downward vectors. $\Sigma \mathbf{F} = 0$ and the scaffold is in equilibrium.

[4]Something in equilibrium is without a change in its state of motion. When we study rotational motion in Chapter 8, we'll see that another condition for mechanical equilibrium is that the net *torque* equals zero.

CHECK POINT

Consider the gymnast hanging from the rings.



1. If she hangs with her weight evenly divided between the two rings, how would scale readings in both supporting ropes compare with her weight?
2. Suppose she hangs with slightly more of her weight supported by the left ring. How will the right scale read?

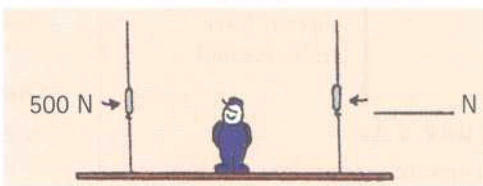
Check Your Answers

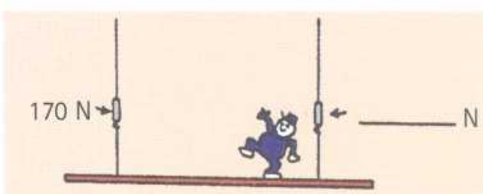
(Are you reading this before you have formulated reasoned answers in your thinking? If so, do you also exercise your body by watching others do push-ups? Exercise your thinking: When you encounter the many Check Point questions throughout this book, think before you check the answers!)

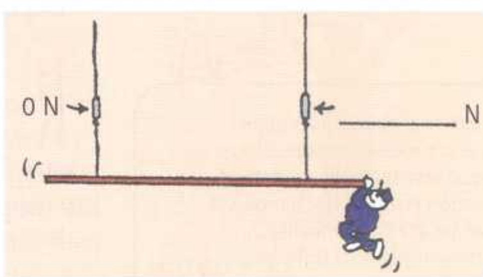
1. The reading on each scale will be half her weight. The sum of the readings on both scales then equals her weight.
2. When more of her weight is supported by the left ring, the reading on the right scale will be less. For vertical or near-vertical ropes, the sum of the upward pulls of both scales will equal her weight. (The upward pulls provided by the rope tensions for nonparallel ropes is treated in Figure 5.25 on page 75.)

Practicing Physics

1. When Burl stands alone in the exact middle of his scaffold, the left scale reads 500 N. Fill in the reading on the right scale. The total weight of Burl and the scaffold must be ______ N.
2. Burl stands farther from the left. Fill in the reading on the right scale.
3. In a silly mood, Burl dangles from the right end. Fill in the reading on the right scale.







Practicing Physics Answers

Do your answers illustrate the equilibrium rule? In Question 1, the right rope must be under **500 N** of tension because Burl is in the middle and both ropes support his weight equally. Since the sum of upward tensions is 1000 N, the total weight of Burl and the scaffold must be **1000 N.** Let's call the upward tension forces +1000 N. Then the downward weights are −1000 N. What happens when you add +1000 N and −1000 N? The answer is that they equal zero. So we see that $\Sigma \mathbf{F} = 0$.

For Question 2, did you get the correct answer of **830 N?** Reasoning: We know from Question 1 that the sum of the rope tensions equals 1000 N, and since the left rope has a tension of 170 N, the other rope must make up the difference—that 1000 N − 170 N = 830 N. Get it? If so, great. If not, talk about it with your friends until you do. Then read further.

The answer to Question 3 is **1000 N.** Do you see that this illustrates ? $\Sigma \mathbf{F} = 0$.

Support Force

Consider a book lying at rest on a table. It is in equilibrium. What forces act on the book? One force is that due to gravity—the *weight* of the book. Since the book is in equilibrium, there must be another force acting on the book to produce a net force of zero—an upward force opposite to the force of gravity. The table exerts this upward force. We call this the upward *support force.* This upward support force, often called the *normal force,* must equal the weight of the book.[5] If we call the upward force positive, then the downward weight is negative, and the two add to become zero. The net force on the book is zero. Another way to say the same thing is $\Sigma \mathbf{F} = 0$.

To understand better that the table pushes up on the book, compare the case of compressing a spring (Figure 2.9). If you push the spring down, you can feel the spring pushing up on your hand. Similarly, the book lying on the table compresses atoms in the table, which behave like microscopic springs. The weight of the book squeezes downward on the atoms, and they squeeze upward on the book. In this way, the compressed atoms produce the support force.

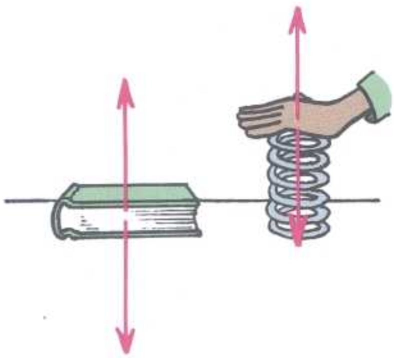


FIGURE 2.9
(Left) The table pushes up on the book with as much force as the downward force of gravity on the book. (Right) The spring pushes up on your hand with as much force as you exert to push down on the spring.

When you step on a bathroom scale, two forces act on the scale. One is your downward push on the scale—the result of gravity pulling on you—and the other is the upward support force of the floor. These forces squeeze a mechanism (in effect, a spring) within the scale that is calibrated to show the magnitude of the support force (Figure 2.10). It is this support force that shows your weight. When you weigh yourself on a bathroom scale at rest, the support force and the force of gravity pulling you down have the same magnitude. Hence we can say that your weight is the force of gravity acting on you.

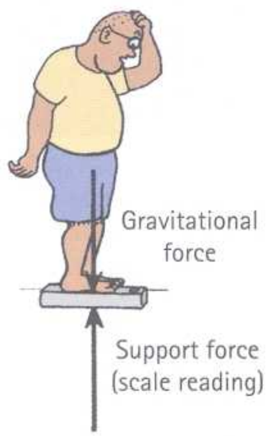


FIGURE 2.10
The upward support is as much as the downward gravitational force.

CHECK POINT

1. What is the net force on a bathroom scale when a 150-pound person stands on it?
2. Suppose you stand on two bathroom scales with your weight evenly divided between the two scales. What will each scale read? What happens when you stand with more of your weight on one foot than the other?

Check Your Answers

1. Zero, as evidenced by the scale remaining at rest. The scale reads the *support force,* which has the same magnitude as weight—not the net force.
2. The reading on each scale is half your weight. Then the sum of the scale readings will balance your weight and the net force on you will be zero. If you lean more on one scale than the other, more than half your weight will be read on that scale but less on the other, so they will still add up to your weight. Like the example of the gymnast hanging by the rings, if one scale reads two-thirds your weight, the other scale will read one-third your weight.

Equilibrium of Moving Things

Rest is only one form of equilibrium. An object moving at constant speed in a straight-line path is also in equilibrium. Equilibrium is a state of no change. A bowling ball rolling at constant speed in a straight line is in equilibrium—until it hits the pins. Whether at rest (static equilibrium) or steadily rolling in a straight-line path (dynamic equilibrium), $\Sigma \mathbf{F} = 0$.

A zero net force on an object doesn't mean the object must be at rest, but that its state of motion remains unchanged. It can be at rest or moving uniformly in a straight line.

[5]This force acts at right angles to the surface. When we say "normal to," we are saying "at right angles to," which is why this force is called a normal force.

It follows from Newton's first law that an object under the influence of only one force cannot be in equilibrium. Net force couldn't be zero. Only when two or more forces act on it can it be in equilibrium. We can test whether or not something is in equilibrium by noting whether or not it undergoes changes in its state of motion.

Consider a crate being pushed horizontally across a factory floor. If it moves at a steady speed in a straight-line path, it is in dynamic equilibrium. This tells us that more than one force acts on the crate. Another force exists—likely the force of friction between the crate and the floor. The fact that the net force on the crate equals zero means that the force of friction must be equal and opposite to our pushing force.

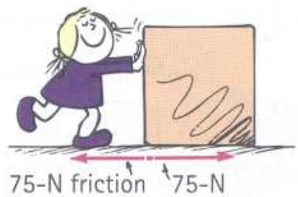


FIGURE 2.11
When the push on the crate is as great as the force of friction between the crate and the floor, the net force on the crate is zero and it slides at an unchanging speed.

The equilibrium rule, $\Sigma \mathbf{F} = 0$, provides a reasoned way to view all things at rest—balancing rocks, objects in your room, or the steel beams in bridges or in building construction. Whatever their configuration, if in static equilibrium, all acting forces always balance to zero. The same is true of objects that move steadily, not speeding up, slowing down, or changing direction. For dynamic equilibrium, all acting forces also balance to zero. The equilibrium rule is one that allows you to see more than meets the eye of the casual observer. It's nice to know the reasons for the stability of things in our everyday world.

There are different forms of equilibrium. In Chapter 8, we'll talk about rotational equilibrium, and, in Part 4, we'll discuss thermal equilibrium associated with heat. Physics is everywhere.

CHECK POINT

An airplane flies at constant speed in a horizontal straight path. In other words, the flying plane is in equilibrium. Two horizontal forces act on the plane. One is the thrust of the propellers that push it forward, and the other is the force of air resistance that acts in the opposite direction. Which force is greater?

Check Your Answer

Both forces have the same magnitude. Call the forward force exerted by the propellers positive. Then the air resistance is negative. Since the plane is in dynamic equilibrium, can you see that the two forces combine to equal zero? Hence it neither gains nor loses speed.

The Moving Earth

When Copernicus announced the idea of a moving Earth in the 16th century, the concept of inertia was not understood. There was much arguing and debate about whether or not Earth moved. The amount of force required to keep Earth moving was beyond imagination. Another argument against a moving Earth was the following: Consider a bird sitting at rest at the top of a tall tree. On the ground below is a fat, juicy worm. The bird sees the worm and drops vertically below and catches it. This would be impossible, it was argued, if Earth moved as Copernicus suggested. If Copernicus were correct, Earth would have to travel at a speed of 107,000 kilometers per hour to circle the Sun in one year. Convert this speed to kilometers per second and you'll get 30 kilometers per second. Even if the bird could descend from its branch in 1 second, the worm would have been swept by the moving Earth a distance of 30 kilometers away. It would be impossible for a bird to drop straight down and catch a worm. But birds in fact *do* catch worms from high tree branches, which seemed to be clear evidence that Earth must be at rest.

FIGURE 2.12
Can the bird drop down and catch the worm if Earth moves at 30 km/s?

Can you refute this argument? You can if you invoke the idea of inertia. You see, not only is Earth moving at 30 kilometers per second but so are the tree, the branch of the tree, the bird that sits on it, the worm below, and even the air in between. All

FIGURE 2.13
When you flip a coin in a high-speed airplane, it behaves as if the airplane were at rest. The coin keeps up with you—inertia in action!

are moving at 30 kilometers per second. Things in motion remain in motion if no unbalanced forces are acting upon them. So, when the bird drops from the branch, its initial sideways motion of 30 kilometers per second remains unchanged. It catches the worm, quite unaffected by the motion of its total environment.

Stand next to a wall. Jump up so that your feet are no longer in contact with the floor. Does the 30-kilometer-per-second wall slam into you? It doesn't, because you are also traveling at 30 kilometers per second—before, during, and after your jump. The 30 kilometers per second is the speed of Earth relative to the Sun, not the speed of the wall relative to you.

People 400 years ago had difficulty with ideas like these, not only because they failed to acknowledge the concept of inertia but because they were not accustomed to moving in high-speed vehicles. Slow, bumpy rides in horsedrawn carriages did not lend themselves to experiments that would reveal the effect of inertia. Today we flip a coin in a high-speed car, bus, or plane, and we catch the vertically moving coin as we would if the vehicle were at rest. We see evidence for the law of inertia when the horizontal motion of the coin before, during, and after the catch is the same. The coin keeps up with us. The vertical force of gravity affects only the vertical motion of the coin.

Our notions of motion today are very different from those of our ancestors. Aristotle did not recognize the idea of inertia because he did not see that all moving things follow the same rules. He imagined that rules for motion in the heavens were very different from the rules of motion on Earth. He saw vertical motion as natural but horizontal motion as unnatural, requiring a sustained force. Galileo and Newton, on the other hand, saw that all moving things follow the same rules. To them, moving things require *no* force to keep moving if there are no opposing forces, such as friction. We can only wonder how differently science might have progressed if Aristotle had recognized the unity of all kinds of motion.

SUMMARY OF TERMS

Inertia The property of things to resist changes in motion.

Newton's first law of motion (the law of inertia) Every object continues in a state of rest or of uniform speed in a straight line unless acted on by a nonzero net force.

Force In the simplest sense, a push or a pull.

Net force The vector sum of forces that act on an object.

Mechanical equilibrium The state of an object or system of objects for which there are no changes in motion. In accord with Newton's first law, if at rest, the state of rest persists. If moving, motion continues without change.

Equilibrium rule For any object or system of objects in equilibrium, the sum of the forces acting equals zero. In equation form, $\Sigma \mathbf{F} = 0$.

REVIEW QUESTIONS

Each chapter in this book concludes with a set of review questions, exercises, and, for some chapters, ranking exercises, and problems. The ***Review Questions*** *are designed to help you comprehend ideas and catch the essentials of the chapter material. You'll notice that answers to the questions can be found within the chapters. In some chapters, there is a set of single-step numerical problems—****Plug and Chug****—that are meant to acquaint you with equations in the chapter. In some chapters* ***Ranking*** *tasks prompt you to compare the magnitudes of various concepts. All chapters have* ***Exercises*** *that stress thinking rather than mere recall of information. Unless you cover only a few chapters in your course, you will likely be expected to tackle only a few exercises for each chapter. Answers should be in complete sentences, with an explanation or sketch when applicable. The large number of exercises is to allow your instructor a wide choice of assignments.* ***Problems*** *go further than Plug and Chugs and feature concepts that are more clearly understood with more challenging computations. Challenging problems are indicated with a bullet (•). Solutions to odd-numbered Rankings, Exercises, and Problems are shown at the back of this book. Additional problems are in the supplement* ***Problem Solving in Conceptual Physics.***

Aristotle on Motion

1. Contrast Aristotle's ideas of natural motion and violent motion.
2. What class of motion, natural or violent, did Aristotle attribute to motion of the Moon?
3. What state of motion did Aristotle attribute to Earth?

Copernicus and the Moving Earth

4. What relationship between the Sun and Earth did Copernicus formulate?

Galileo and the Leaning Tower

5. What did Galileo discover in his legendary experiment on the Leaning Tower of Pisa?

Galileo's Inclined Planes

6. What did Galileo discover about moving bodies and force in his experiments with inclined planes?
7. What does it mean to say that a moving object has inertia? Give an example.
8. Is inertia the *reason* for moving objects maintaining motion or the *name* given to this property?

Newton's First Law of Motion

9. Cite Newton's first law of motion.

Net Force

10. What is the net force on a cart that is pulled to the right with 100 pounds and to the left with 30 pounds?
11. Why do we say that force is a vector quantity?

The Equilibrium Rule

12. Can force be expressed in units of pounds and also in units of newtons?
13. What is the net force on an object that is pulled with 80 newtons to the right and 80 newtons to the left?
14. What is the net force on a bag pulled down by gravity with 18 newtons and pulled upward by a rope with 18 newtons?
15. What does it mean to say something is in mechanical equilibrium?
16. State the equilibrium rule in symbolic notation.

Support Force

17. Consider a book that weighs 15 N at rest on a flat table. How many newtons of support force does the table provide? What is the net force on the book in this case?
18. When you stand at rest on a bathroom scale, how does your weight compare with the support force by the scale?

Equilibrium of Moving Things

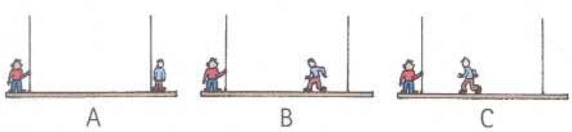
19. A bowling ball at rest is in equilibrium. Is the ball in equilibrium when it moves at constant speed in a straight-line path?
20. What is the test for whether or not a moving object is in equilibrium?
21. If you push on a crate with a force of 100 N and it slides at constant velocity, how much is the friction acting on the crate?

The Moving Earth

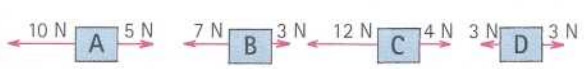
22. What concept was missing in people's minds in the 16th century when they couldn't believe Earth was moving?
23. A bird sitting in a tree is traveling at 30 km/s relative to the faraway Sun. When the bird drops to the ground below, does it still go 30 km/s, or does this speed become zero?
24. Stand next to a wall that travels at 30 km/s relative to the Sun. With your feet on the ground, you also travel the same 30 km/s. Do you maintain this speed when your feet leave the ground? What concept supports your answer?
25. What did Aristotle fail to recognize about the rules of nature for objects on Earth and in the heavens?

RANKING

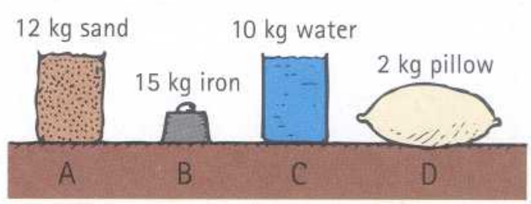
1. The weights of Burl, Paul, and the scaffold produce tensions in the supporting ropes. Rank the tension in the *left* rope, from most to least, in the three situations, A, B, and C.



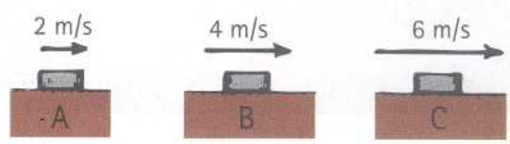
2. Rank the net force on the block from least to most in the four situations, A, B, C, and D.



3. Different materials, A, B, C, and D, rest on a table.
   a. From greatest to least, rank them by how much they resist being set into motion.
   b. From greatest to least, rank them by the support (normal) force the table exerts on them.



4. Three pucks, A, B, and C, are shown sliding across ice at the noted speeds. Air and ice friction forces are negligible.



   a. Rank them, from greatest to least, by the force needed to keep them moving.
   b. Rank them, from greatest to least, by the force needed to stop them in the same time interval.

EXERCISES

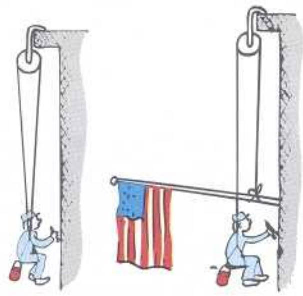
Please do not be intimidated by the large number of exercises in this book. As mentioned earlier, if your course work is to cover many chapters, your instructor will likely assign only a few exercises from each.

1. A ball rolling along a floor doesn't continue rolling indefinitely. Is it because it is seeking a place of rest or because some force is acting upon it? If the latter, identify the force.
2. Copernicus postulated that Earth moves around the Sun (rather than the other way around), but he was troubled about the idea. What concepts of mechanics was he missing (concepts later introduced by Galileo and Newton) that would have eased his doubts?
3. What Aristotelian idea did Galileo discredit in his fabled Leaning Tower demonstration?
4. What Aristotelian idea did Galileo demolish with his experiments with inclined planes?
5. Was it Galileo or Newton who first proposed the concept of inertia?
6. Asteroids have been moving through space for billions of years. What keeps them moving?
7. A space probe may be carried by a rocket into outer space. What keeps the probe moving after the rocket no longer pushes it?
8. In answer to the question "What keeps Earth moving around the Sun?" a friend asserts that inertia keeps it moving. Correct your friend's erroneous assertion.
9. Your friend says that inertia is a force that keeps things in their place, either at rest or in motion. Do you agree? Why or why not?
10. Why is it important that Tim pull slightly downward when he attempts to whip the cloth from beneath the dishes? (What occurs if he pulls slightly upward?)

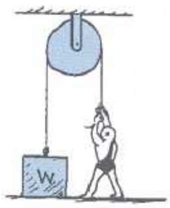
11. Consider a ball at rest in the middle of a toy wagon. When the wagon is pulled forward, the ball rolls against the back of the wagon. Interpret this observation in terms of Newton's first law.
12. In tearing a paper towel or plastic bag from a roll, why is a sharp jerk more effective than a slow pull?
13. If you're in a car at rest that gets hit from behind, you can suffer a serious neck injury called whiplash. What does whiplash have to do with Newton's first law?
14. In terms of Newton's first law (the law of inertia), how does a car headrest help to guard against whiplash in a rear-end collision?
15. Why do you lurch forward in a bus that suddenly slows? Why do you lurch backward when it picks up speed? What law applies here?
16. Suppose that you're in a moving car and the motor stops running. You step on the brakes and slow the car to half speed. If you release your foot from the brakes, will the car speed up a bit, or will it continue at half speed and slow due to friction? Defend your answer.
17. When you push a cart, it moves. When you stop pushing, it comes to rest. Does this violate Newton's law of inertia? Defend your answer.
18. Each bone in the chain of bones forming your spine is separated from its neighbors by disks of elastic tissue. What happens, then, when you jump heavily onto your feet from an elevated position? (*Hint:* Think about the hammerhead in Figure 2.5.) Can you think of a reason why you are a little taller in the morning than at night?
19. Start a ball rolling down a bowling alley and you'll find that it moves slightly slower with time. Does this violate Newton's law of inertia? Defend your answer.
20. Consider a pair of forces, one having a magnitude of 20 N and the other a magnitude of 12 N. What maximum net force is possible for these two forces? What is the minimum net force possible?
21. When any object is in mechanical equilibrium, what can be correctly said about all the forces that act on it? Must the net force necessarily be zero?
22. A monkey hangs stationary at the end of a vertical vine. What two forces act on the monkey? Which, if either, is greater?
23. Can an object be in mechanical equilibrium when only a single force acts on it? Explain.
24. When a ball is tossed straight up, it momentarily comes to a stop at the top of its path. Is it in equilibrium during this brief moment? Why or why not?
25. A hockey puck slides across the ice at a constant speed. Is it in equilibrium? Why or why not?
26. Can you say that no force acts on a body at rest? Or is it correct to say that no *net* force acts on it? Defend your answer.
27. Nellie Newton hangs at rest from the ends of the rope as shown. How does the reading on the scale compare with her weight?

28. Harry the painter swings year after year from his bosun's chair. His weight is 500 N and the rope, unknown to him, has a breaking point of 300 N. Why doesn't the rope break when he is supported as shown at the left? One day, Harry is painting near a flagpole, and, for a change, he ties the free end of the rope to the flagpole instead of to his chair, as shown

at the right. Why did Harry end up taking his vacation early?



29. For the pulley system shown, what is the upper limit of weight the strong man can lift?



30. If the strong man in the previous exercise exerts a downward force of 800 N on the rope, how much upward force is exerted on the block?

31. A force of gravity pulls downward on a book on a table. What force prevents the book from accelerating downward?

32. How many significant forces act on a book at rest on a table? Identify the forces.

33. Consider the normal force on a book at rest on a tabletop. If the table is tilted so that the surface forms an inclined plane, will the magnitude of the normal force change? If so, how?

34. When you push downward on a book at rest on a table, you feel an upward force. Does this force depend on friction? Defend your answer.

35. Place a heavy book on a table and the table pushes up on the book. Why doesn't this upward push cause the book to rise from the table?

36. As you stand on a floor, does the floor exert an upward force against your feet? How much force does it exert? Why are you not moved upward by this force?

37. An empty jug of weight W rests on a table. What is the support force exerted on the jug by the table? What is the support force when water of weight w is poured into the jug?

38. If you pull horizontally on a crate with a force of 200 N, it slides across the floor in dynamic equilibrium. How much friction is acting on the crate?

39. In order to slide a heavy cabinet across the floor at constant speed, you exert a horizontal force of 600 N. Is the force of friction between the cabinet and the floor greater than, less than, or equal to 600 N? Defend your answer.

40. Consider a crate at rest on a factory floor. As a pair of workmen begin lifting it, does the support force on the crate provided by the floor increase, decrease, or remain unchanged? What happens to the support force on the workmen's feet?

41. Two people each pull with 300 N on a rope in a tug of war. What is the net force on the rope? How much force is exerted on each person by the rope?

42. Two forces act on a parachutist falling in air: weight and air drag. If the fall is steady, with no gain or loss of speed, then the parachutist is in dynamic equilibrium. How do the magnitudes of weight and air drag compare?

43. A child learns in school that Earth is traveling faster than 100,000 kilometers per hour around the Sun and, in a frightened tone, asks why we aren't swept off. What is your explanation?

44. Before the time of Galileo and Newton, some learned scholars thought that a stone dropped from the top of a tall mast of a moving ship would fall vertically and hit the deck behind the mast by a distance equal to how far the ship had moved forward while the stone was falling. In light of your understanding of Newton's first law, what do you think about this?

45. Because Earth rotates once every 24 hours, the west wall in your room moves in a direction toward you at a linear speed that is probably more than 1000 kilometers per hour (the exact speed depends on your latitude). When you stand facing the wall, you are carried along at the same speed, so you don't notice it. But when you jump upward, with your feet no longer in contact with the floor, why doesn't the high-speed wall slam into you?

46. If you toss a coin straight upward while riding in a train, where does the coin land when the motion of the train is uniform along a straight-line track? When the train slows while the coin is in the air? When the train is turning?

47. The smokestack of a stationary toy train consists of a vertical spring gun that shoots a steel ball a meter or so straight into the air—so straight that the ball always falls back into the smokestack. Suppose the train moves at constant speed along the straight track. Do you think the ball will still return to the smokestack if shot from the moving train? What if the train gains speed along the straight track? What if it moves at a constant speed on a circular track? Why do your answers differ?

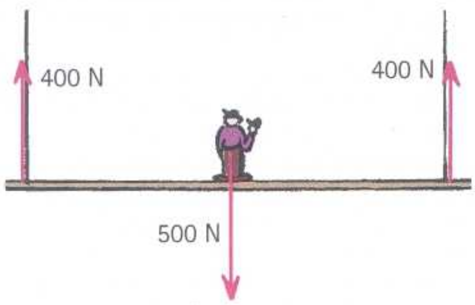
48. Consider an airplane that flies due east on a trip, then returns flying due west. Flying in one direction, the plane flies with Earth's rotation, and in the opposite direction, against Earth's rotation. But, in the absence of winds, the times of flight are equal either way. Why is this so?

PROBLEMS

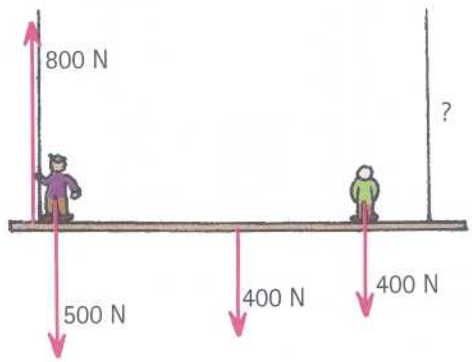
1. Lucy Lightfoot stands with one foot on one bathroom scale and her other foot on a second bathroom scale. Each scale reads 350 N. What is Lucy's weight?

2. Henry Heavyweight weighs 1200 N and stands on a pair of bathroom scales so that one scale reads twice as much as the other. What are the scale readings?

3. The sketch shows a painter's scaffold in mechanical equilibrium. The person in the middle weighs 500 N, and the tensions in each rope are 400 N. What is the weight of the scaffold?



4. A different scaffold that weighs 400 N supports two painters, one 500 N and the other 400 N. The reading in the left scale is 800 N. What is the reading in the right-hand scale?



CHAPTER 2 ONLINE RESOURCES

PhysicsPlace.com™

Videos

- Newton's Law of Inertia
- The Old Tablecloth Trick
- Toilet Paper Roll
- Inertia of a Cylinder
- Inertia of an Anvil
- Definition of a Newton

Quizzes

Flashcards

Links

3 Linear Motion

1 Joan Lucas moves with increasing speed when the distance her horse travels each second increases. **2** Likewise for Sue Johnson and her crew who win medals for high speed in their racing shell. **3** Chelcie Liu asks his students to check their thinking with neighbors and predict which ball will first reach the end of the equal-length tracks.

In this chapter we continue with the ideas of a man who was subjected to house arrest because of his ideas, the Italian scientist Galileo Galilei, who died in the same year that Newton was born. These ideas were to be a foundation for Isaac Newton, who, when asked about his success in science, replied that he stood on the shoulders of giants. Most notable of these was Galileo.

Galileo developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies and generally believed that the Sun goes around Earth. He left Pisa to teach at the University of Padua and became an advocate of the new Copernican theory of the solar system. He was the first man to discover mountains on the moon and to find the moons of Jupiter. Because he published his findings in Italian, the language of the people, instead of in Latin, the language of scholars, and because of the recent invention of the printing press, his ideas reached a wide readership. He soon ran afoul of the Church, and he was warned not to teach or hold to Copernican views. He restrained himself publicly for nearly 15 years and then defiantly published his observations and conclusions, which were counter to Church doctrine. The outcome was a trial in which he was found guilty, and he was forced to renounce his discovery that Earth moves. As he walked out of the court, it is said that he whispered, "But it moves." By then an old man, broken in health and spirit, he was sentenced to perpetual house arrest. Nevertheless, he completed his studies on motion, and his writings were smuggled from Italy and published in Holland. His ideas on motion are the subject of this chapter.

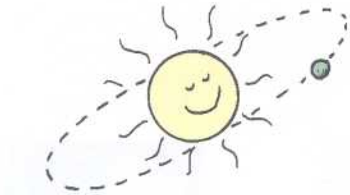


FIGURE 3.1
When you sit on a chair, your speed is zero relative to Earth but 30 km/s relative to the Sun.

Motion Is Relative

Everything moves—even things that appear to be at rest. They move relative to the Sun and stars. As you're reading this, you're moving at about 107,000 kilometers per hour relative to the Sun, and you're moving even faster relative to the center of our galaxy. When we discuss the motion of something, we describe the motion relative to something else. If you walk down the aisle of a moving bus, your speed relative to the floor of the bus is likely quite different from your speed relative to the road. When we say a racing car reaches a speed of 300 kilometers per hour, we mean relative to the track. Unless stated otherwise, when we discuss the speeds of things in our environment, we mean relative to the surface of Earth. Motion is relative.

CHECK POINT

A hungry mosquito sees you resting in a hammock in a 3-m/s breeze. How fast and in what direction should the mosquito fly in order to hover above you for lunch?

Check Your Answer

The mosquito should fly toward you into the breeze. When just above you, it should fly at 3 m/s in order to hover at rest. Unless its grip on your skin is strong enough after landing, it must continue flying at 3 m/s to keep from being blown off. That's why a breeze is an effective deterrent to mosquito bites.

If you look out an airplane window and view another plane flying at the same speed in the opposite direction, you'll see it flying twice as fast—nicely illustrating relative motion.

Speed

Before the time of Galileo, people described moving things as simply "slow" or "fast." Such descriptions were vague. Galileo is credited with being the first to measure speed by considering the distance covered and the time it takes. He defined **speed** as the distance covered per unit of time. Interestingly, Galileo could easily measure distance, but in his day measuring short times was no easy matter. He sometimes used his own pulse and sometimes the dripping of drops from a "water clock" he devised.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

A cyclist who covers 16 meters in a time of 2 seconds, for example, has a speed of 8 meters per second.

Any combination of distance and time units is legitimate for measuring speed; for motor vehicles (or long distances), the units kilometers per hour (km/h) or miles per hour (mi/h or mph) are commonly used. For shorter distances, meters per second (m/s) is more useful. The slash symbol (/) is read as *per* and means "divided by." Throughout this book, we'll primarily use meters per second (m/s). Table 3.1 shows some comparative speeds in different units.[1]

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Videos
Definition of Speed
Average Speed

TABLE 3.1
Approximate Speeds in Different Units

12 mi/h	= 20 km/h	= 6 m/s
25 mi/h	= 40 km/h	= 11 m/s
37 mi/h	= 60 km/h	= 17 m/s
50 mi/h	= 80 km/h	= 22 m/s
62 mi/h	= 100 km/h	= 28 m/s
75 mi/h	= 120 km/h	= 33 m/s
100 mi/h	= 160 km/h	= 44 m/s

INSTANTANEOUS SPEED

Things in motion often have variations in speed. A car, for example, may travel along a street at 50 km/h, slow to 0 km/h at a red light, and speed up to only 30 km/h because of traffic. You can tell the speed of the car at any instant by looking at its

[1]Conversion is based on 1 h = 3600 s, 1 mi = 1609.344 m.

speedometer. The speed at any instant is the **instantaneous speed.** A car traveling at 50 km/h usually goes at that speed for less than 1 hour. If it did go at that speed for a full hour, it would cover 50 km. If it continued at that speed for half an hour, it would cover half that distance: 25 km. If it continued for only 1 minute, it would cover less than 1 km.

FIGURE 3.2

A speedometer gives readings in both miles per hour and kilometers per hour.

AVERAGE SPEED

In planning a trip by car, the driver often wants to know the time of travel. The driver is concerned with the **average speed** for the trip. Average speed is defined as

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

Average speed can be calculated rather easily. For example, if we drive a distance of 80 kilometers in a time of 1 hour, we say our average speed is 80 kilometers per hour. Likewise, if we travel 320 kilometers in 4 hours,

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{320\text{ km}}{4\text{ h}} = 80\text{ km/h}$$

We see that, when a distance in kilometers (km) is divided by a time in hours (h), the answer is in kilometers per hour (km/h).

Since average speed is the whole distance covered divided by the total time of travel, it doesn't indicate the different speeds and variations that may have taken place during shorter time intervals. On most trips, we experience a variety of speeds, so the average speed is often quite different from the instantaneous speed.

If we know average speed and time of travel, distance traveled is easy to find. A simple rearrangement of the definition above gives

$$\text{Total distance covered} = \text{average speed} \times \text{time}$$

If your average speed is 80 kilometers per hour on a 4-hour trip, for example, you cover a total distance of 320 kilometers (80 km/h × 4 h).

If you're cited for speeding, which does the police officer write on your ticket, your *instantaneous speed* or your *average speed?*

CHECK POINT

1. What is the average speed of a cheetah that sprints 100 meters in 4 seconds? If it sprints 50 m in 2 s?
2. If a car moves with an average speed of 60 km/h for an hour, it will travel a distance of 60 km.
   a. How far would it travel if it moved at this rate for 4 h?
   b. For 10 h?
3. In addition to the speedometer on the dashboard of every car is an odometer, which records the distance traveled. If the initial reading is set at zero at the beginning of a trip and the reading is 40 km one-half hour later, what has been your average speed?
4. Would it be possible to attain this average speed and never go faster than 80 km/h?

Check Your Answers

(Are you reading this before you have reasoned answers in your mind? As mentioned in the previous chapter, when you encounter Check Yourself questions throughout this book, check your ***thinking*** *before you read the answers. You'll not only learn more, you'll enjoy learning more.)*

1. In both cases the answer is 25 m/s:

$$\text{Average speed} = \frac{\text{distance covered}}{\text{time interval}} = \frac{100\text{ meters}}{4\text{ seconds}} = \frac{50\text{ meters}}{2\text{ seconds}} = 25\text{ m/s}$$

2. The distance traveled is the average speed × time of travel, so
   a. Distance = 60 km/h × 4 h = 240 km
   b. Distance = 60 km/h × 10 h = 600 km
3. Average speed $= \dfrac{\text{total distance covered}}{\text{time interval}} = \dfrac{40\text{ km}}{0.5\text{ h}} = 80\text{ km/h}$
4. No, not if the trip starts from rest and ends at rest. There are times in which the instantaneous speeds are less than 80 km/h, so the driver must drive at speeds of greater than 80 km/h during one or more time intervals in order to average 80 km/h. In practice, average speeds are usually much lower than high instantaneous speeds.

Velocity

When we know both the speed and the direction of an object, we know its **velocity.** For example, if a car travels at 60 km/h, we know its speed. But if we say it moves at 60 km/h to the north, we specify its *velocity.* Speed is a description of how fast; velocity is how fast *and* in what direction. A quantity such as velocity that specifies direction as well as magnitude is called a **vector quantity.** Recall from Chapter 2 that force is a vector quantity, requiring both magnitude and direction for its description. Likewise, velocity is a vector quantity. In contrast, a quantity that requires only magnitude for a description is called a **scalar quantity.** Speed is a scalar quantity.

Velocity is "directed" speed.

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Velocity
Changing Velocity

CONSTANT VELOCITY

Constant speed means steady speed. Something with constant speed doesn't speed up or slow down. Constant velocity, on the other hand, means both constant speed *and* constant direction. Constant direction is a straight line—the object's path doesn't curve. So constant velocity means motion in a straight line at a constant speed.

CHANGING VELOCITY

If either the speed or the direction changes (or if both change), then the velocity changes. A car on a curved track, for example, may have a constant speed, but, because its direction is changing, its velocity is not constant. We'll see in the next section that it is *accelerating.*

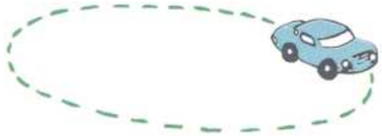

FIGURE 3.3
The car on the circular track may have a constant speed, but its velocity is changing every instant. Why?

CHECK POINT

1. "She moves at a constant speed in a constant direction." Rephrase the same sentence in fewer words.
2. The speedometer of a car moving to the east reads 100 km/h. It passes another car that moves to the west at 100 km/h. Do both cars have the same speed? Do they have the same velocity?
3. During a certain period of time, the speedometer of a car reads a constant 60 km/h. Does this indicate a constant speed? A constant velocity?

Check Your Answers

1. "She moves at a constant velocity."
2. Both cars have the same speed, but they have opposite velocities because they are moving in opposite directions.
3. The constant speedometer reading indicates a constant speed but not a constant velocity, because the car may not be moving along a straight-line path, in which case it is accelerating.

Acceleration

We can change the velocity of something by changing its speed, by changing its direction, or by changing both its speed *and* its direction. How quickly velocity changes is **acceleration:**

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

We are familiar with acceleration in an automobile. When the driver depresses the gas pedal (appropriately called the accelerator), the passengers then experience acceleration (or "pickup," as it is sometimes called) as they are pressed against their seats. The key idea that defines acceleration is *change.* Suppose we are driving and, in 1 second, we steadily increase our velocity from 30 kilometers per hour to 35 kilometers per hour, and then to 40 kilometers per hour in the next second, to 45 in the next second, and so on. We change our velocity by 5 kilometers per hour each second. This change in velocity is what we mean by acceleration.

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\ \text{km/h}}{1\ \text{s}} = 5\ \text{km/h·s}$$

In this case, the acceleration is 5 kilometers per hour second (abbreviated as 5 km/h·s). Note that a unit for time enters twice: once for the unit of velocity and again for the interval of time in which the velocity is changing. Also note that acceleration is not just the total change in velocity; it is the *time rate of change,* or *change per second,* in velocity.

FIGURE 3.4

We say that a body undergoes acceleration when there is a *change* in its state of motion.

CHECK POINT

1. A particular car can go from rest to 90 km/h in 10 s. What is its acceleration?
2. In 2.5 s, a car increases its speed from 60 km/h to 65 km/h while a bicycle goes from rest to 5 km/h. Which undergoes the greater acceleration? What is the acceleration of each?

Check Your Answers

1. Its acceleration is 9 km/h·s. Strictly speaking, this would be its average acceleration, for there may have been some variation in its rate of picking up speed.
2. The accelerations of both the car and the bicycle are the same: 2 km/h·s.

$$\text{Acceleration}_{\text{car}} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{65\ \text{km/h} - 60\ \text{km/h}}{2.5\ \text{s}} = \frac{5\ \text{km/h}}{2.5\ \text{s}} = 2\ \text{km/h·s}$$

$$\text{Acceleration}_{\text{bike}} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\ \text{km/h} - 0\ \text{km/h}}{2.5\ \text{s}} = \frac{5\ \text{km/h}}{2.5\ \text{s}} = 2\ \text{km/h·s}$$

Although the velocities are quite different, the rates of *change* of velocity are the same. Hence, the accelerations are equal.

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Definition of Acceleration
Numerical Example of Acceleration

The term *acceleration* applies to decreases as well as to increases in velocity. We say the brakes of a car, for example, produce large retarding accelerations; that is, there is a large decrease per second in the velocity of the car. We often call this *deceleration.* We experience deceleration when the driver of a bus or car applies the brakes and we tend to lurch forward.

FIGURE 3.5

Rapid deceleration is sensed by the driver, who lurches forward (in accord with Newton's first law).

Can you see that a car has three controls that change velocity—the gas pedal (accelerator), the brakes, and the steering wheel?

We accelerate whenever we move in a curved path, even if we are moving at constant speed, because our direction is changing—hence, our velocity is changing. We experience this acceleration as we tend to lurch toward the outer part of the curve. We distinguish speed and velocity for this reason and define *acceleration* as the rate at which velocity changes, thereby encompassing changes both in speed and in direction.

Anyone who has stood in a crowded bus has experienced the difference between velocity and acceleration. Except for the effects of a bumpy road, you can stand with no extra effort inside a bus that moves at constant velocity, no matter how fast it is going. You can flip a coin and catch it exactly as if the bus were at rest. It is only when the bus accelerates—speeds up, slows down, or turns—that you experience difficulty standing.

In much of this book, we will be concerned only with motion along a straight line. When straight-line motion is being considered, it is common to use *speed* and *velocity* interchangeably. When direction doesn't change, acceleration may be expressed as the rate at which *speed* changes.

$$\text{Acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

CHECK POINT

1. What is the acceleration of a race car that whizzes past you at a constant velocity of 400 km/h?
2. Which has the greater acceleration, an airplane that goes from 1000 km/h to 1005 km/h in 10 seconds or a skateboard that goes from zero to 5 km/h in 1 second?

Check Your Answers

1. Zero, because its velocity doesn't change.
2. Both gain 5 km/h, but the skateboard does so in one-tenth the time. The skateboard therefore has the greater acceleration—in fact, ten times greater. A little figuring will show that the acceleration of the airplane is 0.5 km/h·s, whereas acceleration of the slower-moving skateboard is 5 km/h·s. Velocity and acceleration are very different concepts. Distinguishing between them is very important.

ACCELERATION ON GALILEO'S INCLINED PLANES

Galileo developed the concept of acceleration in his experiments on inclined planes. His main interest was falling objects, and, because he lacked accurate timing devices, he used inclined planes effectively to slow accelerated motion and to investigate it more carefully.

Galileo found that a ball rolling down an inclined plane picks up the same amount of speed in successive seconds; that is, the ball rolls with unchanging acceleration. For example, a ball rolling down a plane inclined at a certain angle might be found to pick up a speed of 2 meters per second for each second it rolls. This gain per second is its acceleration. Its instantaneous velocity at 1-second intervals, at this acceleration, is then 0, 2, 4, 6, 8, 10, and so forth, meters per second. We can see that the instantaneous speed or velocity of the ball at any given time after being released from rest is simply equal to its acceleration multiplied by the time:[2]

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

[2]Note that this relationship follows from the definition of acceleration. From $a = v/t$, simple rearrangement (multiplying both sides of the equation by t) gives $v = at$.

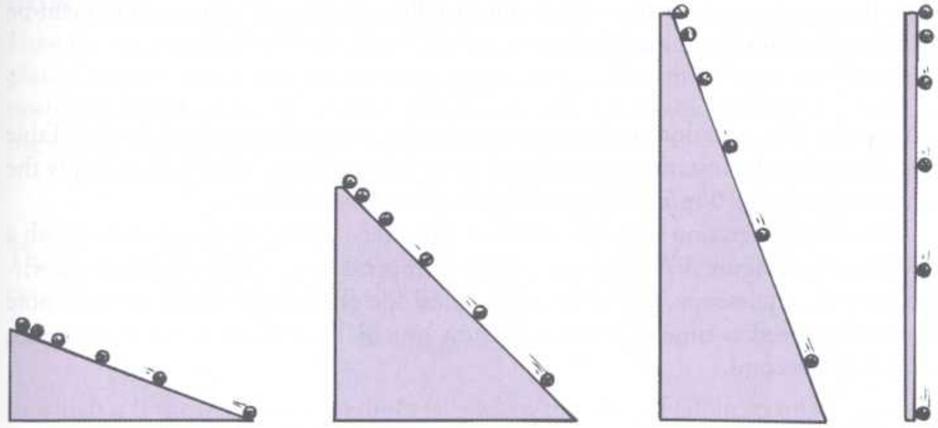

FIGURE 3.6

INTERACTIVE FIGURE

The greater the slope of the incline, the greater the acceleration of the ball. What is its acceleration if the ball falls vertically?

If we substitute the acceleration of the ball in this relationship (2 meters per second squared), we can see that, at the end of 1 second, the ball is traveling at 2 meters per second; at the end of 2 seconds, it is traveling at 4 meters per second; at the end of 10 seconds, it is traveling at 20 meters per second; and so on. The instantaneous speed or velocity at any time is simply equal to the acceleration multiplied by the number of seconds it has been accelerating.

Galileo found greater accelerations for steeper inclines. The ball attains its maximum acceleration when the incline is tipped vertically. Then it falls with the acceleration of a falling object (Figure 3.6). Regardless of the weight or size of the object, Galileo discovered that, when air resistance is small enough to be neglected, all objects fall with the same unchanging acceleration.

How nice, the acceleration due to gravity is 10 m/s each second all the way down. Why this is so, for any mass, awaits you in Chapter 4.

Free Fall

HOW FAST

Things fall because of the force of gravity. When a falling object is free of all restraints—no friction, with the air or otherwise—and falls under the influence of gravity alone, the object is in a state of **free fall.** (We'll consider the effects of air resistance on falling objects in Chapter 4.) Table 3.2 shows the instantaneous speed of a freely falling object at 1-second intervals. The important thing to note in these numbers is the way in which the speed changes. *During each second of fall, the object gains a speed of 10 meters per second.* This gain per second is the acceleration. Free-fall acceleration is approximately equal to 10 meters per second each second, or, in shorthand notation, 10 m/s^2 (read as 10 meters per second squared). Note that the unit of time, the second, enters twice—once for the unit of speed and again for the time interval during which the speed changes.

In the case of freely falling objects, it is customary to use the letter g to represent the acceleration (because the acceleration is due to *gravity*). The value of g is very different on the surface of the Moon and on the surfaces of other planets. Here on Earth, g varies slightly in different locations, with an average value equal to 9.8 meters per second each second, or, in shorter notation, 9.8 m/s^2. We round this off to 10 m/s^2 in our present discussion and in Table 3.2 to establish the ideas involved more clearly; multiples of 10 are more obvious than multiples of 9.8. Where accuracy is important, the value of 9.8 m/s^2 should be used.

TABLE 3.2

Free-Fall from Rest

Time of Fall (seconds)	Velocity Acquired (meters/second)
0	0
1	10
2	20
3	30
4	40
5	50
.	.
.	.
.	.
t	$10t$

Note in Table 3.2 that the instantaneous speed or velocity of an object falling from rest is consistent with the equation that Galileo deduced with his inclined planes:

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

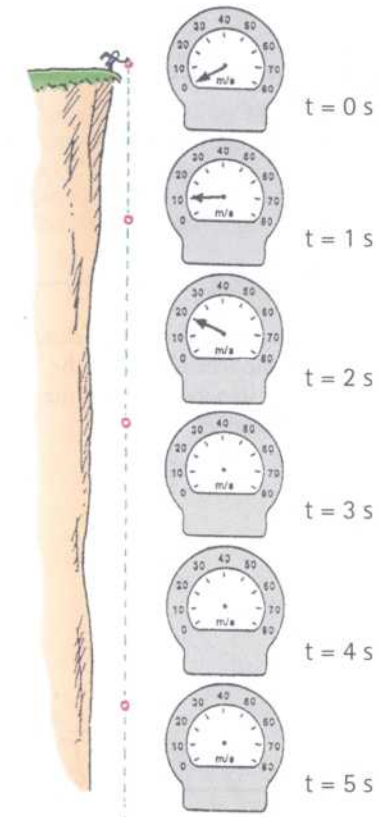

FIGURE 3.7
Pretend that a falling rock is equipped with a speedometer. In each succeeding second of fall, you'd find the rock's speed increasing by the same amount: 10 m/s. Sketch in the missing speedometer needle at $t =$ 3 s, 4 s, and 5 s. (Table 3.2 shows the speeds we would read at various seconds of fall.)

The instantaneous velocity v of an object falling from rest[3] after a time t can be expressed in shorthand notation as

$$v = gt$$

To see that this equation makes good sense, take a moment to check it with Table 3.2. Note that the instantaneous velocity or speed in meters per second is simply the acceleration $g = 10 \text{ m/s}^2$ multiplied by the time t in seconds.

Free-fall acceleration is clearer when we consider a falling object equipped with a speedometer (Figure 3.7). Suppose a rock is dropped from a high cliff and you witness it with a telescope. If you focus the telescope on the speedometer, you'd note increasing speed as time progresses. By how much? The answer is, by 10 m/s each succeeding second.

CHECK POINT

What would the speedometer reading on the falling rock shown in Figure 3.7 be 5 s after it drops from rest? How about 6 s after it is dropped? 6.5 s after it is dropped?

Check Your Answer

The speedometer readings would be 50 m/s, 60 m/s, and 65 m/s, respectively. You can reason this from Table 3.2 or use the equation $v = gt$, where g is 10 m/s^2.

So far, we have been considering objects moving straight downward in the direction of the pull of gravity. How about an object thrown straight upward? Once released, it continues to move upward for a time and then comes back down. At its highest point, when it is changing its direction of motion from upward to downward, its instantaneous speed is zero. Then it starts downward *just as if it had been dropped from rest at that height.*

During the upward part of this motion, the object slows as it rises. It should come as no surprise that it slows at the rate of 10 meters per second each second—the same acceleration it experiences on the way down. So, as Figure 3.8 shows, the instantaneous speed at points of equal elevation in the path is the same whether the object is moving upward or downward. The velocities are opposite, of course, because they are in opposite directions. Note that the downward velocities have a negative sign, indicating the downward direction (it is customary to call *up* positive, and *down* negative.) Whether moving upward or downward, the acceleration is 10 m/s^2 the whole time.

CHECK POINT

A ball is thrown straight upward and leaves your hand at 20 m/s. What predictions can you make about the ball? (Please think about this *before* reading the suggested predictions!)

Check Your Answer

There are several. One prediction is that it will slow to 10 m/s 1 second after it leaves your hand and will come to a momentary stop 2 seconds after leaving your hand, when it reaches the top of its path. This is because it loses 10 m/s each second going up. Another prediction is that 1 second later, 3 seconds total, it will be moving downward at 10 m/s. In another second, it will return to its starting point and be moving at 20 m/s. So the time each way is 2 seconds, and its total time in flight takes 4 seconds. We'll now treat how far it travels up and down.

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Free Fall: How Fast?
$v = gt$
Free Fall: How Far?

[3]If, instead of being dropped from rest, the object is thrown downward at speed v_0, the speed v after any elapsed time t is $v = v_0 + gt$. We will not be concerned with this added complication here; we will instead learn as much as we can from the simplest cases. That will be a lot!

HOW FAR

How *far* an object falls is altogether different from how *fast* it falls. With his inclined planes, Galileo found that the distance a uniformly accelerating object travels is proportional to the *square of the time*. The distance traveled by a uniformly accelerating object starting from rest is

$$\text{Distance traveled} = \frac{1}{2}(\text{acceleration} \times \text{time} \times \text{time})$$

This relationship applies to the distance something falls. We can express it, for the case of a freely falling object, in shorthand notation as

$$d = \frac{1}{2}gt^2$$

in which d is the distance something falls when the time of fall in seconds is substituted for t and squared.[4] If we use 10 m/s^2 for the value of g, the distance fallen for various times will be as shown in Table 3.3.

Note that an object falls a distance of only 5 meters during the first second of fall, although its speed is then 10 meters per second. This may be confusing, for we may think that the object should fall a distance of 10 meters. But for it to fall 10 meters in its first second of fall, it would have to fall at an *average* speed of 10 meters per second for the entire second. It starts its fall at 0 meters per second, and its speed is 10 meters per second only in the last instant of the 1-second interval. Its average speed during this interval is the average of its initial and final speeds, 0 and 10 meters per second. To find the average value of these or any two numbers, we simply add the two numbers and divide by 2. This equals 5 meters per second, which, over a time interval of 1 second, gives a distance of 5 meters. As the object continues to fall in succeeding seconds, it will fall through ever-increasing distances because its speed is continuously increasing.

CHECK POINT

A cat steps off a ledge and drops to the ground in 1/2 second.

a. What is its speed on striking the ground?
b. What is its average speed during the 1/2 second?
c. How high is the ledge from the ground?

Check Your Answers

a. Speed: $v = gt = 10\text{ m/s}^2 \times 1/2\text{ s} = 5\text{ m/s}$

b. Average speed: $\bar{v} = \dfrac{\text{initial } v + \text{final } v}{2} = \dfrac{0\text{ m/s} + 5\text{ m/s}}{2} = 2.5\text{ m/s}$

We put a bar over the symbol to denote average speed: $\bar{v}$.

c. Distance: $d = \bar{v}t = 2.5\text{ m/s} \times 1/2\text{ s} = 1.25\text{ m}$

Or equivalently,

$$d = \frac{1}{2}gt^2 = \frac{1}{2} \times 10\text{ m/s}^2 \times (\frac{1}{2}\text{ s})^2 = 1.25\text{ m}$$

Notice that we can find the distance by either of these equivalent relationships.

[4]Distance fallen from rest: d = average velocity × time

$$d = \frac{\text{initial velocity} + \text{final velocity}}{2} \times \text{time}$$

$$d = \frac{0 + gt}{2} \times t$$

$$d = \frac{1}{2}gt^2$$

(See Appendix B for further explanation.)

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Air Resistance and Falling Objects
Falling Distance

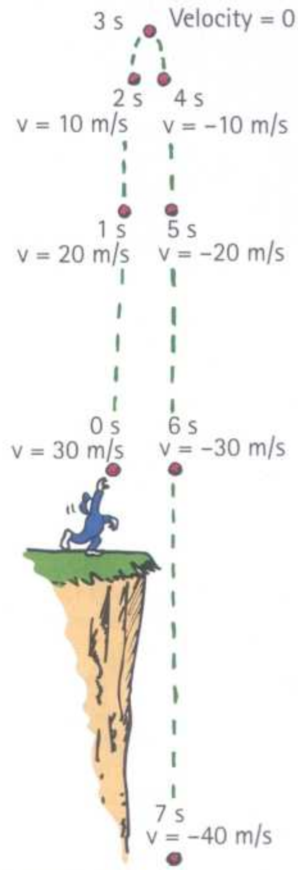


FIGURE 3.8
INTERACTIVE FIGURE
The rate at which the velocity changes each second is the same.

TABLE 3.3
Distance Fallen in Free Fall

Time of Fall (seconds)	Distance Fallen (meters)
0	0
1	5
2	20
3	45
4	80
5	125
·	·
·	·
·	·
t	$\frac{1}{2}10t^2$

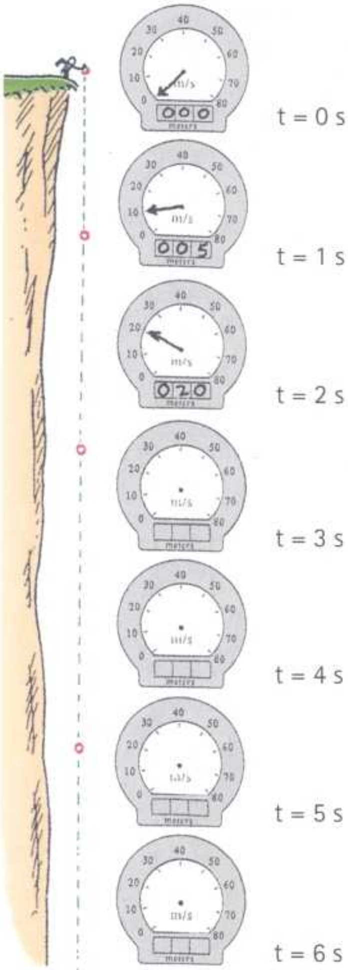


FIGURE 3.9
Pretend that a falling rock is equipped with a speedometer and an odometer. Speed readings increase by 10 m/s and distance readings by $1/2\, gt^2$. Can you complete the speedometer positions and odometer readings?

It is a common observation that many objects fall with unequal accelerations. A leaf, a feather, or a sheet of paper may flutter to the ground slowly. The fact that air resistance is responsible for these different accelerations can be shown very nicely with a closed glass tube containing light and heavy objects—a feather and a coin, for example. In the presence of air, the feather and coin fall with quite different accelerations. But, if the air in the tube is removed by a vacuum pump and the tube is quickly inverted, the feather and coin fall with the same acceleration (Figure 3.10). Although air resistance appreciably alters the motion of things like falling feathers, the motion of heavier objects like stones and baseballs at ordinary low speeds is not appreciably affected by the air. The relationships $v = gt$ and $d = 1/2\, gt^2$ can be used to a very good approximation for most objects falling in air from an initial position of rest.

FIGURE 3.10
A feather and a coin fall at equal accelerations in a vacuum.

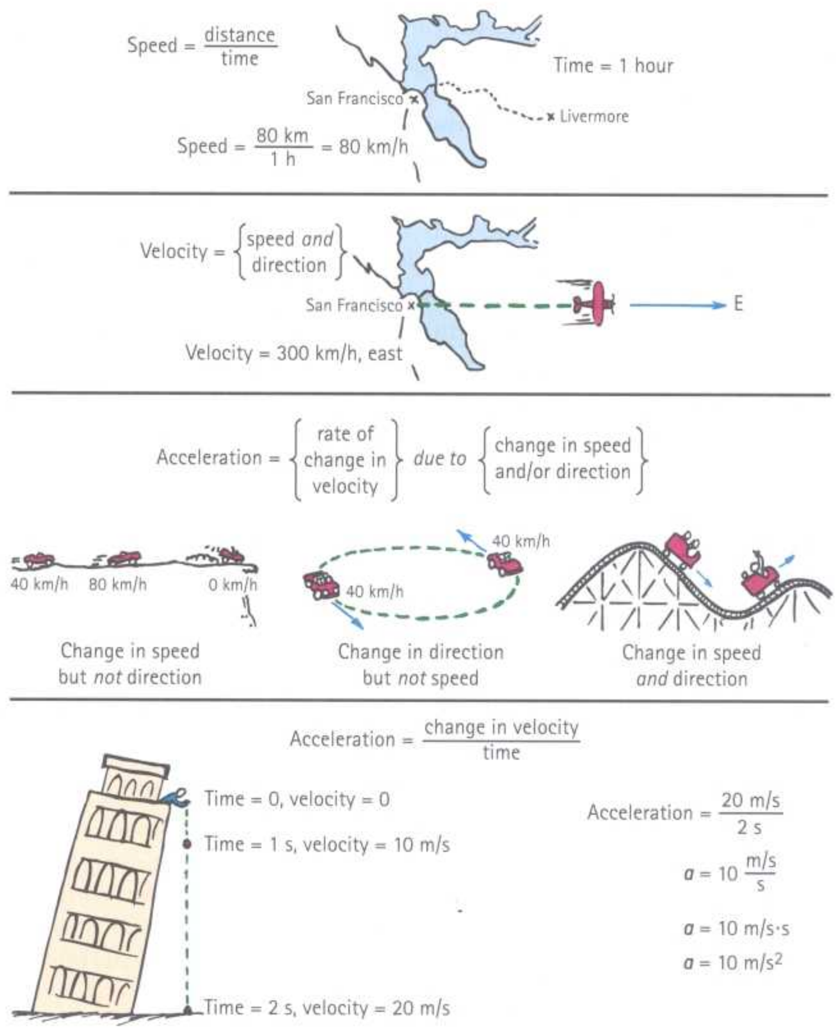


FIGURE 3.11
Motion analysis.

Hang Time

Some athletes and dancers have great jumping ability. Leaping straight up, they seem to "hang in the air," defying gravity. Ask your friends to estimate the "hang time" of the great jumpers—the time a jumper is airborne with feet off the ground. They may say 2 or 3 seconds. But, surprisingly, the hang time of the greatest jumpers is almost always less than 1 second! A longer time is one of many illusions we have about nature.

A related illusion is the vertical height a human can jump. Most of your classmates probably cannot jump higher than 0.5 meter. They can step over a 0.5-meter fence, but, in doing so, their body rises only slightly. The height of the barrier is different than the height a jumper's "center of gravity" rises. Many people can leap over a 1-meter fence, but only rarely does anybody raise the "center of gravity" of their body 1 meter. Even basketball stars Michael Jordan and Kobe Bryant in their prime couldn't raise their body 1.25 meters high, although they could easily reach considerably above the more-than-3-meter-high basket.

Jumping ability is best measured by a standing vertical jump. Stand facing a wall with feet flat on the floor and arms extended upward. Make a mark on the wall at the top of your reach. Then make your jump and, at the peak, make another mark. The distance between these two marks measures your vertical leap. If it's more than 0.6 meter (2 feet), you're exceptional.

Here's the physics. When you leap upward, jumping force is applied only while your feet make contact with the ground. The greater the force, the greater your launch speed and the higher the jump. When your feet leave the ground, your upward speed immediately decreases at the steady rate of g—10 m/s^2. At the top of your jump, your upward speed decreases to zero. Then you begin to fall, gaining speed at exactly the same rate, g. If you land as you took off, upright with legs extended, then time rising equals time falling; hang time is time up plus time down. While airborne, no amount of leg or arm pumping or other bodily motions can change your hang time.

The relationship between time up or down and vertical height is given by

$$d = \frac{1}{2}gt^2$$

If we know the vertical height d, we can rearrange this expression to read

$$t = \sqrt{\frac{2d}{g}}$$

The world-record vertical standing jump is 1.25 meters.[5] Let's use this jumping height of 1.25 meters for d, and use the more precise value of 9.8 m/s^2 for g. Solving for t, half the hang time, we get

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(1.25\text{ m})}{9.8\text{ m/s}^2}} = 0.50\text{ s}$$

Double this (because this is the time for one way of an up-and-down round-trip) and we see that the record-breaking hang time is 1 second.

We're discussing vertical motion here. How about running jumps? We'll see in Chapter 10 that hang time depends only on the jumper's vertical speed at launch. While airborne, the jumper's horizontal speed remains constant and only the vertical speed undergoes acceleration. Interesting physics!

[5]For a running jump, liftoff speed can be increased and hang time extended as the foot bounds off the floor. We'll discuss this in Chapter 8.

HOW QUICKLY "HOW FAST" CHANGES

Much of the confusion that arises in analyzing the motion of falling objects comes about because it is easy to get "how fast" mixed up with "how far." When we wish to specify how fast something is falling, we are talking about *speed* or *velocity,* which is expressed as $v = gt$. When we wish to specify how far something falls, we are talking about *distance,* which is expressed as $d = 1/2\ gt^2$. Speed or velocity (how fast) and distance (how far) are entirely different from each other.

A most confusing concept, and probably the most difficult encountered in this book, is "how quickly does how fast change"—acceleration. What makes acceleration so complex is that it is *a rate of a rate.* It is often confused with velocity, which is itself a rate (the rate of change of position). Acceleration is not velocity, nor is it even a change in velocity. Acceleration is the rate at which velocity itself changes.

Please remember that it took people nearly 2000 years from the time of Aristotle to reach a clear understanding of motion, so be patient with yourself if you find that you require a few hours to achieve as much!

SUMMARY OF TERMS

Speed How fast something moves; the distance traveled per unit of time.

Instantaneous speed The speed at any instant.

Average speed The total distance traveled divided by the time of travel.

Velocity The speed of an object and a specification of its direction of motion.

Vector quantity Quantity in physics that has both magnitude and direction.

Scalar quantity Quantity that can be described by magnitude without direction.

Acceleration The rate at which velocity changes with time; the change in velocity may be in magnitude, or direction, or both.

Free fall Motion under the influence of gravity only.

SUMMARY OF EQUATIONS

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

$$\text{Acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

Velocity acquired in free fall, from rest: $v = gt$

Distance fallen in free fall, from rest: $d = \frac{1}{2} gt^2$

REVIEW QUESTIONS

Motion Is Relative

1. As you read this, how fast are you moving relative to the chair you are sitting on? Relative to the Sun?

Speed

2. What two units of measurement are necessary for describing speed?

Instantaneous Speed

3. What kind of speed is registered by an automobile speedometer—average speed or instantaneous speed?

Average Speed

4. Distinguish between instantaneous speed and average speed.
5. What is the average speed in kilometers per hour for a horse that gallops a distance of 15 km in a time of 30 min?
6. How far does a horse travel if it gallops at an average speed of 25 km/h for 30 min?

Velocity

7. Distinguish between speed and velocity.

Constant Velocity

8. If a car moves with a constant velocity, does it also move with a constant speed?

Changing Velocity

9. If a car is moving at 90 km/h and it rounds a corner, also at 90 km/h, does it maintain a constant speed? A constant velocity? Defend your answer.

Acceleration

10. Distinguish between velocity and acceleration.
11. What is the acceleration of a car that increases its velocity from 0 to 100 km/h in 10 s?
12. What is the acceleration of a car that maintains a constant velocity of 100 km/h for 10 s? (Why do some of your classmates who correctly answer the previous question get this question wrong?)
13. When are you most aware of motion in a moving vehicle—when it is moving steadily in a straight line or when it is accelerating? If a car moved with absolutely constant velocity (no bumps at all), would you be aware of motion?
14. Acceleration is generally defined as the time rate of change of velocity. When can it be defined as the time rate of change of speed?

Acceleration on Galileo's Inclined Planes

15. What did Galileo discover about the amount of speed a ball gained each second when rolling down an inclined plane? What did this say about the ball's acceleration?
16. What relationship did Galileo discover for the velocity acquired on an incline?

17. What relationship did Galileo discover about a ball's acceleration and the steepness of an incline? What acceleration occurs when the plane is vertical?

Free Fall—How Fast

18. What exactly is meant by a "freely falling" object?
19. What is the gain in speed per second for a freely falling object?
20. What is the velocity acquired by a freely falling object 5 s after being dropped from a rest position? What is the velocity 6 s after?
21. The acceleration of free fall is about 10 m/s^2. Why does the seconds unit appear twice?
22. When an object is thrown upward, how much speed does it lose each second?

How Far

23. What relationship between distance traveled and time did Galileo discover for accelerating objects?
24. What is the distance fallen for a freely falling object 1 s after being dropped from a rest position? What is it 4 s after?
25. What is the effect of air resistance on the acceleration of falling objects? What is the acceleration with no air resistance?

How Quickly "How Fast" Changes

26. Consider these measurements: 10 m, 10 m/s, and 10 m/s^2. Which is a measure of distance, which of speed, and which of acceleration?

PROJECTS

1. Grandma is interested in your educational progress. She perhaps has little science background and may be mathematically challenged. Write a letter to Grandma, without using equations, and explain to her the difference between velocity and acceleration. Tell her why some of your classmates confuse the two, and state some examples that clear up the confusion.
2. Stand flatfooted next to a wall. Make a mark at the highest point you can reach. Then jump vertically and mark this highest point. The distance between the marks is your vertical jumping distance. Use this data to calculate your personal hang time.

PLUG AND CHUG

These are "plug-in-the-number" type activities to familiarize you with the equations that link the concepts of physics. They are mainly one-step substitutions and are less challenging than the Problems.

$$\textbf{Speed} = \frac{\textbf{distance}}{\textbf{time}}$$

1. Calculate your walking speed when you step 1 meter in 0.5 second.
2. Calculate the speed of a bowling ball that travels 4 meters in 2 seconds.

$$\textbf{Average speed} = \frac{\textbf{total distance covered}}{\textbf{time interval}}$$

3. Calculate your average speed if you run 50 meters in 10 seconds.
4. Calculate the average speed of a tennis ball that travels the full length of the court, 24 meters, in 0.5 second.
5. Calculate the average speed of a cheetah that runs 140 meters in 5 seconds.
6. Calculate the average speed (in km/h) of Larry, who runs to the store 4 kilometers away in 30 minutes.

$$\textbf{Distance} = \textbf{average speed} \times \textbf{time}$$

7. Calculate the distance (in km) that Larry runs if he maintains an average speed of 8 km/h for 1 hour.
8. Calculate the distance you will travel if you maintain an average speed of 10 m/s for 40 seconds.
9. Calculate the distance you will travel if you maintain an average speed of 10 km/h for one-half hour.

$$\textbf{Acceleration} = \frac{\textbf{change of velocity}}{\textbf{time interval}}$$

10. Calculate the acceleration of a car (in km/h·s) that can go from rest to 100 km/h in 10 s.
11. Calculate the acceleration of a bus that goes from 10 km/h to a speed of 50 km/h in 10 seconds.
12. Calculate the acceleration of a ball that starts from rest, rolls down a ramp, and gains a speed of 25 m/s in 5 seconds.
13. On a distant planet, a freely falling object gains speed at a steady rate of 20 m/s during each second of fall. Calculate its acceleration.

$$\textbf{Instantaneous speed} = \textbf{acceleration} \times \textbf{time}$$

14. Calculate the instantaneous speed (in m/s) at the 10-second mark for a car that accelerates at 2 m/s^2 from a position of rest.
15. Calculate the speed (in m/s) of a skateboarder who accelerates from rest for 3 s down a ramp at an acceleration of 5 m/s^2.

Velocity acquired in free fall, from rest:

$$v = gt \textbf{ (where } g = \textbf{10 m/s}^2\textbf{)}$$

16. Calculate the instantaneous speed of an apple that falls freely from a rest position and accelerates at 10 m/s^2 for 1.5 s.

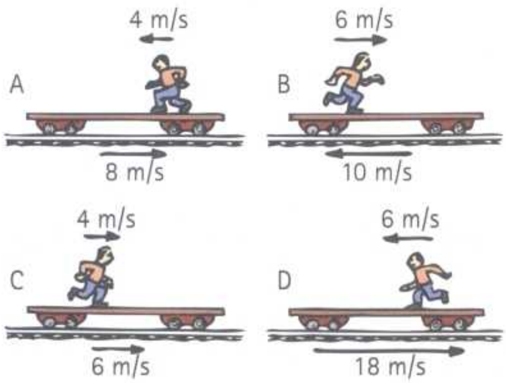
17. An object is dropped from rest and falls freely. After 7 s, calculate its instantaneous speed.
18. A skydiver steps from a high-flying helicopter. In the absence of air resistance, how fast would she be falling at the end of a 12-s jump?
19. On a distant planet, a freely falling object has an acceleration of 20 m/s^2. Calculate the speed that an object dropped from rest on this planet acquires in 1.5 s.

Distance fallen in free fall, from rest: $d = \frac{1}{2} gt^2$

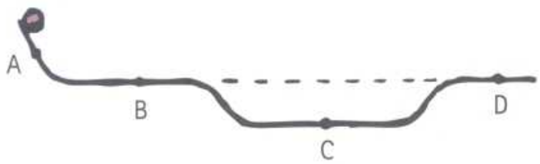
20. An apple drops from a tree and hits the ground in 1.5 s. Calculate how far it falls.
21. Calculate the vertical distance an object dropped from rest covers in 12 s of free fall.
22. On a distant planet a freely falling object has an acceleration of 20 m/s^2. Calculate the vertical distance an object dropped from rest on this planet covers in 1.5 s.

RANKING

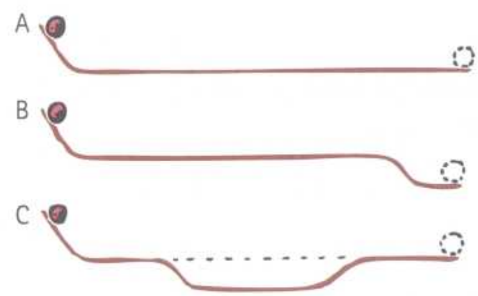
1. Jogging Jake runs along a train flatcar that moves at the velocities shown in positions A–D. From greatest to least, rank the velocity of Jake relative to a stationary observer on the ground. (Call the direction to the right positive.)



2. A track is made of a piece of channel iron bent as shown. A ball released at the left end of the track continues past the various points. Rank the speed of the ball at points A, B, C, and D, from fastest to slowest. (Watch for tie scores.)

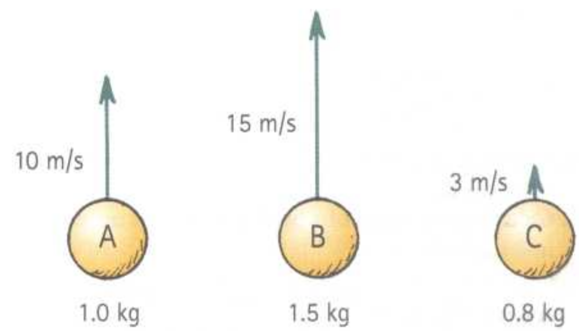


3. A ball is released at the left end of these different tracks. The tracks are bent from equal-length pieces of channel iron.



a. From fastest to slowest, rank the speed of the ball at the right end of the track.
b. From longest to shortest, rank the tracks in terms of the *time* for the ball to reach the end.
c. From greatest to least, rank the tracks in terms of the *average speed* of the ball. Or do all balls have the same average speed on all three tracks?

4. Three balls of different masses are thrown straight upward with initial speeds as indicated.

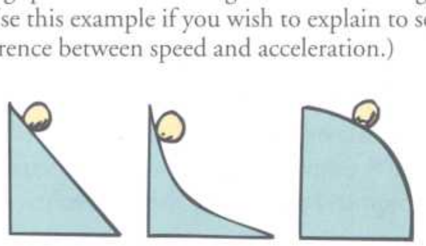


a. From fastest to slowest, rank the speeds of the balls 1 s after being thrown.
b. From greatest to least, rank the accelerations of the balls 1 s after being thrown. (Or are the accelerations the same?)

EXERCISES

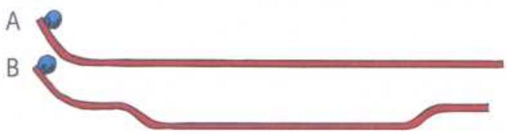
1. What is the impact speed when a car moving at 100 km/h bumps into the rear of another car traveling in the same direction at 98 km/h?
2. Suzie Surefoot can paddle a canoe in still water at 8 km/h. How successful will she be at canoeing upstream in a river that flows at 8 km/h?

3. Is a fine for speeding based on one's average speed or one's instantaneous speed? Explain.
4. One airplane travels due north at 300 km/h while another travels due south at 300 km/h. Are their speeds the same? Are their velocities the same? Explain.
5. Light travels in a straight line at a constant speed of 300,000 km/s. What is the acceleration of light?
6. Can an automobile with a velocity toward the north simultaneously have an acceleration toward the south? Explain.
7. You're in a car traveling at some specified speed limit. You see a car moving at the same speed coming toward you. How fast is the car approaching you, compared with the speed limit?
8. Can an object reverse its direction of travel while maintaining a constant acceleration? If so, give an example. If not, provide an explanation.
9. For straight-line motion, how does a speedometer indicate whether or not acceleration is occurring?
10. Correct your friend who says, "The dragster rounded the curve at a constant velocity of 100 km/h."
11. You are driving north on a highway. Then, without changing speed, you round a curve and drive east. (a) Does your velocity change? (b) Do you accelerate? Explain.
12. Jacob says acceleration is how fast you go. Emily says acceleration is how fast you get fast. They look to you for confirmation. Who's correct?
13. Starting from rest, one car accelerates to a speed of 50 km/h, and another car accelerates to a speed of 60 km/h. Can you say which car underwent the greater acceleration? Why or why not?
14. Cite an example of something with a constant speed that also has a varying velocity. Can you cite an example of something with a constant velocity and a varying speed? Defend your answers.
15. Cite an instance in which your speed could be zero while your acceleration is nonzero.
16. Cite an example of something that undergoes acceleration while moving at constant speed. Can you also give an example of something that accelerates while traveling at constant velocity? Explain.
17. (a) Can an object be moving when its acceleration is zero? If so, give an example. (b) Can an object be accelerating when its speed is zero? If so, give an example.
18. Can you cite an example in which the acceleration of a body is opposite in direction to its velocity? If so, what is your example?
19. On which of these hills does the ball roll down with increasing speed and decreasing acceleration along the path? (Use this example if you wish to explain to someone the difference between speed and acceleration.)



20. Suppose that the three balls shown in Exercise 19 start simultaneously from the tops of the hills. Which one reaches the bottom first? Explain.
21. What is the acceleration of a car that moves at a steady velocity of 100 km/h for 100 s? Explain your answer.
22. Which is greater, an acceleration from 25 km/h to 30 km/h or one from 96 km/h to 100 km/h if both occur during the same time?
23. Galileo experimented with balls rolling on inclined planes of various angles. What is the range of accelerations from angles 0° to 90° (from what acceleration to what)?
24. Be picky and correct your friend who says, "In free fall, air resistance is more effective in slowing a feather than a coin."
25. Suppose that a freely falling object were somehow equipped with a speedometer. By how much would its reading in speed increase with each second of fall?
26. Suppose that the freely falling object in the preceding exercise were also equipped with an odometer. Would the readings of distance fallen each second indicate equal or different falling distances for successive seconds?
27. For a freely falling object dropped from rest, what is the acceleration at the end of the fifth second of fall? At the end of the tenth second of fall? Defend your answers.
28. If air resistance can be neglected, how does the acceleration of a ball that has been tossed straight upward compare with its acceleration if simply dropped?
29. When a ballplayer throws a ball straight up, by how much does the speed of the ball decrease each second while ascending? In the absence of air resistance, by how much does it increase each second while descending? How much time is required for rising compared to falling?
30. Someone standing at the edge of a cliff (as in Figure 3.8) throws a ball nearly straight up at a certain speed and another ball nearly straight down with the same initial speed. If air resistance is negligible, which ball will have the greater speed when it strikes the ground below?
31. Answer the previous question for the case where air resistance is *not* negligible—where air drag affects motion.
32. If you drop an object, its acceleration toward the ground is 10 m/s^2. If you throw it down instead, would its acceleration after throwing be greater than 10 m/s^2? Why or why not?
33. In the preceding exercise, can you think of a reason why the acceleration of the object thrown downward through the air might be appreciably less than 10 m/s^2?
34. While rolling balls down an inclined plane, Galileo observes that the ball rolls 1 cubit (the distance from elbow to fingertip) as he counts to 10. How far will the ball have rolled from its starting point when he has counted to 20?
35. Consider a vertically launched projectile when air drag is negligible. When is the acceleration due to gravity greater? When ascending, at the top, or when descending? Defend your answer.
36. Extend Tables 3.2 and 3.3 to include times of fall of 6 to 10 s, assuming no air resistance.
37. If it were not for air resistance, why would it be dangerous to go outdoors on rainy days?
38. As speed increases for an object in free fall, does acceleration increase also?
39. A ball tossed upward will return to the same point with the same initial speed when air resistance is negligible. When air resistance is not negligible, how does the return speed compare with its initial speed?

40. Two balls are released simultaneously from rest at the left end of equal-length tracks A and B as shown. Which ball reaches the end of its track first?



41. Refer to the pair of tracks in Exercise 40. (a) On which track is the average speed greater? (b) Why is the speed of the ball at the end of the tracks the same?
42. In this chapter, we studied idealized cases of balls rolling down smooth planes and objects falling with no air resistance. Suppose a classmate complains that all this attention focused on idealized cases is worthless because idealized cases simply don't occur in the everyday world. How would you respond to this complaint? How do you suppose the author of this book would respond?
43. A person's hang time would be considerably greater on the Moon. Why?
44. Why does a stream of water get narrower as it falls from a faucet?

45. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between velocity and acceleration.

PROBLEMS

1. You toss a ball straight up with an initial speed of 30 m/s. How high does it go, and how long is it in the air (neglecting air resistance)?
2. A ball is tossed with enough speed straight up so that it is in the air several seconds. (a) What is the velocity of the ball when it reaches its highest point? (b) What is its velocity 1 s before it reaches its highest point? (c) What is the change in its velocity during this 1-s interval? (d) What is its velocity 1 s after it reaches its highest point? (e) What is the change in velocity during this 1-s interval? (f) What is the change in velocity during the 2-s interval? (Careful!) (g) What is the acceleration of the ball during any of these time intervals and at the moment the ball has zero velocity?
3. What is the instantaneous velocity of a freely falling object 10 s after it is released from a position of rest? What is its average velocity during this 10-s interval? How far will it fall during this time?
4. A car takes 10 s to go from $v = 0$ m/s to $v = 25$ m/s at constant acceleration. If you wish to find the distance traveled using the equation $d = 1/2\ at^2$, what value should you use for a?
5. Surprisingly, very few athletes can jump more than 2 feet (0.6 m) straight up. Use $d = 1/2gt^2$ and solve for the time one spends moving upward in a 0.6-m vertical jump. Then double it for the "hang time"—the time one's feet are off the ground.

• 6. A dart leaves the barrel of a blowgun at a speed v. The length of the blowgun barrel is L. Assume that the acceleration of the dart in the barrel is uniform.
   a. Show that the dart moves inside the barrel for a time of $\frac{2L}{v}$.
   b. If the dart's exit speed is 15.0 m/s and the length of the blowgun is 1.4 m, show that the time the dart is in the barrel is 0.19 s.

CHAPTER 3 ONLINE RESOURCES

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Interactive Figures

- 3.6, 3.8

Videos

- Definition of Speed
- Average Speed
- Velocity
- Changing Velocity
- Definition of Acceleration
- Numerical Example of Acceleration
- Free Fall: How Fast?
- $v = gt$
- Free Fall: How Far?
- Air Resistance and Falling Objects
- Falling Distance

Quizzes

Flashcards

Links

4 Newton's Second Law of Motion

1 Efrain Lopez shows that when the forces on the blue block balance to zero, no acceleration occurs. **2** Wingsuit skydivers do what flying squirrels have always done, but faster. They jump from mountains or airplanes and after high terminal speeds use a parachute to safely land. **3** When Emily Abrams kicks the ball, it undergoes acceleration.

Galileo introduced the concept of acceleration, the rate at which velocity changes with time—$a = \Delta v/\Delta t$. But what produces acceleration? That question is answered in Newton's second law. It is *force.* (Newton himself dealt first with momentum and impulse, topics we address in Chapter 6, but nowadays we like to start with acceleration and force.) Newton's second law links these fundamental concepts of acceleration and force to one more profound concept, *mass,* as given by the famous equation, $a = F/m$. Interestingly, although Newton's insights of nature bloomed before he was 24 years of age, he was 42 when he included his three laws of motion in what is generally acknowledged as the greatest scientific book ever written, the *Principia Mathematica Philosophiae Naturalis.* He wrote the work in Latin and completed it in 18 months. It appeared in print in 1687, but it wasn't printed in English until 1729, two years after his death. When asked how he was able to make so many discoveries, Newton replied that he found his solutions to problems not by sudden insight but by continually thinking very long and hard about them until he worked them out. We've treated his first law in Chapter 2, defined acceleration in Chapter 3, and in this chapter we combine what we've learned—Newton's second law of motion.

Isaac Newton (1642–1727)

FIGURE 4.1
Kick the ball and it accelerates.

PhysicsPlace.com™
Video
Force Causes Acceleration

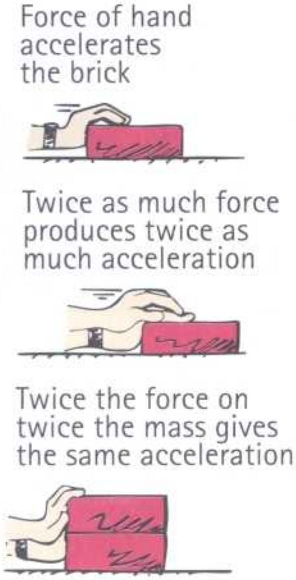

FIGURE 4.2
Acceleration is directly proportional to force.

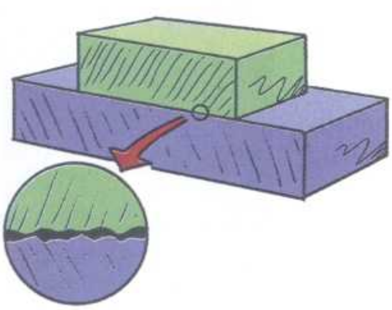

FIGURE 4.3
Friction results from the mutual contact of irregularities in the surfaces of sliding objects. Even surfaces that appear to be smooth have irregular surfaces when viewed at the microscopic level.

Force Causes Acceleration

Consider a hockey puck at rest on ice. Apply a force, and it starts to move—it accelerates. When the hockey stick is no longer pushing it, the puck moves at constant velocity. Apply another force by striking the puck again, and again the motion changes. Applied force produces acceleration.

Most often, the applied force is not the only force acting on an object. Other forces may act as well. Recall, from Chapter 2, that the combination of forces acting on an object is the *net force*. Acceleration depends on the *net force*. To increase the acceleration of an object, you must increase the net force acting on it. If you double the net force on an object, its acceleration doubles; if you triple the net force, its acceleration triples; and so on. This makes good sense. We say an object's acceleration is directly proportional to the net force acting on it. We write

$$\text{Acceleration} \sim \text{net force}$$

The symbol ~ stands for "is directly proportional to." That means, for instance, that if one doubles, the other also doubles.

CHECK POINT

1. You push on a crate that sits on a smooth floor, and it accelerates. If you apply four times the net force, how much greater will be the acceleration?
2. If you push with the same increased force on the same crate, but it slides on a very rough floor, how will the acceleration compare with pushing the crate on a smooth floor? *(Think before you read the answer below!)*

Check Your Answers

1. It will have four times as much acceleration.
2. It will have less acceleration because friction will reduce the net force.

Friction

When surfaces slide or tend to slide over one another, a force of friction acts. When you apply a force to an object, friction usually reduces the net force and the resulting acceleration. Friction is caused by the irregularities in the surfaces in mutual contact, and it depends on the kinds of material and how much they are pressed together. Even surfaces that appear to be very smooth have microscopic irregularities that obstruct motion. Atoms cling together at many points of contact. When one object slides against another, it must either rise over the irregular bumps or else scrape atoms off. Either way requires force.

The direction of the friction force is always in a direction opposing motion. An object sliding *down* an incline experiences friction directed *up* the incline; an object that slides to the *right* experiences friction toward the *left*. Thus, if an object is to move at constant velocity, a force equal to the opposing force of friction must be applied so that the two forces exactly cancel each other. The zero net force then results in zero acceleration and constant velocity.

No friction exists on a crate that sits at rest on a level floor. But, if you push the crate horizontally, you'll disturb the contact surfaces and friction is produced. How much? If the crate is still at rest, then the friction that opposes motion is just enough to cancel your push. If you push horizontally with, say, 70 newtons, friction builds up to become 70 newtons. If you push harder—say, 100 newtons—and the crate is on the verge of sliding, the friction between the crate and floor opposes your push

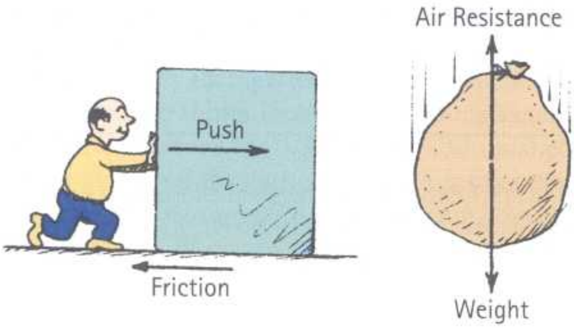

FIGURE 4.4

The direction of the force of friction always opposes the direction of motion. (Left) Push the crate to the right, and friction acts toward the left. (Right) The sack falls downward, and air friction (air resistance) acts upward. (What is the acceleration of the sack when air resistance equals the sack's weight?)

with 100 newtons. If 100 newtons is the most the surfaces can muster, then, when you push a bit harder, the clinging gives way and the crate slides.[1]

Interestingly, the friction of sliding is somewhat less than the friction that builds up before sliding takes place. Physicists and engineers distinguish between *static friction* and *sliding friction*. For given surfaces, static friction is somewhat greater than sliding friction. If you push on a crate, it takes more force to get it going than it takes to keep it sliding. Before the time of antilock brake systems, slamming on the brakes of a car was quite problematic. When tires lock, they slide, providing less friction than if they are made to roll to a stop. A rolling tire does not slide along the road surface, and friction is static friction, with more grab than sliding friction. But once the tires start to slide, the frictional force is reduced—not a good thing. An antilock brake system keeps the tires below the threshold of breaking loose into a slide.

It's also interesting that the force of friction does not depend on speed. A car skidding at low speed has approximately the same friction as the same car skidding at high speed. If the friction force of a crate that slides against a floor is 90 newtons at low speed, to a close approximation it is 90 newtons at a greater speed. It may be more when the crate is at rest and on the verge of sliding, but, once the crate is sliding, the friction force remains approximately the same.

More interesting still, friction does not depend on the area of contact. If you slide the crate on its smallest surface, all you do is concentrate the same weight on a smaller area with the result that the friction is the same. So those extra wide tires you see on some cars provide no more friction than narrower tires. The wider tire simply spreads the weight of the car over more surface area to reduce heating and wear. Similarly, the friction between a truck and the ground is the same whether the truck has four tires or eighteen! More tires spread the load over more ground area and reduce the pressure per tire. Interestingly, stopping distance when brakes are applied is not affected by the number of tires. But the wear that tires experience very much depends on the number of tires.

Friction is not restricted to solids sliding over one another. Friction occurs also in liquids and gases, both of which are called *fluids* (because they flow). Fluid friction occurs as an object pushes aside the fluid it is moving through. Have you ever attempted a 100-m dash through waist-deep water? The friction of fluids is appreciable, even at low speeds. So unlike the friction between solid surfaces, fluid friction depends on speed. A very common form of fluid friction for something moving through air is *air resistance,* also called *air drag*. You usually aren't aware of air resistance when walking or jogging, but you notice it at higher speeds when riding a bicycle or when skiing downhill. Air resistance increases with increasing speed.

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Video
Friction

Tires have treads not to increase friction, but to displace and redirect water from between the road surface and the underside of the tire. Many racing cars use tires without treads because they race on dry days.

FIGURE 4.5

Friction between the tire and the ground is nearly the same whether the tire is wide or narrow. The purpose of the greater contact area is to reduce heating and wear.

[1]Even though it may not seem so yet, most of the concepts in physics are not really complicated. But friction is different. Unlike most concepts in physics, it is a very complicated phenomenon. The findings are empirical (gained from a wide range of experiments) and the predictions approximate (also based on experiment).

The falling sack shown in Figure 4.4 will reach a constant velocity when air resistance balances the sack's weight.

CHECK POINT

What net force does a sliding crate experience when you exert a force of 110 N and friction between the crate and the floor is 100 N?

Check Your Answer

10 N in the direction of your push (110 N – 100 N).

Mass and Weight

The acceleration imparted to an object depends not only on applied forces and friction forces but on the inertia of the object. How much inertia an object possesses depends on the amount of matter in the object—the more matter, the more inertia. In speaking of how much matter something has, we use the term *mass*. The greater the mass of an object, the greater its inertia. Mass is a measure of the inertia of a material object.

Mass corresponds to our intuitive notion of weight. We casually say that something has a lot of matter if it weighs a lot. But there is a difference between mass and weight. We can define each as follows:

> **Mass:** ***The quantity of matter in an object. It is also the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, or change its state of motion in any way.***
>
> **Weight:** ***The force upon an object due to gravity.***

In the absence of acceleration, mass and weight are directly proportional to each other.[2] If the mass of an object is doubled, its weight is also doubled; if the mass is halved, the weight is halved. Because of this, mass and weight are often interchanged. Also, mass and weight are sometimes confused because it is customary to measure the quantity of matter in things (mass) by their gravitational attraction to Earth (weight). But mass is more fundamental than weight; it is a fundamental quantity that completely escapes the notice of most people.

There are times when weight corresponds to our unconscious notion of inertia. For example, if you are trying to determine which of two small objects is the heavier one, you might shake them back and forth in your hands or move them in some way instead of lifting them. In doing so, you are judging which of the two is more difficult to get moving, feeling which of the two is more resistant to a change in motion. You are really comparing the inertias of the objects.

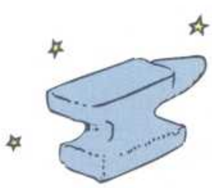


FIGURE 4.6
An anvil in outer space—between Earth and the Moon, for example—may be weightless, but it is not massless.

In the United States, the quantity of matter in an object is commonly described by the gravitational pull between it and Earth, or its *weight*, usually expressed in *pounds*. In most of the world, however, the measure of matter is commonly expressed in a mass unit, the kilogram. At the surface of Earth, a brick with a mass of 1 kilogram weighs 2.2 pounds. In metric units, the unit of force is the **newton,** which is equal to a little less than a quarter-pound (like the weight of a quarter-pound hamburger *after* it is cooked). A 1-kilogram brick weighs about 10 newtons

[2] Weight and mass are directly proportional; weight = mg, where g is the constant of proportionality and has the value 10 N/kg (or more precisely, 9.8 N/kg). Equivalently, g is the acceleration due to gravity, 10 m/s^2 (the units N/kg are equivalent to m/s^2). In Chapter 9 we'll extend the definition of weight as the force that an object exerts on a supporting surface.

(more precisely, 9.8 N).[3] Away from Earth's surface, where the influence of gravity is less, a 1-kilogram brick weighs less. It would also weigh less on the surface of planets with less gravity than Earth. On the Moon's surface, for example, where the gravitational force on things is only 1/6 as strong as on Earth, a 1-kilogram brick weighs about 1.6 newtons (or 0.36 pounds). On planets with stronger gravity, it would weigh more, but the mass of the brick is the same everywhere. The brick offers the same resistance to speeding up or slowing down regardless of whether it's on Earth, on the Moon, or on any other body attracting it. In a drifting spaceship, where a scale with a brick on it reads zero, the brick still has mass. Even though it doesn't press down on the scale, the brick has the same resistance to a change in motion as it has on Earth. Just as much force would have to be exerted by an astronaut in the spaceship to shake it back and forth as would be required to shake it back and forth while on Earth. You'd have to provide the same amount of push to accelerate a huge truck to a given speed on a level surface on the Moon as on Earth. The difficulty of *lifting* it against gravity (weight), however, is something else. Mass and weight are different from each other (Figure 4.7).

FIGURE 4.7

The astronaut in space finds that it is just as difficult to shake the "weightless" anvil as it would be on Earth. If the anvil were more massive than the astronaut, which would shake more—the anvil or the astronaut?

A nice demonstration that distinguishes mass and weight is the massive ball suspended on the string, shown by David Yee in the Chapter 2 opener photo, and in Figure 4.8. The top string breaks when the lower string is pulled with a gradual increase in force, but the bottom string breaks when the lower string is jerked. Which of these cases illustrates the weight of the ball, and which illustrates the mass of the ball? Note that only the top string bears the weight of the ball. So, when the lower string is gradually pulled, the tension supplied by the pull is transmitted to the top string. The total tension in the top string is caused by the pull plus the weight of the ball. The top string breaks when the breaking point is reached. But, when the bottom string is jerked, the mass of the ball—its tendency to remain at rest—is responsible for the bottom string breaking.

It is also easy to confuse mass and volume. When we think of a massive object, we often think of a big object. An object's size (volume), however, is not necessarily a good way to judge its mass. Which is easier to get moving: a car battery or an empty cardboard box of the same size? So, we find that mass is neither weight nor volume.

FIGURE 4.8

Why will a slow, continuous increase in downward force break the string above the massive ball, while a sudden increase will break the lower string?

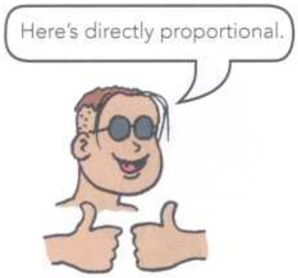
CHECK POINT

1. Does a 2-kg iron brick have twice as much *inertia* as a 1-kg iron brick? Twice as much *mass?* Twice as much *volume?* Twice as much *weight?*
2. Would it be easier to lift a cement truck on Earth's surface or to lift it on the Moon's surface?

Check Your Answers

1. The answers to all parts are *yes*.
2. A cement truck would be easier to lift on the Moon because the gravitational force is less on the Moon. When you *lift* an object, you are contending with the force of gravity (its weight). Although its mass is the same anywhere, its weight is only 1/6 as much on the Moon, so only 1/6 as much effort is required to lift it there. To move it horizontally, however, you are not pushing against gravity. When mass is the only factor, equal forces will produce equal accelerations, whether the object is on Earth or the Moon.

[3]So 2.2 lb equal 9.8 N, or 1 N is approximately equal to 0.22 lb—about the weight of an apple. In the metric system it is customary to specify quantities of matter in units of mass (in grams or kilograms) and rarely in units of weight (in newtons). In the United States and countries that use the British system of units, however, quantities of matter are customarily specified in units of weight (in pounds). (The British unit of mass, the *slug*, is not well known.) See Appendix A for more about systems of measurement.



Mass Resists Acceleration

Push your friend on a skateboard and your friend accelerates. Now push equally hard on an elephant on a skateboard and the acceleration is much less. You'll see that the amount of acceleration depends not only on the force but on the mass being pushed. The same force applied to twice the mass produces half the acceleration; for three times the mass, one-third the acceleration. We say that, for a given force, the acceleration produced is inversely proportional to the mass. That is,

$$\text{Acceleration} \sim \frac{1}{\text{mass}}$$

By inversely we mean that the two values change in opposite directions. As the denominator increases, the whole quantity decreases. For example, the quantity 1/100 is less than 1/10.

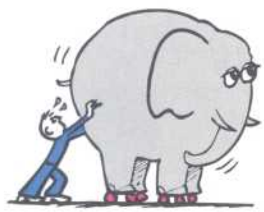


FIGURE 4.9

INTERACTIVE FIGURE

The greater the mass, the greater the force must be for a given acceleration.

FIGURE 4.10

An enormous force is required to accelerate this three-story-high earth mover when it carries a typical 350-ton load.

Newton's Second Law of Motion

Newton was the first to discover the relationship among three basic physical concepts—acceleration, force, and mass. He proposed one of the most important rules of nature, his second law of motion. Newton's second law states

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

In summarized form, this is

$$\text{Acceleration} \sim \frac{\text{net force}}{\text{mass}}$$

We use the wiggly line $\sim$ as a symbol meaning "is proportional to." We say that acceleration a is directly proportional to the overall net force F and inversely proportional to the mass m. By this we mean that, if F increases, a increases by the same factor (if F doubles, a doubles); but if m increases, a decreases by the same factor (if m doubles, a is cut in half).

By using consistent units, such as newtons (N) for force, kilograms (kg) for mass, and meters per second squared (m/s^2) for acceleration, the proportionality may be

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Tutorial
Newton's Second Law
Video
Newton's Second Law

When two things are directly proportional to each other, as one increases, the other increases also. However, when two things are inversely proportional to each other, as one increases, the other decreases.

expressed as an exact equation:

$$\text{Acceleration} = \frac{\text{net force}}{\text{mass}}$$

In its briefest form, where a is acceleration, F_{net} is net force, and m is mass, it becomes

$$a = \frac{F_{\text{net}}}{m}$$

An object is accelerated in the direction of the force acting on it. Applied in the direction of the object's motion, a force will increase the object's speed. Applied in the opposite direction, it will decrease the speed of the object. Applied at right angles, it will deflect the object. Any other direction of application will result in a combination of speed change and deflection. *The acceleration of an object is always in the direction of the net force.*

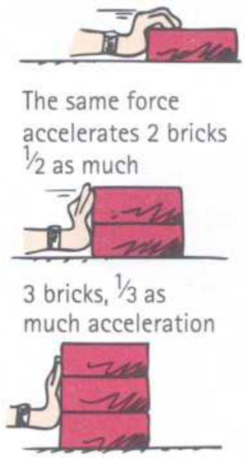

FIGURE 4.11
Acceleration is inversely proportional to mass.

CHECK POINT

1. In the previous chapter, acceleration was defined to be the time rate of change of velocity; that is, a = (change in v)/time. Are we in this chapter saying that acceleration is instead the ratio of force to mass; that is, $a = F/m$? Which is it?
2. A jumbo jet cruises at constant velocity of 1000 km/h when the thrusting force of its engines is a constant 100,000 N. What is the acceleration of the jet? What is the force of air resistance on the jet?

Check Your Answers

1. Acceleration is *defined* as the time rate of change of velocity and is *produced* by a force. How much force/mass (the cause) determines the rate change in v/time (the effect). So whereas we defined acceleration in Chapter 3, in this chapter we define the terms that produce acceleration.
2. The acceleration is zero because the velocity is constant. Since the acceleration is zero, it follows from Newton's second law that the net force is zero, which means that the force of air drag must just equal the thrusting force of 100,000 N and act in the opposite direction. So the air drag on the jet is 100,000 N. (Note that we don't need to know the velocity of the jet to answer this question. We need only to know that it is constant, our clue that acceleration and therefore net force is zero.)

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Free Fall Acceleration Explained

When Acceleration Is g—Free Fall

Although Galileo introduced both the concepts of inertia and acceleration, and although he was the first to measure the acceleration of falling objects, he could not explain *why* objects of various masses fall with equal accelerations. Newton's second law provides the explanation.

We know that a falling object accelerates toward Earth because of the gravitational force of attraction between the object and Earth. When the force of gravity is the only force—that is, when friction (such as air resistance) is negligible—we say that the object is in a state of free fall.

The greater the mass of an object, the greater is the gravitational force of attraction between it and Earth. The double brick in Figure 4.12, for example, has twice the gravitational attraction of the single brick. Why, then, as Aristotle supposed, doesn't the double brick fall twice as fast? The answer is that the acceleration of an object depends not only on the force—in this case, the weight—but also on the object's resistance to motion, its inertia. Whereas a force produces an acceleration,

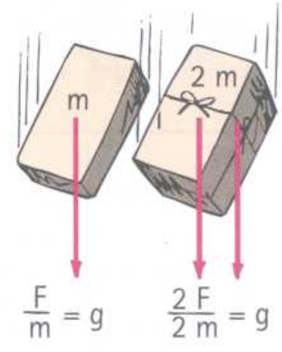

FIGURE 4.12
INTERACTIVE FIGURE
The ratio of weight (F) to mass (m) is the same for all objects in the same locality; hence, their accelerations are the same in the absence of air resistance.

fyi

- We see in free fall that weight/mass = g. So we can say that weight = mg.

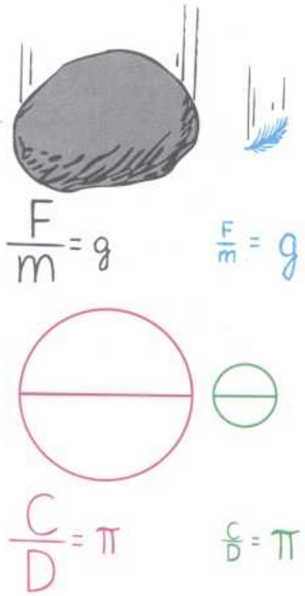

FIGURE 4.13

The ratio of weight (F) to mass (m) is the same for the large rock and the small feather; similarly, the ratio of circumference (C) to diameter (D) is the same for the large and the small circle.

When Galileo tried to explain why all objects fall with equal accelerations, wouldn't he have loved to know the rule $a = F/m$?

inertia is a *resistance* to acceleration. So twice the force exerted on twice the inertia produces the same acceleration as half the force exerted on half the inertia. Both accelerate equally. The acceleration due to gravity is symbolized by g. We use the symbol g, rather than a, to denote that acceleration is due to gravity alone.

The ratio of weight to mass for freely falling objects equals a constant—g. This is similar to the constant ratio of circumference to diameter for circles, which equals the constant π (Figure 4.13).

We now understand that the acceleration of free fall is independent of an object's mass. A boulder 100 times more massive than a pebble falls with the same acceleration as the pebble because, although the force on the boulder (its weight) is 100 times greater than the force on the pebble, its resistance to a change in motion (its mass) is 100 times that of the pebble. The greater force offsets the equally greater mass.

CHECK POINT

In a vacuum, a coin and a feather fall at the same rate, side by side. Would it be correct to say that equal forces of gravity act on both the coin and the feather when in a vacuum?

Check Your Answer

No, no, no, a thousand times no! These objects accelerate equally not because the forces of gravity on them are equal, but because the *ratios* of their weights to their masses are equal. Although air resistance is not present in a vacuum, gravity is. (You'd know this if you stuck your hand into a vacuum chamber and the truck shown in Figure 4.10 rolled over it!) If you answered *yes* to this question, let this be a warning to be more careful when you think physics!

When Acceleration Is Less Than g—Nonfree Fall

Objects falling in a vacuum are one thing, but what of the practical cases of objects falling in air? Although a feather and a coin will fall equally fast in a vacuum, they fall quite differently in air. How do Newton's laws apply to objects falling in air? The answer is that Newton's laws apply for *all* objects, whether freely falling or falling in the presence of resistive forces. The accelerations, however, are quite different for the two cases. The important thing to keep in mind is the idea of *net force*. In a vacuum or in cases in which air resistance can be neglected, the net force is the weight because it is the only force. In the presence of air resistance, however, the net force is less than the weight—it is the weight minus air drag, the force arising from air resistance.[4]

[4]In mathematical notation,

$$a = \frac{F_{net}}{m} = \frac{mg - R}{m}$$

where mg is the weight and R is the air resistance. Note that when $R = mg$, $a = 0$; then, with no acceleration, the object falls at constant velocity. With elementary algebra we can go another step and get

$$a = \frac{F_{net}}{m} = \frac{mg - R}{m} = g - \frac{R}{m}$$

We see that the acceleration a will always be less than g if air resistance R impedes falling. Only when $R = 0$ does $a = g$.

The force of air drag experienced by a falling object depends on two things. First, it depends on the frontal area of the falling object—that is, on the amount of air the object must plow through as it falls. Second, it depends on the speed of the falling object; the greater the speed, the greater the number of air molecules an object encounters per second and the greater the force of molecular impact. Air drag depends on the size and the speed of a falling object.

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Falling and Air Resistance

In some cases, air drag greatly affects falling; in other cases, it doesn't. Air drag is important for a falling feather. Because a feather has so much area for an object so light in weight, it doesn't have to fall very fast before the upward-acting air resistance cancels the downward-acting weight. The net force on the feather is then zero and acceleration terminates. When acceleration terminates, we say that the object has reached its **terminal speed.** If we are concerned with direction, down for falling objects, we say the object has reached its terminal velocity. The same idea applies to all objects falling in air. Consider skydiving. As a falling skydiver gains speed, air drag may finally build up until it equals the weight of the skydiver. If and when this happens, the *net force* becomes zero and the skydiver no longer accelerates; she has reached her terminal velocity. For a feather, terminal velocity is a few centimeters per second, whereas, for a skydiver, it is about 200 kilometers per hour. A skydiver may vary this speed by varying position. Head or feet first is a way of encountering less air and thus less air drag and attaining maximum terminal velocity. A smaller terminal velocity is attained by spreading oneself out like a flying squirrel.

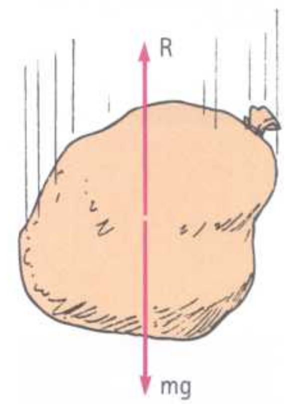


FIGURE 4.14

When weight mg is greater than air resistance R, the falling sack of mail accelerates. At higher speeds, R increases. When $R = mg$, acceleration reaches zero, and the sack reaches its terminal velocity.

Terminal velocities are very much less if the skydiver wears a wingsuit, as shown in the center opening photo at the beginning of this chapter. The wingsuit not only increases the frontal area of the diver, but provides a lift similar to that achieved by flying squirrels when they fashion their bodies into "wings." This new and exhilarating sport, *wingsuit flying,* goes beyond what flying squirrels can accomplish, for a wingsuit flyer can achieve horizontal speeds of more than 160 km/h (100 mph). Looking more like flying bullets than flying squirrels, high-performance wingsuits allow these "bird people" to glide with remarkable precision. To land safely, parachutes are deployed. Projects to land without a parachute, however, are underway.

The large frontal area provided by a parachute produces low terminal speeds for safe landings. To understand the physics of a parachute, consider a man and woman parachuting together from the same altitude (Figure 4.15). Suppose that the man is twice as heavy as the woman and that their same-sized parachutes are initially opened. Having parachutes of the same size means that, at equal speeds, the air resistance is the same on both of them. Who reaches the ground first—the heavy man or the lighter woman? The answer is that the person who falls faster gets to the ground first—that is, the person with the greatest terminal speed. At first we might think that, because the parachutes are the same, the terminal speeds for each would be the same and, therefore, that both would reach the ground at the same time. This doesn't happen, however, because air drag depends on speed. Greater speed means greater force of air impact. The woman will reach her terminal speed when the air drag against her parachute equals her weight. When this occurs, the air drag against the parachute of the man will not yet equal his weight. He must fall faster than she does for the air drag to match his greater weight.[5] Terminal velocity is greater for the heavier person, with the result that the heavier person reaches the ground first.

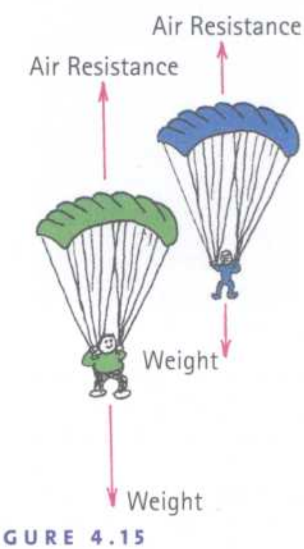


FIGURE 4.15

The heavier parachutist must fall faster than the lighter parachutist for air resistance to cancel his greater weight.

[5]Terminal speed for the twice-as-heavy man will be about 41% greater than the woman's terminal speed, because the retarding force of air resistance is proportional to speed squared. ($v_{man}^2/v_{woman}^2 = 1.41^2 = 2.$)

fyi

- Headfirst, with arms tucked in, skydivers can reach terminal speeds of about 180 km/h (110 mph). Terminal speeds are less with a wingsuit, and greatly reduced with a parachute.

CHECK POINT

Nellie Newton skydives from a high-flying helicopter. As she falls faster and faster through the air, does her acceleration increase, decrease, or remain the same?

Check Your Answer

Acceleration decreases because the net force on Nellie decreases. Net force is equal to her weight minus her air resistance, and since air resistance increases with increasing speed, net force and hence acceleration decrease. By Newton's second law,

$$a = \frac{f_{net}}{m} = \frac{mg - R}{m}$$

where mg is her weight and R is the air resistance she encounters. As R increases, a decreases. Note that if she falls fast enough so that $R = mg$, $a = 0$, then with no acceleration she falls at constant speed.

Consider a pair of tennis balls, one a regular hollow ball and the other filled with iron pellets. Although they are the same size, the iron-filled ball is considerably heavier than the regular ball. If you hold them above your head and drop them simultaneously, you'll see that they strike the ground at about the same time. But if you drop them from a greater height—say, from the top of a building—you'll note the heavier ball strikes the ground first. Why? In the first case, the balls do not gain much speed in their short fall. The air drag they encounter is small compared with their weights, even for the regular ball. The tiny difference in their arrival time is not noticed. But, when they are dropped from a greater height, the greater speeds of fall are met with greater air resistance. At any given speed, each ball encounters the same air resistance because each has the same size. This same air resistance may be a lot compared with the weight of the lighter ball, but only a little compared with the weight of the heavier ball (like the parachutists in Figure 4.15). For example, 1 N of air drag acting on a 2-N object will reduce its acceleration by half, but 1 N of air drag on a 200-N object will only slightly diminish its acceleration. So, even with equal air resistances, the accelerations of each are different. There is a moral to be learned here. Whenever you consider the acceleration of something, use the equation of Newton's second law to guide your thinking: The acceleration is equal to the ratio of *net* force to the mass. For the falling tennis balls, the net force on the hollow ball is appreciably reduced as air drag builds up, while the net force on the iron-filled ball is only slightly reduced. Acceleration decreases as net force decreases, which, in turn, decreases as air drag increases. If and when the air drag builds up to equal the weight of the falling object, then the net force becomes zero and acceleration terminates.

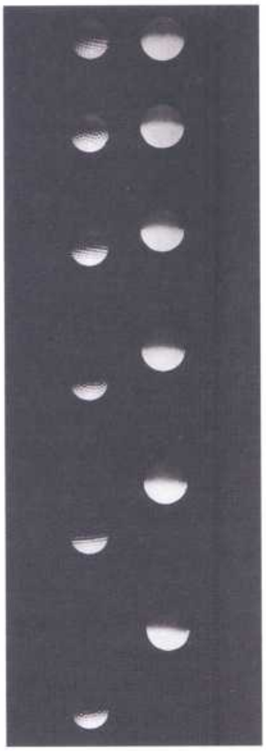


FIGURE 4.16

A stroboscopic study of a golf ball (left) and a Styrofoam ball (right) falling in air. The air resistance is negligible for the heavier golf ball, and its acceleration is nearly equal to g. Air resistance is not negligible for the lighter Styrofoam ball, which reaches its terminal velocity sooner.

SUMMARY OF TERMS

Force Any influence that can cause an object to be accelerated, measured in newtons (or in pounds, in the British system).

Friction The resistive force that opposes the motion or attempted motion of an object either past another object with which it is in contact or through a fluid.

Mass The quantity of matter in an object. More specifically, it is the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, deflect it, or change in any way its state of motion.

Weight The force due to gravity on an object (mg).

Volume The quantity of space an object occupies.

Newton's second law The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object.

Newton The SI unit of force. One newton (symbol N) is the force that will give an object of mass 1 kg an acceleration of 1 m/s^2.

Kilogram The fundamental SI unit of mass. One kilogram (symbol kg) is the mass of 1 liter (1 L) of water at 4 C°.

Free fall Motion under the influence of gravitational pull only.

Terminal speed The speed at which the acceleration of a falling object terminates because air resistance balances its weight. When direction is specified, then we speak of **terminal velocity.**

SUMMARY OF EQUATIONS

Weight $= mg$

Acceleration: $a = \dfrac{F_{\text{net}}}{m}$

Force $= ma$

REVIEW QUESTIONS

Force Causes Acceleration

1. Is acceleration proportional to net force, or does acceleration equal net force?

Friction

2. How does friction affect the net force on an object?
3. How great is the force of friction compared with your push on a crate that doesn't move on a level floor?
4. As you increase your push, will friction on the crate increase also?
5. Once the crate is sliding, how hard do you push to keep it moving at constant velocity?
6. Which is normally greater, static friction or sliding friction on the same object?
7. How does the force of friction for a sliding object vary with speed?
8. Slide a block on its widest surface, then tip the block so it slides on its narrowest surface. In which case is friction greater?
9. Does fluid friction vary with speed? With area of contact?

Mass and Weight

10. What relationship does mass have with inertia?
11. What relationship does mass have with weight?
12. Which is more fundamental, *mass* or *weight*? Which varies with location?
13. Fill in the blanks: Shake something to and fro and you're measuring its ______. Lift it against gravity and you're measuring its ______.
14. Fill in the blanks: The Standard International unit for mass is the ______. The Standard International unit for force is the ______.
15. What is the approximate weight of a quarter-pound hamburger after it is cooked?
16. What is the weight of a 1-kilogram brick?
17. In the string-pull illustration in Figure 4.8, a gradual pull of the lower string results in the top string breaking. Does this illustrate the ball's weight or its mass?
18. In the string-pull illustration in Figure 4.8, a sharp jerk on the bottom string results in the bottom string breaking. Does this illustrate the ball's weight or its mass?
19. Clearly distinguish among *mass, weight*, and *volume*.
20. Is acceleration *directly* proportional to mass, or is it *inversely* proportional to mass? Give an example.

Newton's Second Law of Motion

21. State Newton's second law of motion.
22. If we say that one quantity is *directly proportional* to another quantity, does this mean they are *equal* to each other? Explain briefly, using mass and weight as an example.
23. If the net force acting on a sliding block is somehow tripled, by how much does the acceleration increase?
24. If the mass of a sliding block is tripled while a constant net force is applied, by how much does the acceleration decrease?
25. If the mass of a sliding block is somehow tripled at the same time the net force on it is tripled, how does the resulting acceleration compare with the original acceleration?
26. How does the direction of acceleration compare with the direction of the net force that produces it?

When Acceleration Is g—Free Fall

27. What is meant by *free fall*?
28. The ratio of circumference to diameter for all circles is π. What is the ratio of force to mass for freely falling bodies?
29. Why doesn't a heavy object accelerate more than a light object when both are freely falling?

When Acceleration Is Less Than g—Nonfree Fall

30. What is the net force that acts on a 10-N freely falling object?
31. What is the net force that acts on a 10-N falling object when it encounters 4 N of air resistance? 10 N of air resistance?

32. What two principal factors affect the force of air resistance on a falling object?
33. What is the acceleration of a falling object that has reached its terminal velocity?
34. Why does a heavy parachutist fall faster than a lighter parachutist who wears a parachute of the same size?
35. If two objects having the same size fall through air at different speeds, which encounters the greater air resistance?

PROJECT

1. Write a letter to Grandma, similar to the one of Project 1 in Chapter 3. Tell her that Galileo introduced the concepts of acceleration and inertia and was familiar with forces but didn't see the connection among these three concepts. Tell her how Isaac Newton did see the connection and how it explains why heavy and light objects in free fall gain the same speed in the same time. In this letter, it's okay to use an equation or two, as long as you make it clear to Grandma that an equation is a shorthand notation of ideas you've explained.
2. Drop a sheet of paper and a coin at the same time. Which reaches the ground first? Why? Now crumple the paper into a small, tight wad and again drop it with the coin. Explain the difference observed. Will they fall together if dropped from a second-, third-, or fourth-story window? Try it and explain your observations.
3. Drop a book and a sheet of paper, and note that the book has a greater acceleration—g. Place the paper beneath the book so that it is forced against the book as both fall, so both fall at g. How do the accelerations compare if you place the paper on top of the raised book and then drop both? You may be surprised, so try it and see. Then explain your observation.
4. Drop two balls of different weight from the same height, and, at small speeds, they practically fall together. Will they roll together down the same inclined plane? If each is suspended from an equal length of string, making a pair of pendulums, and displaced through the same angle, will they swing back and forth in unison? Try it and see; then explain using Newton's laws.
5. The net force acting on an object and the resulting acceleration are always in the same direction. You can demonstrate this with a spool. If the spool is gently pulled horizontally to the right, in which direction will it roll?

PLUG AND CHUG

Make these simple one-step calculations and familiarize yourself with the equations that link the concepts of force, mass, and acceleration.

Weight $= mg$

1. Calculate the weight in newtons of a person having a mass of 50 kg.
2. Calculate the weight in newtons of a 2000-kg elephant.
3. Calculate the weight in newtons of a 2.5-kg melon. What is its weight in pounds?
4. An apple weighs about 1 N. What is its mass in kilograms? What is its weight in pounds?
5. Susie Small finds that she weighs 300 N. Calculate her mass.

Acceleration: $a = \dfrac{F_{net}}{m}$

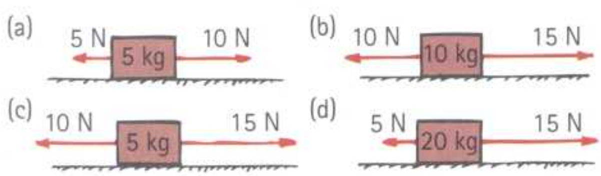
6. Calculate the acceleration of a 2000-kg, single-engine airplane just before takeoff when the thrust of its engine is 500 N.
7. Calculate the acceleration of a 300,000-kg jumbo jet just before takeoff when the thrust on the aircraft is 120,000 N.
8. (a) Calculate the acceleration of a 2-kg block on a horizontal friction-free air table when you exert a horizontal net force of 20 N. (b) What acceleration occurs if the friction force is 4 N?

Force $= ma$

9. Calculate the horizontal force that must be applied to a 1-kg puck to make it accelerate on a horizontal friction-free air table with the same acceleration it would have if it were dropped and fell freely.
10. Calculate the horizontal force that must be applied to produce an acceleration of 1.8 g for a 1.2-kg puck on a horizontal friction-free air table.

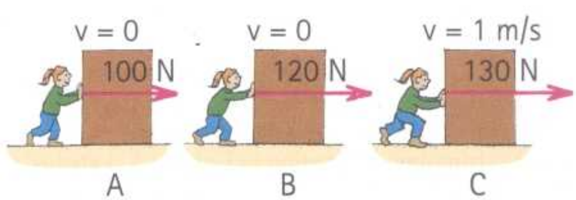
RANKING

1. Boxes of various masses are on a friction-free, level table. From greatest to least, rank the

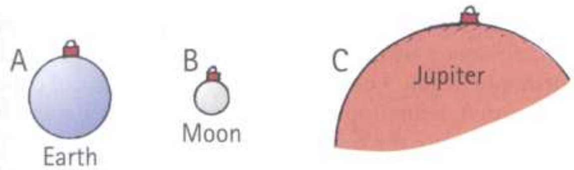


a. net forces on the boxes.
b. accelerations of the boxes.

2. In all three cases, A, B, and C, the crate is in equilibrium (no acceleration). From greatest to least, rank the amount of friction between the crate and the floor.

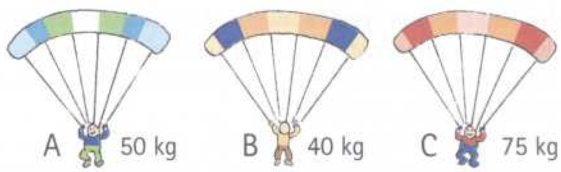


3. Consider a 100-kg box of tools in the locations A, B, and C. From greatest to least, rank the



a. masses of the 100-kg box of tools.
b. weights of the 100-kg box of tools.

4. Three parachutists, A, B, and C, each have reached terminal velocity at the same distance above the ground below.

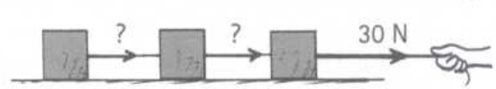


a. From fastest to slowest, rank the amount of their terminal velocities.
b. From longest to shortest times, rank their order in reaching the ground.

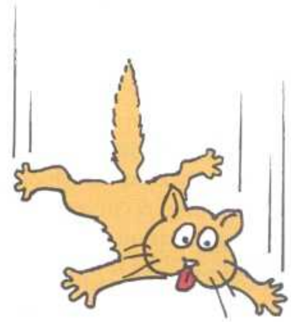
EXERCISES

1. Can the velocity of an object reverse direction while maintaining a constant acceleration? If so, give an example; if not, provide an explanation.
2. On a long alley, a bowling ball slows down as it rolls. Is any horizontal force acting on the ball? How do you know?
3. Is it possible to move in a curved path in the absence of a force? Defend your answer.
4. An astronaut tosses a rock on the Moon. What force(s) act(s) on the rock during its curved path?
5. Since an object weighs less on the surface of the Moon than on Earth's surface, does it have less inertia on the Moon's surface?
6. Which contains more apples, a 1-pound bag of apples on Earth or a 1-pound bag of apples on the Moon? Which contains more apples, a 1-kilogram bag of apples on Earth or a 1-kilogram bag of apples on the Moon?
7. A crate remains at rest on a factory floor while you push on it with a horizontal force *F*. How big is the friction force exerted on the crate by the floor? Explain.
8. A 400-kg bear grasping a vertical tree slides down at constant velocity. What is the friction force that acts on the bear?
9. In an orbiting space shuttle, you are handed two identical boxes, one filled with sand and the other filled with feathers. How can you determine which is which without opening the boxes?
10. Your empty hand is not hurt when it bangs lightly against a wall. Why does it hurt if you're carrying a heavy load? Which of Newton's laws is most applicable here?
11. Why is a massive cleaver more effective for chopping vegetables than an equally sharp knife?
12. Does the mass of an astronaut change when he or she is visiting the International Space Station? Defend your answer.
13. When a junked car is crushed into a compact cube, does its mass change? Its weight? Explain.
14. Gravity on the surface of the Moon is only 1/6 as strong as gravity on Earth. What is the weight of a 10-kg object on the Moon and on Earth? What is its mass on each?
15. Does a dieting person more accurately lose mass or lose weight?
16. What weight change occurs when your mass increases by 2 kg?
17. What is your own mass in kilograms? Your weight in newtons?
18. A grocery bag can withstand 300 N of force before it rips apart. How many kilograms of apples can it safely hold?
19. Consider a heavy crate resting on the bed of a flatbed truck. When the truck accelerates, the crate also accelerates and remains in place. Identify the force that accelerates the crate.
20. Explain how Newton's first law of motion can be considered to be a consequence of Newton's second law.
21. When a car is moving in reverse, backing from a driveway, the driver applies the brakes. In what direction is the car's acceleration?
22. The auto in the sketch moves forward as the brakes are applied. A bystander says that during the interval of braking, the auto's velocity and acceleration are in opposite directions. Do you agree or disagree?

23. Aristotle claimed that the speed of a falling object depends on its weight. We now know that objects in free fall, whatever their weights, undergo the same gain in speed. Why does weight not affect acceleration?
24. When blocking in football, a defending lineman often attempts to get his body under the body of his opponent and push upward. What effect does this have on the friction force between the opposing lineman's feet and the ground?
25. A race car travels along a raceway at a constant velocity of 200 km/h. What horizontal net force acts on the car?
26. Three identical blocks are pulled, as shown, on a horizontal frictionless surface. If tension in the rope held by the hand is 30 N, what is the tension in the other ropes?



27. To pull a wagon across a lawn with constant velocity, you have to exert a steady force. Reconcile this fact with Newton's first law, which says that motion with constant velocity requires no force.
28. Free fall is motion in which gravity is the only force acting. (a) Is a skydiver who has reached terminal speed in free fall? (b) Is a satellite above the atmosphere that circles Earth in free fall?
29. When a coin is tossed upward, what happens to its velocity while ascending? Its acceleration? (Neglect air resistance.)
30. How much force acts on a tossed coin when it is halfway to its maximum height? How much force acts on it when it reaches its peak? (Neglect air resistance.)
31. Sketch the path of a ball tossed vertically into the air. (Neglect air resistance.) Draw the ball halfway to the top, at the top, and halfway down to its starting point. Draw a force vector on the ball in all three positions. Is the vector the same or different in the three locations? Is the acceleration the same or different in the three locations?
32. As you leap upward in a standing jump, how does the force that you exert on the ground compare with your weight?
33. When you jump vertically off the ground, what is your acceleration when you reach your highest point?
34. What is the acceleration of a rock at the top of its trajectory when it has been thrown straight upward? (Is your answer consistent with Newton's second law?)
35. A common saying goes, "It's not the fall that hurts you; it's the sudden stop." Translate this into Newton's laws of motion.
36. A friend says that, as long as a car is at rest, no forces act on it. What do you say if you're in the mood to correct the statement of your friend?
37. When your car moves along the highway at constant velocity, the net force on it is zero. Why, then, do you have to keep running your engine?
38. What is the net force on a 1-N apple when you hold it at rest above your head? What is the net force on it after you release it?
39. A "shooting star" is usually a grain of sand from outer space that burns up and gives off light as it enters the atmosphere. What exactly causes this burning?
40. Does a stick of dynamite contain force?
41. A parachutist, after opening her parachute, finds herself gently floating downward, no longer gaining speed. She feels the upward pull of the harness, while gravity pulls her down. Which of these two forces is greater? Or are they equal in magnitude?
42. Does a falling object increase in speed if its acceleration of fall decreases?
43. What is the net force acting on a 1-kg ball in free fall?
44. What is the net force acting on a falling 1-kg ball if it encounters 2 N of air resistance?
45. A friend says that, before the falling ball in the previous exercise reaches terminal velocity, it *gains* speed while acceleration *decreases*. Do you agree or disagree with your friend? Defend your answer.
46. Why will a sheet of paper fall more slowly than one that is wadded into a ball?
47. Upon which will air resistance be greater—a sheet of falling paper or the same paper wadded into a ball that falls at a faster terminal speed? (Careful!)
48. Hold a Ping-Pong ball and a golf ball at arm's length and drop them simultaneously. You'll see them hit the floor at about the same time. But, if you drop them off the top of a high ladder, you'll see the golf ball hit first. What is your explanation?
49. How does the force of gravity on a raindrop compare with the air drag it encounters when it falls at constant velocity?
50. If you hold your book horizontally with a piece of paper beneath it, then drop both, they fall together. Repeat, but this time place the paper on *top* of the book. Describe the motion of the paper relative to the book. (Try it and see!)
51. When a parachutist opens her parachute after reaching terminal speed, in what direction does she accelerate?
52. How does the terminal speed of a parachutist before opening a parachute compare to terminal speed after? Why is there a difference?
53. How does the gravitational force on a falling body compare with the air resistance it encounters before it reaches terminal velocity? After reaching terminal velocity?
54. Why is it that a cat that accidentally falls from the top of a 50-story building hits a safety net below no faster than if it fell from the twentieth story?



55. Under what conditions would a metal sphere dropping through a viscous liquid be in equilibrium?
56. When and if Galileo dropped two balls from the top of the Leaning Tower of Pisa, air resistance was not really negligible. Assuming that both balls were of the same size, one made of wood and one of metal, which ball actually struck the ground first? Why?
57. If you drop a pair of tennis balls simultaneously from the top of a building, they will strike the ground at the same time. If you fill one of the balls with lead pellets and then drop them together, which one will hit the ground first? Which one will experience greater air resistance? Defend your answers.
58. In the absence of air resistance, if a ball is thrown vertically upward with a certain initial speed, on returning to its original level it will have the same speed. When air resistance is a factor, will the ball be moving faster, the same, or more slowly than its throwing speed when it gets back to the same level? Why? (Physicists often use a "principle of exaggeration" to help them analyze a problem. Consider the exaggerated case of a feather, not a ball, because the effect of air resistance on the feather is more pronounced and therefore easier to visualize.)
59. If a ball is thrown vertically into the air in the presence of air resistance, would you expect the time during which it rises to be longer or shorter than the time during which it falls? (Again use the "principle of exaggeration.")
60. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between mass and weight.

PROBLEMS

1. One pound is the same as 4.45 newtons. What is the weight in pounds of 1 newton?

2. If your friend Katelyn weighs 500 N, what is her weight in pounds?

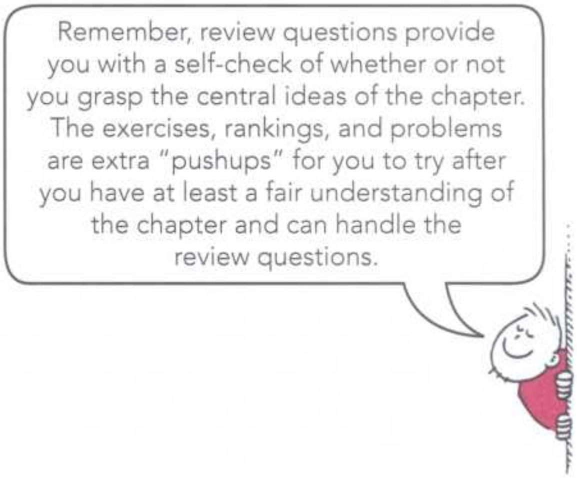
3. Consider a 40-kg block of cement that is pulled sideways with a net force of 200 N. Show that its acceleration is 5 m/s^2.

4. Consider a mass of 1 kg accelerated 1 m/s^2 by a force of 1 N. Show that the acceleration would be the same for a force of 2 N acting on 2 kg.

5. Consider a business jet of mass 30,000 kg in takeoff when the thrust for each of two engines is 30,000 N. Show that its acceleration is 2 m/s^2.

6. Leroy, who has a mass of 100 kg, is skateboarding at 9.0 m/s when he smacks into a brick wall and comes to a dead stop in 0.2 s.
a. Show that his deceleration is 45 m/s^2.
b. Show that the force of impact is 4500 N. (ouch!)

• **7.** A rock band's tour bus, mass M, is accelerating away from a STOP sign at rate a when a piece of heavy metal, mass $M/6$, falls onto the top of the bus and remains there.
a. Show that the bus's acceleration is now $\frac{6}{7}a$.
b. If the initial acceleration of the bus is 1.2 m/s^2, show that when the bus carries the heavy metal with it, the acceleration will be 1.0 m/s^2.



CHAPTER 4 ONLINE RESOURCES

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Interactive Figures

- 4.9, 4.12

Tutorial

- Newton's Second Law

Videos

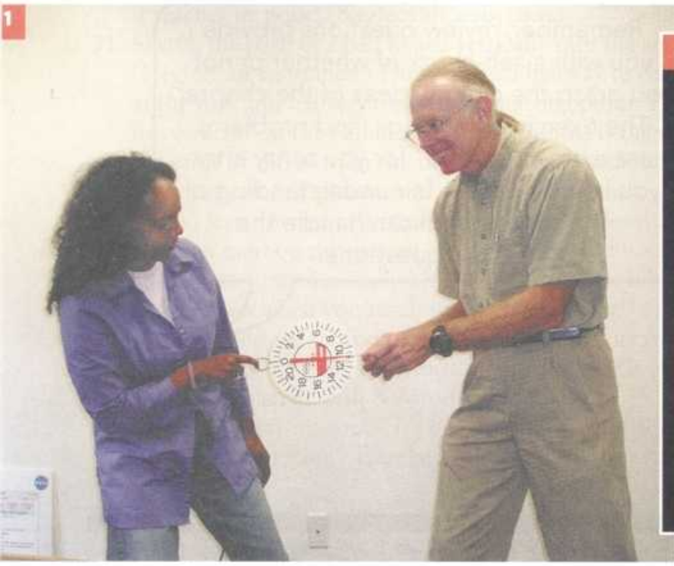
- Force Causes Acceleration
- Friction
- Newton's Second Law
- Free-Fall Acceleration Explained
- Falling and Air Resistance

Quizzes

Flashcards

Links

5 Newton's Third Law of Motion



1 Darlene Librero pulls with one finger; Paul Doherty pulls with both hands. Who exerts more force on the scale? **2** Does the racquet hit the ball or does the ball hit the racquet? Answer: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet—that's the law! **3** Wife Lil and I demonstrate Newton's third law— that you cannot touch without being touched.

When Isaac Newton was 26 years old he was appointed the Lucasian Professor of Mathematics at Trinity College in Cambridge. He had personal conflicts with the religious positions of the College, namely questioning the idea of the Trinity as a foundational tenet of Christianity at that time. At the age of 46, his energies turned somewhat from science when he was elected to a 1-year term as a member of Parliament. (At 57, he was elected to a second term.) In his two years in Parliament, he never gave a speech. One day he rose and the House fell silent to hear the great man. Newton's "speech" was very brief; he simply requested that a window be closed because of a draft.

A further turn from his work in science was his appointment as warden, and then as master, of the mint. Newton resigned his professorship and directed his efforts toward greatly improving the workings of the mint, to the dismay of counterfeiters who were then flourishing. He maintained his membership in the Royal Society and at age 60 was elected president, then was reelected each year for the rest of his life.

Although Newton's hair turned gray at age 30, it remained full, long, and wavy all his life, and, unlike others in his time, he did not wear a wig. He was a modest man, overly sensitive to criticism, and he never married. He remained healthy in body and mind into old age. At 80, he still had all his teeth, his eyesight and hearing were sharp, and his mind was alert. In his lifetime he was regarded by his countrymen as the greatest scientist who ever lived. In 1705, he was knighted by Queen Anne. Newton died at the age of 84 and was buried in Westminster Abbey along with England's monarchs and heroes. His laws of motion were all that was needed 242 years later to put humans on the Moon. This chapter presents the third of his three laws of motion.

Forces and Interactions

So far we've treated force in its simplest sense—as a push or pull. Yet no push or pull ever occurs alone. Every force is part of an *interaction* between one thing and another. When you push on a wall with your fingers, more is happening than your push on the wall. You're interacting with the wall, which also pushes back on you. This is evident in your bent fingers, as illustrated in Figure 5.1. There is a pair of forces involved: your push on the wall and the wall pushes back on you. These forces are equal in magnitude (have the same strength) and opposite in direction, and they constitute a single interaction. In fact, you can't push on the wall *unless* the wall pushes back.[1]

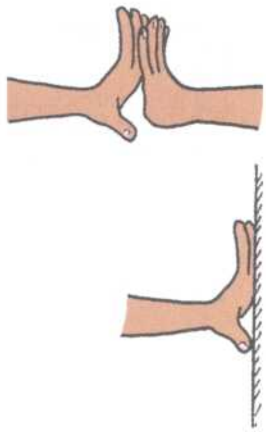


FIGURE 5.1

INTERACTIVE FIGURE

You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall *unless* it pushes back on you!

Consider a boxer's fist hitting a massive punching bag. The fist hits the bag (and dents it) while the bag hits back on the fist (and stops its motion). A pair of forces is involved in hitting the bag. The force pair can be quite large. But what of hitting a piece of tissue paper, as discussed earlier? The boxer's fist can only exert as much force on the tissue paper as the tissue paper can exert on the fist. Furthermore, the fist can't exert any force at all unless what is being hit exerts the same amount of force back. An interaction requires a *pair* of forces acting on *two* separate objects.

FIGURE 5.2

When you lean against a wall, you exert a force on the wall. The wall simultaneously exerts an equal and opposite force on you. Hence you don't topple over.

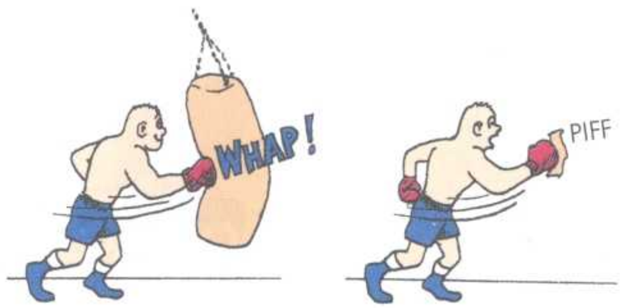


FIGURE 5.3

He can hit the massive bag with considerable force. But with the same punch he can exert only a tiny force on the tissue paper in midair.

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Video
Forces and Interaction

Other examples: You pull on a rope attached to a cart, acceleration occurs. When doing so, the cart pulls back on you, as evidenced perhaps by the tightening of the rope wrapped around your hand. A hammer hits a stake and drives it into the ground. In doing so, the stake exerts an equal amount of force on the hammer, which brings the hammer to an abrupt halt. One thing interacts with another—you with the cart, or the hammer with the stake.

Which exerts the force and which receives the force? Isaac Newton's response was that neither force has to be identified as "exerter" or "receiver"; he concluded that both objects must be treated equally. For example, when you pull the cart, the cart pulls on you. This pair of forces, your pull on the cart and the cart's pull on you, makes up the single interaction between you and the cart. In the interaction between the hammer and the stake, the hammer exerts a force against the stake but is itself brought to a halt in the process. Such observations led Newton to his third law of motion.

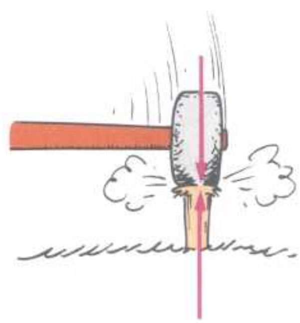

FIGURE 5.4

In the interaction between the hammer and the stake, each exerts the same amount of force on the other.

[1]We tend to think that only living things are capable of pushing and pulling. But inanimate things can do the same. So please don't be troubled about the idea of the inanimate wall pushing on you. It does, just as another person leaning against you would.

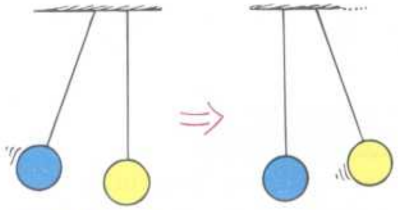

FIGURE 5.5
The impact forces between the blue ball and the yellow ball move the yellow ball and stop the blue ball.

Newton's Third Law of Motion

Newton's third law states:

Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

We can call one force the *action force* and the other the *reaction force.* Then we can express Newton's third law in the form:

To every action there is always an opposed equal reaction.

FIGURE 5.6
In the interaction between the car and the truck, is the force of impact the same on each? Is the damage the same?

It doesn't matter which force we call *action* and which we call *reaction.* The important thing is that they are co-parts of a single interaction and that neither force exists without the other.

When you walk, you interact with the floor. You push against the floor, and the floor pushes against you. The pair of forces occurs at the same time (they are *simultaneous*). Likewise, the tires of a car push against the road while the road pushes back on the tires—the tires and road simultaneously push against each other. In swimming, you interact with the water, pushing the water backward, while the water simultaneously pushes you forward—you and the water push against each other. The reaction forces are what account for our motion in these examples. These forces depend on friction; a person or car on ice, for example, may be unable to exert the action force to produce the needed reaction force. Forces occur in *force pairs.* Neither force exists without the other.

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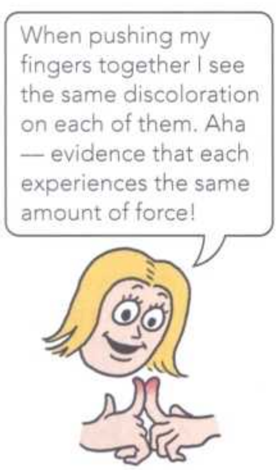
Tutorial
Newton's Third Law



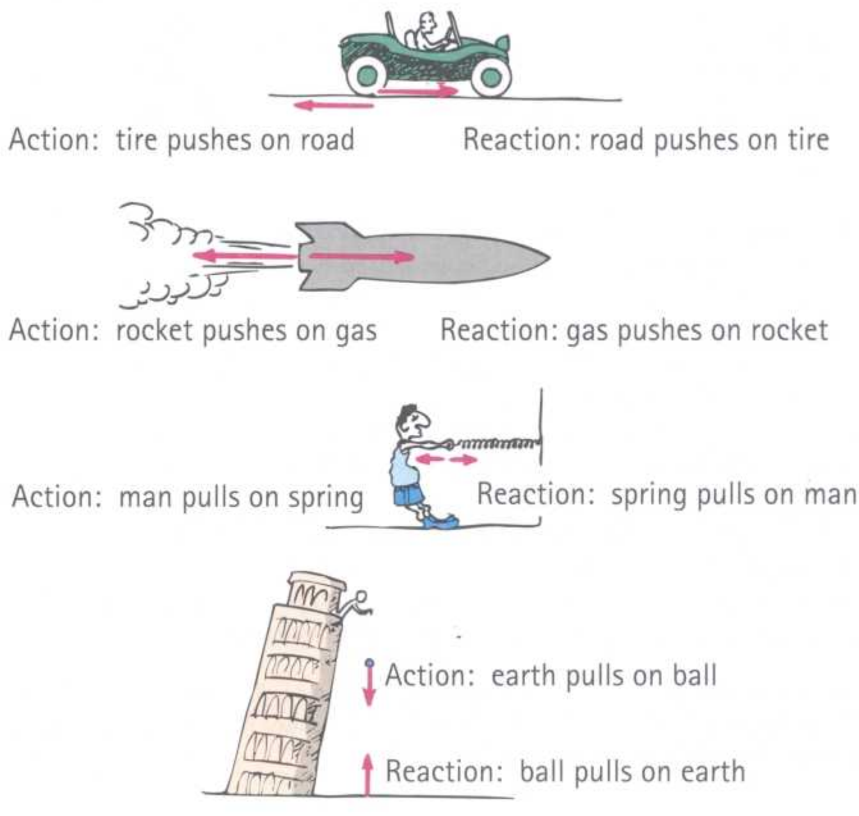


FIGURE 5.7
Action and reaction forces. Note that when action is "*A* exerts force on *B*," the reaction is then simply "*B* exerts force on *A*."

CHECK POINT

Does a speeding missile possess force?

Check Your Answer

No, a force is not something an object *has*, like mass, but is part of an interaction between one object and another. A speeding missile may possess the capability of exerting a force on another object when interaction occurs, but it does not possess force as a thing in itself. As we will see in the following chapters, a speeding missile possesses momentum and kinetic energy.

DEFINING YOUR SYSTEM

An interesting question often arises: Since action and reaction forces are equal and opposite, why don't they cancel to zero? To answer this question, we must consider the *system* involved. Consider, for example, a system consisting of a single orange, Figure 5.8. The dashed line surrounding the orange encloses and defines the system. The vector that pokes outside the dashed line represents an external force on the system. The system accelerates in accord with Newton's second law. In Figure 5.9, we see that this force is provided by an apple, which doesn't change our analysis. The apple is outside the system. The fact that the orange simultaneously exerts a force on the apple, which is external to the system, may affect the apple (another system), but not the orange. You can't cancel a force on the orange with a force on the apple. So, in this case, the action and reaction forces don't cancel.

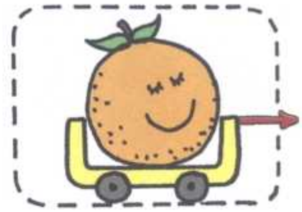


FIGURE 5.8
INTERACTIVE FIGURE

A force acts on the orange, and the orange accelerates to the right.

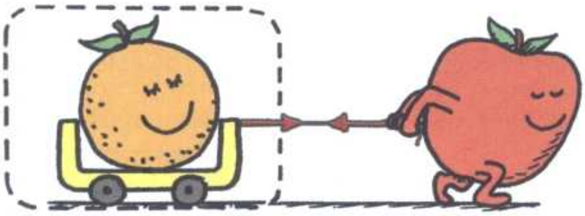


FIGURE 5.9
INTERACTIVE FIGURE

The force on the orange, provided by the apple, is not cancelled by the reaction force on the apple. The orange still accelerates.

A system may be as tiny as an atom or as large as the universe.

Now let's consider a larger system, enclosing *both* the orange and the apple. We see the system bounded by the dashed line in Figure 5.10. Notice that the force pair is *internal* to the orange–apple system. Then these forces *do* cancel each other. They play no role in accelerating the system. A force external to the system is needed for acceleration. That's where friction with the floor plays a role (Figure 5.11). When

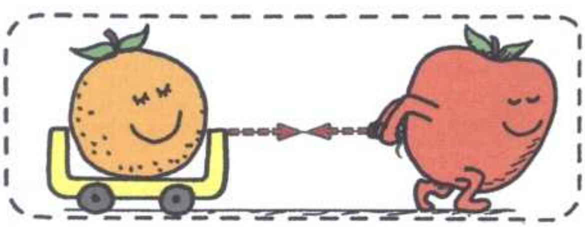


FIGURE 5.10
INTERACTIVE FIGURE

In the larger system of orange + apple, action and reaction forces are internal and cancel. If these are the only horizontal forces, with no external force, no acceleration of the system occurs.

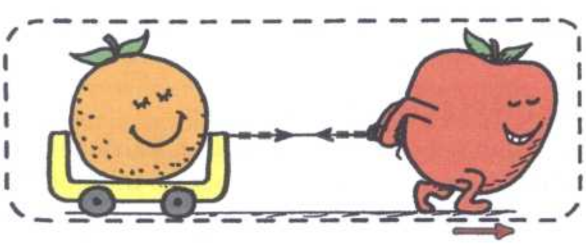


FIGURE 5.11
INTERACTIVE FIGURE

An external horizontal force occurs when the floor pushes on the apple (reaction to the apple's push on the floor). The orange–apple system accelerates.

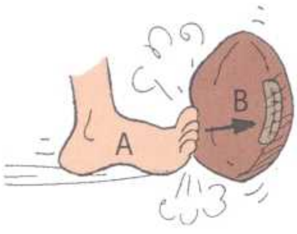


FIGURE 5.12
A acts on B, and B accelerates.

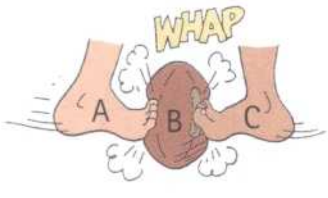


FIGURE 5.13
Both A and C act on B. They can cancel each other, so B does not accelerate.

the apple pushes against the floor, the floor simultaneously pushes on the apple—an external force on the system. The system accelerates to the right.

Inside a football are trillions and trillions of interatomic forces at play. They hold the ball together, but they play no role in accelerating the ball. Although every one of the interatomic forces is part of an action–reaction pair within the ball, they combine to zero, no matter how many of them there are. A force external to the football, like a kick, is needed to accelerate it. In Figure 5.12, we note a single interaction between the foot and the football.

The football in Figure 5.13, however, does not accelerate. In this case, there are two interactions occurring—two forces acting on the football. If they are simultaneous, equal, and opposite, then the net force is zero. Do the two opposing kicks make up an action–reaction pair? No, for they act on the same object, not on different objects. They may be equal and opposite, but, unless they act on different objects, they are not an action–reaction pair. Get it?

If this is confusing, it may be well to note that Newton had difficulties with the third law himself. (See insightful examples of Newton's third law on pages 21 and 22 in the *Concept Development Practice Book*.)

CHECK POINT

1. On a cold, rainy day, you find yourself in a car with a dead battery. You must push the car to move it and get it started. Why can't you move the car by remaining comfortably inside and pushing against the dashboard?
2. Why does a book sitting on a table never accelerate "spontaneously" in response to the trillions of interatomic forces acting within it?
3. We know that Earth pulls on the Moon. Does it follow that the Moon also pulls on Earth?
4. Can you identify the action and reaction forces in the case of an object falling in a vacuum?

Check Your Answers

1. In this case, the system to be accelerated is the car. If you remain inside and push on the dashboard, the force pair you produce acts and reacts within the system. These forces cancel out as far as any motion of the car is concerned. To accelerate the car, there must be an interaction between the car and something external—for example, you on the outside pushing against the road and on the car.
2. Every one of these interatomic forces is part of an action–reaction pair within the book. These forces add up to zero, no matter how many of them there are. This is what makes Newton's *first* law apply to the book. The book has zero acceleration unless an *external* force acts on it.
3. Yes, both pulls make up an action–reaction pair of forces associated with the gravitational interaction between Earth and Moon. We can say that (1) Earth pulls on Moon and (2) Moon likewise pulls on Earth; but it is more insightful to think of this as a single interaction—both Earth and Moon simultaneously pulling on each other, each with the *same* amount of force. You can't push or pull on something unless that something simultaneously pushes or pulls on you. That's the law!
4. To identify a pair of action–reaction forces in any situation, first identify the pair of interacting objects involved—Body A and Body B. Body A, the falling object, is interacting (gravitationally) with Body B, the whole Earth. So Earth pulls downward on the object (call it action), while the object pulls upward on Earth (reaction).

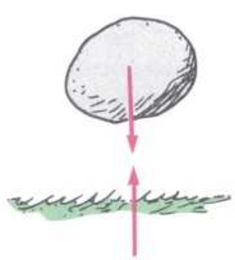


FIGURE 5.14
Earth is pulled up by the boulder with just as much force as the boulder is pulled downward by Earth.

ACTION AND REACTION ON DIFFERENT MASSES

As strange as it may first seem, a falling object pulls upward on Earth with as much force as Earth pulls downward on it. The resulting acceleration of the falling object is evident, while the upward acceleration of Earth is too small to detect. So strictly speaking, when you step off a curb, the street rises ever so slightly to meet you.

We can see that Earth accelerates slightly in response to a falling object by considering the exaggerated examples of two planetary bodies, parts (a) through (e) in Figure 5.15. The forces between bodies A and B are equal in magnitude and oppositely directed in *each* case. If acceleration of planet A is unnoticeable in (a), then it is more noticeable in (b), where the difference between the masses is less extreme. In (c), where both bodies have equal mass, acceleration of object A is as evident as it is for B. Continuing, we see that the acceleration of A becomes even more evident in (d) and even more so in (e).

The role of different masses is evident in a fired cannon. When a cannon is fired, there is an interaction between the cannon and the cannonball (Figure 5.16). A pair of forces acts on both cannon and cannonball. The force exerted on the cannonball is as great as the reaction force exerted on the cannon; hence, the cannon recoils. Since the forces are equal in magnitude, why doesn't the cannon recoil with the same speed as the cannonball? In analyzing changes in motion, Newton's second law reminds us that we must also consider the masses involved. Suppose we let F represent both the action and reaction force, m the mass of the cannonball, and $\Large{m}$ the mass of the much more massive cannon. The accelerations of the cannonball and the cannon are then found by comparing the ratio of force to mass. The accelerations are:

$$\text{Cannonball: } \frac{F}{m} = \Large{a}$$

$$\text{Cannon: } \frac{F}{\Large{m}} = a$$

This shows why the change in velocity of the cannonball is so large compared with the change in velocity of the cannon. A given force exerted on a small mass produces a large acceleration, while the same force exerted on a large mass produces a small acceleration.

Going back to the example of the falling object, if we used similarly exaggerated symbols to represent the acceleration of Earth reacting to a falling object, the symbol m for the Earth's mass would be astronomical in size. The force F, the weight of the falling object, divided by this large mass would result in a microscopic a to represent the acceleration of Earth toward the falling object.

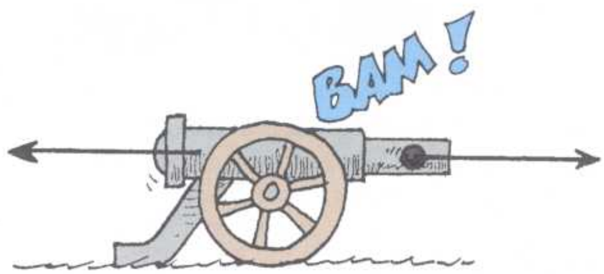


FIGURE 5.16

INTERACTIVE FIGURE

The force exerted against the recoiling cannon is just as great as the force that drives the cannonball inside the barrel. Why, then, does the cannonball accelerate more than the cannon?

We can extend the idea of a cannon recoiling from the ball it fires to understanding rocket propulsion. Consider an inflated balloon recoiling when air is expelled (Figure 5.17). If the air is expelled downward, the balloon accelerates upward. The same principle applies to a rocket, which continually "recoils" from the ejected exhaust gas. Each molecule of exhaust gas is like a tiny cannonball shot from the rocket (Figure 5.18).

A common misconception is that a rocket is propelled by the impact of exhaust gases against the atmosphere. In fact, before the advent of rockets, it was generally thought that sending a rocket to the Moon was impossible. Why? Because there is no air above Earth's atmosphere for the rocket to push against. But this is like saying

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Videos

Action and Reaction on Different Masses

Action and Reaction on Rifle and Bullet

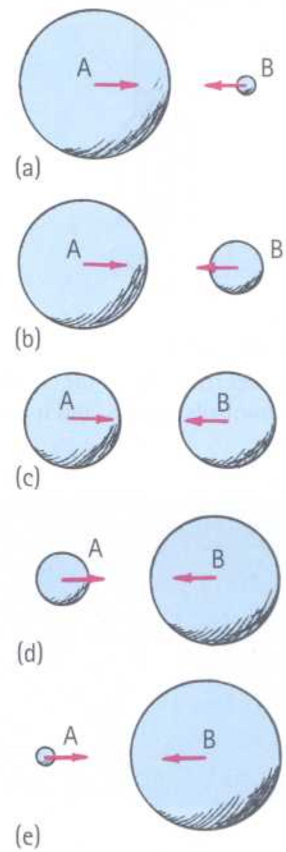


FIGURE 5.15

Which falls toward the other, A or B? Although the forces between each pair are the same, do accelerations differ?

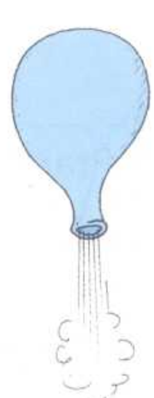


FIGURE 5.17

The balloon recoils from the escaping air, and it moves upward.

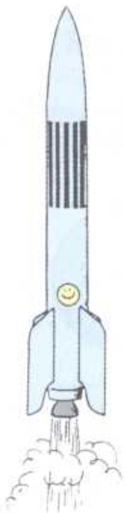


FIGURE 5.18

The rocket recoils from the "molecular cannonballs" it fires, and it moves upward.

FIGURE 5.19

Geese fly in a V formation because air pushed downward at the tips of their wings swirls upward, creating an updraft that is strongest off to the side of the bird. A trailing bird gets added lift by positioning itself in this updraft, pushes air downward, and creates another updraft for the next bird, and so on. The result is a flock flying in a V formation.

a cannon wouldn't recoil unless the cannonball had air to push against. Not true! Both the rocket and recoiling cannon accelerate because of the reaction forces exerted by the material they fire—not because of any pushes on the air. In fact, a rocket operates better above the atmosphere where there is no air resistance.

Using Newton's third law, we can understand how a helicopter gets its lifting force. The whirling blades are shaped to force air particles down (action), and the air forces the blades up (reaction). This upward reaction force is called *lift.* When lift equals the weight of the aircraft, the helicopter hovers in midair. When lift is greater, the helicopter climbs upward.

This is true for birds and airplanes. Birds fly by pushing air downward. The air in turn pushes the bird upward. When the bird is soaring, the wings must be shaped so that moving air particles are deflected downward. Slightly tilted wings that deflect oncoming air downward produce lift on an airplane. Air that is pushed downward continuously maintains lift. This supply of air is obtained by the forward motion of the aircraft, which results from propellers or jets that push air backward. The air, in turn, pushes the propellers or jets forward. We will learn in Chapter 14 that the curved surface of a wing is an airfoil, which enhances the lifting force.

We see Newton's third law at work everywhere. A fish pushes the water backward with its fins, and the water pushes the fish forward. When the wind pushes against the branches of a tree and the branches push back on the wind, we have whistling sounds. Forces are interactions between different things. Every contact requires at least a twoness; there is no way that an object can exert a force on nothing. Forces, whether large shoves or slight nudges, always occur in pairs, each of which is opposite to the other. Thus, we cannot touch without being touched.

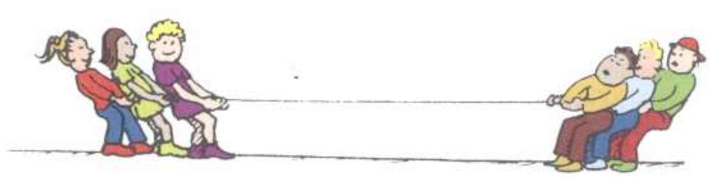
FIGURE 5.20

You cannot touch without being touched—Newton's third law.

Practicing Physics

Tug of War

Perform a tug-of-war between guys and gals. Do it on a polished floor that's somewhat slippery, with guys wearing socks and gals wearing rubber-soled shoes. Who will surely win, and why? (*Hint:* Who wins a tug-of-war, those who pull harder on the rope or those who push harder against the floor?)



CHECK POINT

1. A car accelerates along a road. Identify the force that moves the car.
2. A high-speed bus and an innocent bug have a head-on collision. The force of impact splatters the poor bug over the windshield. Is the corresponding force that the bug exerts against the windshield greater, less, or the same? Is the resulting deceleration of the bus greater than, less than, or the same as that of the bug?

Check Your Answers

1. It is the road that pushes the car along. Really! Only the road provides the horizontal force to move the car forward. How does it do this? The rotating tires of the car push back on the road (action). The road simultaneously pushes forward on the tires (reaction). How about that!
2. The magnitudes of both forces are the same, for they constitute an action–reaction force pair that makes up the interaction between the bus and the bug. The accelerations, however, are very different because the masses are different. The bug undergoes an enormous and lethal deceleration, while the bus undergoes a very tiny deceleration—so tiny that the very slight slowing of the bus is unnoticed by its passengers. But if the bug were more massive—as massive as another bus, for example—the slowing down would unfortunately be very apparent. (Can you see the wonder of physics here? Although so much is *different* for the bug and the bus, the amount of force each encounters is the *same*. Amazing!)

Jellyfish have been using rocket or jet propulsion for eons.

Summary of Newton's Three Laws

Newton's first law, the law of inertia: An object at rest tends to remain at rest; an object in motion tends to remain in motion at constant speed along a straight-line path. This property of objects to resist change in motion is called *inertia*. Mass is a measure of inertia. Objects will undergo changes in motion only in the presence of a net force.

Newton's second law, the law of acceleration: When a net force acts on an object, the object will accelerate. The acceleration is directly proportional to the net force and inversely proportional to the mass. Symbolically, $a = F/m$. Acceleration is always in the direction of the net force. When objects fall in a vacuum, the net force is simply the weight—the pull of gravity—and the acceleration is g (the symbol g denotes that acceleration is due to gravity alone). When objects fall in air, the net force is equal to the weight minus the force of air resistance, and the acceleration is less than g. If and when the force of air resistance equals the weight of a falling object, acceleration terminates, and the object falls at constant speed (called *terminal speed*).

Newton's third law, the law of action–reaction: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. Forces occur in pairs, one action and the other reaction, which together constitute the interaction between one object and the other. Action and reaction always occur simultaneously and act on different objects. Neither force exists without the other.

Isaac Newton's three laws of motion are rules of nature that enable us to see how beautifully so many things connect with one another. We see these rules in operation in our everyday environment.

FIGURE 5.21

This vector, scaled so that 1 cm equals 20 N, represents a force of 60 N to the right.

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Tutorial
Vectors

The valentine vector says, "I was only a scalar until you came along and gave me direction."

Vectors

We have learned that any quantity that requires both magnitude and direction for a complete description is a **vector quantity.** Examples of vector quantities include force, velocity, and acceleration. By contrast, a quantity that can be described by magnitude only, not involving direction, is called a **scalar quantity.** Mass, volume, and speed are scalar quantities.

A vector quantity is nicely represented by an arrow. When the length of the arrow is scaled to represent the quantity's magnitude, and the direction of the arrow shows the direction of the quantity, we refer to the arrow as a **vector.**

Adding vectors that act along parallel directions is simple enough: If they act in the same direction, they add; if they act in opposite directions, they subtract. The sum of two or more vectors is called their **resultant.** To find the resultant of two vectors that don't act in exactly the same or opposite direction, we use the *parallelogram rule.*[2] Construct a parallelogram wherein the two vectors are adjacent sides—the diagonal of the parallelogram shows the resultant. In Figure 5.22, the parallelograms are rectangles.

FIGURE 5.22
INTERACTIVE FIGURE

The pair of vectors at right angles to each other make two sides of a rectangle, the diagonal of which is their resultant.

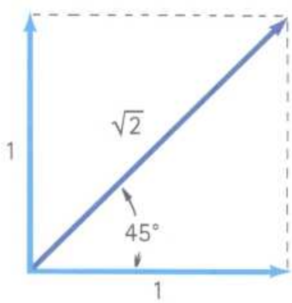


FIGURE 5.23

When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

In the special case of two vectors that are equal in magnitude and perpendicular to each other, the parallelogram is a square (Figure 5.23). Since for any square the length of a diagonal is $\sqrt{2}$, or 1.41, times one of the sides, the resultant is $\sqrt{2}$ times one of the vectors. For example, the resultant of two equal vectors of magnitude 100 acting at a right angle to each other is 141.

FORCE VECTORS

Figure 5.24 shows a pair of forces acting on a box. One is 30 newtons and the other is 40 newtons. Simple measurement shows the resultant of this pair of forces is 50 newtons.

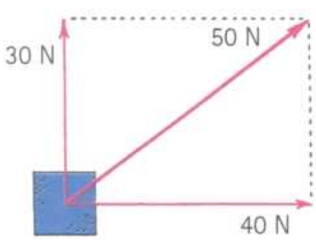
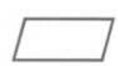


FIGURE 5.24

The resultant of the 30-N and 40-N forces is 50 N.

Figure 5.25 shows Nellie Newton hanging at rest from a clothesline. Note that the clothesline acts like a pair of ropes that make different angles with the vertical. Which side has the greater tension? Investigation will show there are three forces acting on Nellie: her weight, a tension in the left-hand side of the rope, and a tension in the right-hand side of the rope. Because of the different angles, different rope tensions will occur in each side. Figure 5.25 shows a step-by-step solution. Because Nellie hangs in equilibrium, her weight must be supported by two rope

[2]A parallelogram is a four-sided figure with opposite sides parallel to each other. Usually, you determine the length of the diagonal by measurement; but, in the special case in which the two vectors **X** and **Y** are perpendicular (a square or a rectangle), you can apply the Pythagorean Theorem, $\mathbf{R}^2 = \mathbf{X}^2 + \mathbf{Y}^2$, to find the resultant: $\mathbf{R} = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2}$.



tensions, which must add vectorially to be equal and opposite to her weight. The parallelogram rule shows that the tension in the right-hand rope is greater than the tension in the left-hand rope. If you measure the vectors, you'll see that tension in the right rope is about twice the tension in the left rope. Both rope tensions combine to support her weight.

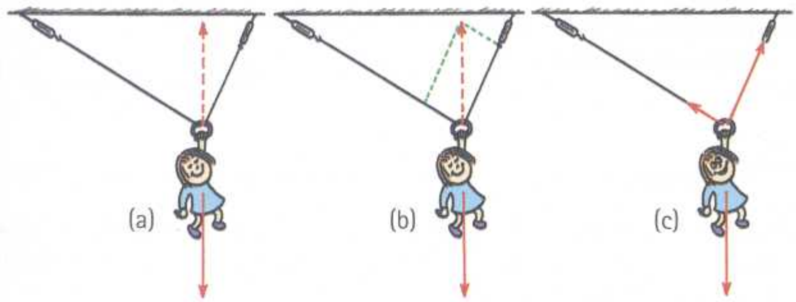


FIGURE 5.25
INTERACTIVE FIGURE

(a) Nellie's weight is shown by the downward vertical vector. An equal and opposite vector is needed for equilibrium, shown by the dashed vector. (b) This dashed vector is the diagonal of a parallelogram defined by the green lines. (c) Both rope tensions are shown by the constructed vectors. Tension is greater in the right rope, the one more likely to break.

More about force vectors can be found in Appendix D at the end of this book and in the *Practicing Physics* book.

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Vector Representations: How to Add and Subtract Vectors
Geometric Addition of Vectors

VELOCITY VECTORS

Recall, from Chapter 3, the difference between speed and velocity—speed is a measure of "how fast"; velocity is a measure of both how fast and "in which direction." If the speedometer in a car reads 100 kilometers per hour (km/h), you know your speed. If there is also a compass on the dashboard, indicating that the car is moving due north, for example, you know your velocity—100 km/h north. To know your velocity is to know your speed and your direction.

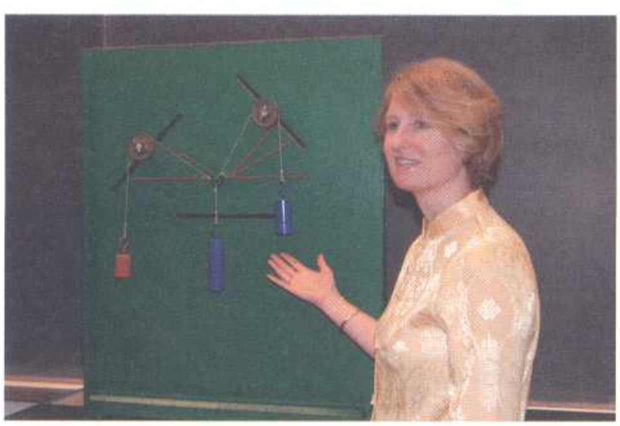


FIGURE 5.26

Diana Lininger Markham illustrates the vector arrangement of Figure 5.25.

Consider an airplane flying due north at 80 km/h relative to the surrounding air. Suppose that the plane is caught in a 60-km/h crosswind (wind blowing at right angles to the direction of the airplane) that blows it off its intended course. This example is represented with vectors in Figure 5.27 with velocity vectors scaled so that 1 centimeter (cm) represents 20 km/h. Thus, the 80-km/h velocity of the airplane is shown by the 4-cm vector, and the 60-km/h crosswind is shown by the 3-cm vector. The diagonal of the constructed parallelogram (a rectangle, in this case) measures 5 cm, which represents 100 km/h. So the airplane moves at 100 km/h relative to the ground, in a direction between north and northeast.

The pair of 6-unit and 8-unit vectors at right angles to each other say, "We may be a six and an eight, but together we're a perfect ten."

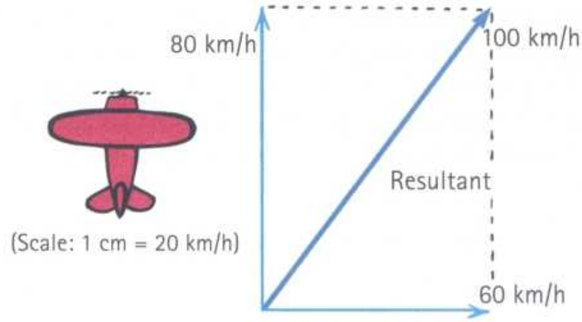


FIGURE 5.27
The 60-km/h crosswind blows the 80-km/h aircraft off course at 100 km/h.

CHECK POINT

Consider a motorboat that normally travels 10 km/h in still water. If the boat heads directly across the river, which also flows at a rate of 10 km/h, what will be its velocity relative to the shore?

Check Your Answer

When the boat heads cross-stream (at right angles to the river flow), its velocity is 14.1 km/h, 45 degrees downstream (in accord with the diagram in Figure 5.23).

COMPONENTS OF VECTORS

Just as two vectors at right angles can be combined into one resultant vector, any vector can be resolved into two *component* vectors perpendicular to each other. These two vectors are known as the **components** of the given vector they replace (Figure 5.28). The process of determining the components of a vector is called *resolution.* Any vector drawn on a piece of paper can be resolved into a vertical and a horizontal component.

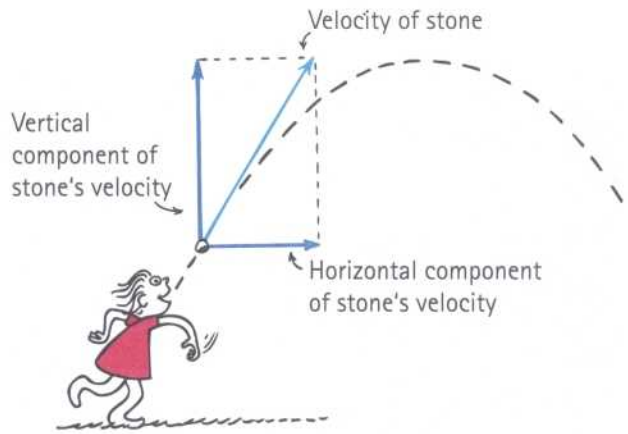


FIGURE 5.28
The horizontal and vertical components of a stone's velocity.

Vector resolution is illustrated in Figure 5.29. A vector **V** is drawn in the proper direction to represent a vector quantity. Then vertical and horizontal lines *(axes)* are

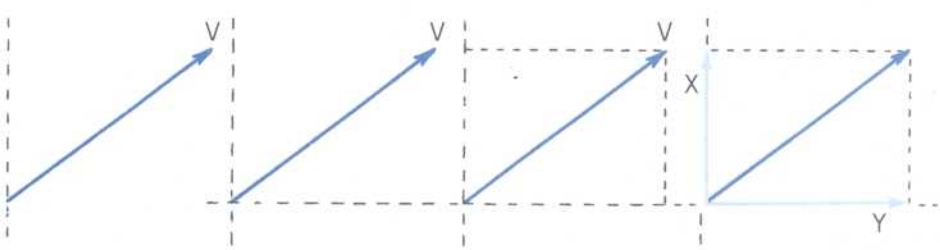


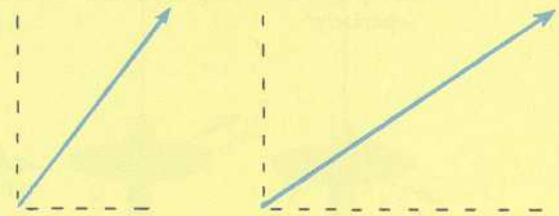
FIGURE 5.29
Construction of the vertical and horizontal components of a vector.

drawn at the tail of the vector. Next, a rectangle is drawn that has **V** as its diagonal. The sides of this rectangle are the desired components, vectors **X** and **Y.** In reverse, note that the vector sum of vectors **X** and **Y** is **V.**

We'll return to vector components when we treat projectile motion in Chapter 10.

CHECK POINT

With a ruler, draw the horizontal and vertical components of the two vectors shown. Measure the components and compare your findings with the answers given at the bottom of the page.



Answers

Left vector: The horizontal component is 2 cm; the vertical component is 2.6 cm.
Right vector: The horizontal component is 3.8 cm; the vertical component is 2.6 cm.

SUMMARY OF TERMS

Newton's third law Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

Vector quantity A quantity that has both magnitude and direction. Examples are force, velocity, and acceleration.

Scalar quantity A quantity that has magnitude but not direction. Examples are mass, volume, and speed.

Vector An arrow drawn to scale used to represent a vector quantity.

Resultant The net result of a combination of two or more vectors.

Components Mutually perpendicular vectors, usually horizontal and vertical, whose vector sum is a given vector.

REVIEW QUESTIONS

Forces and Interactions

1. When you push against a wall with your fingers, they bend because they experience a force. Identify this force.
2. A boxer can hit a heavy bag with great force. Why can't he hit a piece of tissue paper in midair with the same amount of force?
3. How many forces are required for an interaction?

Newton's Third Law of Motion

4. State Newton's third law of motion.
5. Consider hitting a baseball with a bat. If we call the force on the bat against the ball the *action* force, identify the *reaction* force.
6. Consider the apple and the orange (Figure 5.9). If the system is considered to be only the orange, is there a net force on the system when the apple pulls?
7. If the system is considered to be the apple and the orange together (Figure 5.10), is there a net force on the system when the apple pulls (ignoring friction with the floor)?
8. To produce a net force on a system, must there be an externally applied net force?
9. Consider the system of a single football. If you kick it, is there a net force to accelerate the system? If a friend kicks it at the same time with an equal and opposite force, is there a net force to accelerate the system?

Action and Reaction on Different Masses

10. Earth pulls down on you with a gravitational force that you call your weight. Do you pull up on Earth with the same amount of force?
11. If the forces that act on a cannonball and the recoiling cannon from which it is fired are equal in magnitude,

why do the cannonball and cannon have very different accelerations?

12. Identify the force that propels a rocket.
13. How does a helicopter get its lifting force?
14. Can you physically touch a person without that person touching you with the same amount of force?

Summary of Newton's Three Laws

15. Fill in the blanks: Newton's first law is often called the law of ________; Newton's second law is the law of ________; and Newton's third law is the law of ________ and ________.
16. Which of the three laws deals with interactions?

Vectors

17. Cite three examples of a vector quantity and three examples of a scalar quantity.
18. Why is speed considered a scalar and velocity a vector?
19. According to the parallelogram rule, what quantity is represented by the diagonal of a constructed parallelogram?
20. Consider Nellie hanging at rest in Figure 5.25. If the ropes were vertical, with no angle involved, what would be the tension in each rope?
21. When Nellie's ropes make an angle, what quantity must be equal and opposite to her weight?
22. When a pair of vectors are at right angles, is the resultant always greater in magnitude than either of the vectors separately?

PROJECT

Hold your hand like a flat wing outside the window of a moving automobile. Then slightly tilt the front edge upward and notice the lifting effect. Can you see Newton's laws at work here?

PLUG AND CHUG

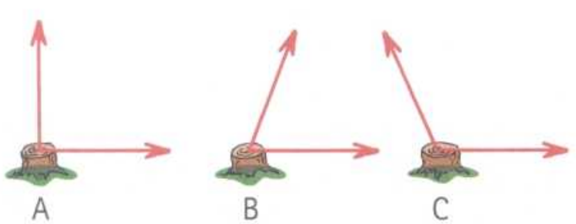
1. Calculate the resultant of the pair of velocities 100 km/h north and 75 km/h south. Calculate the resultant if both of the velocities are directed north.

Resultant of two vectors at right angles to each other:
$R = \sqrt{X^2 + Y^2}$

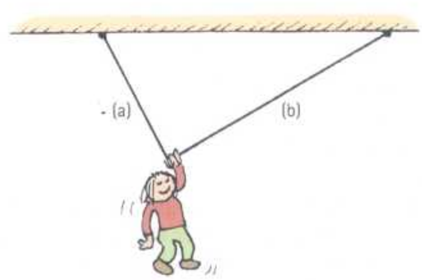
2. Calculate the magnitude of the resultant of a pair of 100-km/h velocity vectors that are at right angles to each other.
3. Calculate the resultant of a horizontal vector with a magnitude of 4 units and a vertical vector with a magnitude of 3 units.
4. Calculate the resultant velocity of an airplane that normally flies at 200 km/h if it encounters a 50-km/h wind from the side (at a right angle to the airplane).

RANKING

1. As seen from above, a stubborn stump is pulled by a pair of ropes, each with a force of 200 N, but at different angles as shown. From greatest to least, rank the net force on the stump.

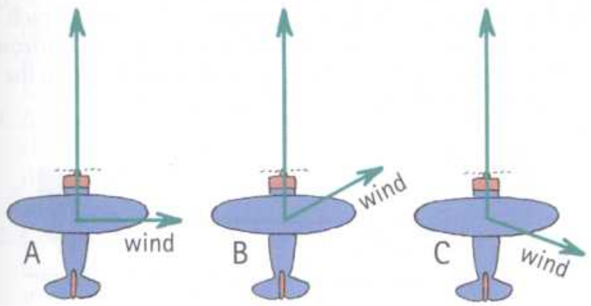


2. Nellie Newton hangs motionless by one hand from a clothesline. Which side of the line, a or b, has the greater

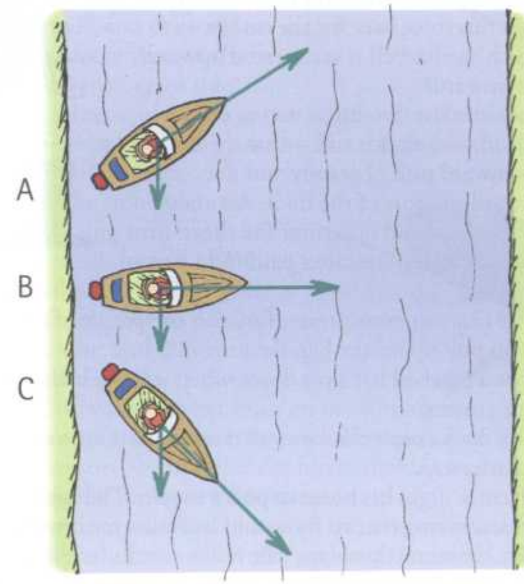


a. horizontal component of tension?
b. vertical component of tension?
c. tension?

3. Here we see a top view of an airplane being blown off course by wind in three different directions. Use a pencil and the parallelogram rule and sketch the vectors that show the resulting velocities for each case. Rank the speeds of the airplane across the ground from fastest to slowest.



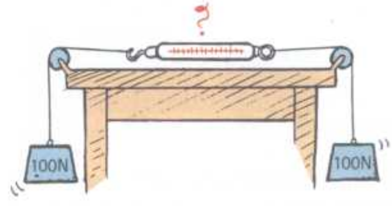
4. Here we see top views of three motorboats crossing a river. All have the same speed relative to the water, and all experience the same river flow. Construct resultant vectors showing the speed and direction of the boats. Rank them from most to least for
a. the time for the boats to reach the opposite shore.
b. the fastest ride.



EXERCISES

1. A rocket becomes progressively easier to accelerate as it travels through space. Why is this so? (*Hint:* About 90% of the mass of a newly launched rocket is fuel.)
2. The photo shows Steve Hewitt and daughter Gretchen. Is Gretchen touching her dad, or is dad touching her? Explain.

3. When you rub your hands together, can you push harder on one hand than the other?
4. For each of the following interactions, identify action and reaction forces. (a) A hammer hits a nail. (b) Earth gravity pulls down on a book. (c) A helicopter blade pushes air downward.
5. You hold an apple over your head. (a) Identify all the forces acting on the apple and their reaction forces. (b) When you drop the apple, identify all the forces acting on it as it falls and the corresponding reaction forces. Neglect air drag.
6. Identify the action–reaction pairs of forces for the following situations: (a) You step off a curb. (b) You pat your tutor on the back. (c) A wave hits a rocky shore.
7. Consider a baseball player batting a ball. (a) Identify the action–reaction pairs when the ball is being hit and (b) while the ball is in flight.
8. What physics is involved for a passenger feeling pushed backward into the seat of an airplane when it accelerates along the runway during takeoff?
9. If you drop a rubber ball on the floor, it bounces back up. What force acts on the ball to provide the bounce?
10. When you kick a football, what action and reaction forces are involved? Which force, if any, is greater?
11. Is it true that when you drop from a branch to the ground below, you pull upward on Earth? If so, then why is the acceleration of Earth not noticed?
12. Within a book on a table, there are billions of forces pushing and pulling on all the molecules. Why is it that these forces never by chance add up to a net force in one direction, causing the book to accelerate "spontaneously" across the table?
13. Two 100-N weights are attached to a spring scale as shown. Does the scale read 0, 100, or 200 N, or does it give some other reading? (*Hint:* Would it read any differently if one of the ropes were tied to the wall instead of to the hanging 100-N weight?)



14. If you exert a horizontal force of 200 N to slide a crate across a factory floor at constant velocity, how much friction is exerted by the floor on the crate? Is the force of friction equal and oppositely directed to your 200-N

push? If the force of friction isn't the reaction force to your push, what is?

15. When the athlete holds the barbell overhead, the reaction force is the weight of the barbell on his hand. How does this force vary for the case in which the barbell is accelerated upward? Downward?

16. Consider the two forces acting on the person who stands still—namely, the downward pull of gravity and the upward support of the floor. Are these forces equal and opposite? Do they form an action–reaction pair? Why or why not?

17. Why can you exert greater force on the pedals of a bicycle if you pull up on the handlebars?

18. Does a baseball bat slow down when it hits a ball? Defend your answer.

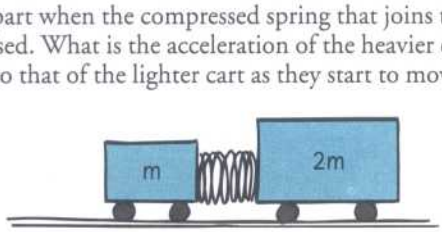
19. Why does a rope climber pull downward on the rope to move upward?

20. A farmer urges his horse to pull a wagon. The horse refuses, saying that to try would be futile, for it would flout Newton's third law. The horse concludes that she can't exert a greater force on the wagon than the wagon exerts on her and, therefore, that she won't be able to accelerate the wagon. What is your explanation to convince the horse to pull?

21. You push a heavy car by hand. The car, in turn, pushes back with an opposite but equal force on you. Doesn't this mean that the forces cancel one another, making acceleration impossible? Why or why not?

22. The strong man will push the two initially stationary freight cars of equal mass apart before he himself drops straight to the ground. Is it possible for him to give either of the cars a greater speed than the other? Why or why not?

23. Suppose that two carts, one twice as massive as the other, fly apart when the compressed spring that joins them is released. What is the acceleration of the heavier cart relative to that of the lighter cart as they start to move apart?



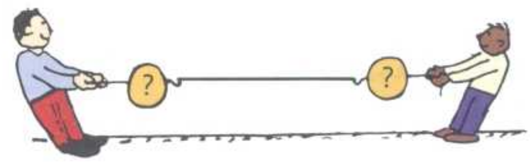
24. If a Mack truck and Honda Civic have a head-on collision, upon which vehicle is the impact force greater? Which vehicle experiences the greater deceleration? Explain your answers.

25. Ken and Joanne are astronauts floating some distance apart in space. They are joined by a safety cord whose ends are tied around their waists. If Ken starts pulling on the cord, will he pull Joanne toward him, or will he pull himself toward Joanne, or will both astronauts move? Explain.

26. Which team wins in a tug-of-war—the team that pulls harder on the rope, or the team that pushes harder against the ground? Explain.

27. In a tug-of-war between Sam and Maddy, each pulls on the rope with a force of 250 N. What is the tension in the rope? If both remain motionless, what horizontal force does each exert against the ground?

28. Your instructor challenges you and your friend to each pull on a pair of scales attached to the ends of a horizontal rope, in tug-of-war fashion, so that the readings on the scales will differ. Can this be done? Explain.



29. Two people of equal mass attempt a tug-of-war with a 12-m rope while standing on frictionless ice. When they pull on the rope, each of them slides toward the other. How do their accelerations compare, and how far does each person slide before they meet?

30. What aspect of physics was not known by the writer of this newspaper editorial that ridiculed early experiments by Robert H. Goddard on rocket propulsion above Earth's atmosphere? "Professor Goddard . . . does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react . . . he seems to lack the knowledge ladled out daily in high schools."

31. Which of the following are scalar quantities, which are vector quantities, and which are neither? (a) velocity; (b) age; (c) speed; (d) acceleration; (e) temperature.

32. What can you correctly say about two vectors that add together to equal zero?

33. Can a pair of vectors with unequal magnitudes ever add to zero? Can three unequal vectors add to zero? Defend your answers.

34. When can a nonzero vector have a zero horizontal component?

35. When, if ever, can a vector quantity be added to a scalar quantity?

36. Which is more likely to break—a hammock stretched tightly between a pair of trees or one that sags more when you sit on it?

37. A heavy bird sits on a clothesline. Will the tension in the clothesline be greater if the line sags a lot or if it sags a little?

38. The rope supports a lantern that weighs 50 N. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

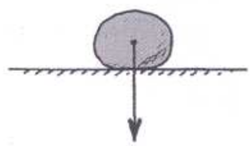
39. The rope is repositioned as shown and still supports the 50-N lantern. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

40. Why does vertically falling rain make slanted streaks on the side windows of a moving automobile? If the streaks make an angle of 45°, what does this tell you about the relative speed of the car and the falling rain?

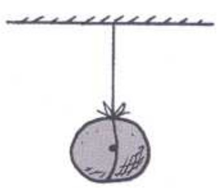
41. A balloon floats motionless in the air. A balloonist begins climbing the supporting cable. In which direction does the balloon move as the balloonist climbs? Defend your answer.

42. Consider a stone at rest on the ground. There are two interactions that involve the stone. One is between the stone and Earth as a whole: Earth pulls down on the stone (its weight) and the stone pulls up on Earth. What is the other interaction?

43. A stone is shown at rest on the ground. (a) The vector shows the weight of the stone. Complete the vector diagram showing another vector that results in zero net force on the stone. (b) What is the conventional name of the vector you have drawn?



44. Here a stone is suspended at rest by a string. (a) Draw force vectors for all the forces that act on the stone. (b) Should your vectors have a zero resultant? (c) Why or why not?

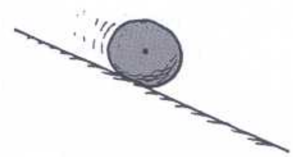


45. Here the same stone is being accelerated vertically upward. (a) Draw force vectors to some suitable scale showing relative forces acting on the stone. (b) Which is the longer vector, and why?

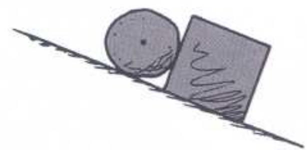
46. Suppose the string in the preceding exercise breaks and the stone slows in its upward motion. Draw a force vector diagram of the stone when it reaches the top of its path.

47. What is the acceleration of the stone of Exercise 46 at the top of its path?

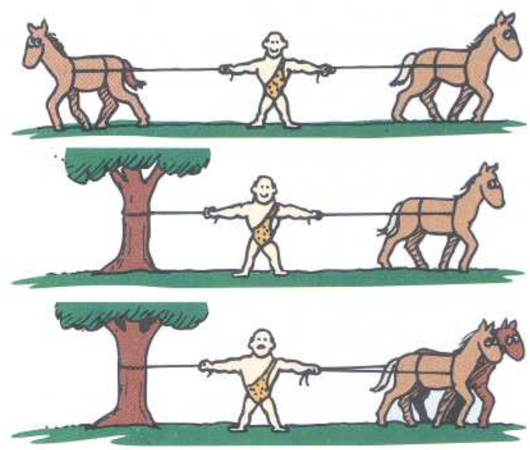
48. Here the stone is sliding down a friction-free incline. (a) Identify the forces that act on it, and draw appropriate force vectors. (b) By the parallelogram rule, construct the resultant force on the stone (carefully showing that it has a direction parallel to the incline—the same direction as the stone's acceleration).



49. Here the stone is at rest, interacting with both the surface of the incline and the block. (a) Identify all the forces that act on the stone, and draw appropriate force vectors. (b) Show that the net force on the stone is zero. (*Hint 1:* There are two normal forces on the stone. *Hint 2:* Be sure the vectors you draw are for forces that act *on* the stone, not *by* the stone on the surfaces.)



50. The strong man can withstand the tension force exerted by the two horses pulling in opposite directions. How would the tension compare if only one horse pulled and the left rope were tied to a tree? How would the tension compare if the two horses pulled in the same direction, with the left rope tied to the tree?



PROBLEMS

1. A boxer punches a sheet of paper in midair and brings it from rest up to a speed of 25 m/s in 0.05 s. (a) What acceleration is imparted to the paper? (b) If the mass of the paper is 0.003 kg, what force does the boxer exert on it? (c) How much force does the paper exert on the boxer?

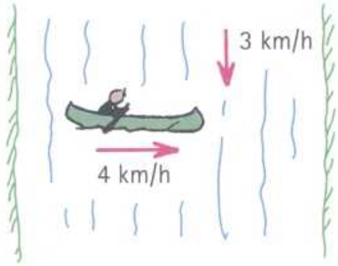
2. If you stand next to a wall on a frictionless skateboard and push the wall with a force of 40 N, how hard does the wall push on you? If your mass is 80 kg, show that your acceleration is 0.5 m/s^2.

3. If raindrops fall vertically at a speed of 3 m/s and you are running at 4 m/s, how fast do they hit your face?

4. Forces of 3.0 N and 4.0 N act at right angles on a block of mass 2.0 kg. Show that the acceleration of the block is 2.5 m/s^2.

5. Consider an airplane that normally has an airspeed of 100 km/h in a 100-km/h crosswind blowing from west to east. Calculate its ground velocity when its nose is pointed north in the crosswind.

6. You are paddling a canoe at a speed of 4 km/h directly across a river that flows at 3 km/h, as shown in the figure. (a) What is your resultant speed relative to the shore? (b) In approximately what direction should you paddle the canoe so that it reaches a destination directly across the river?



• 7. When two identical air pucks with repelling magnets are held together on an air table and released, they end up moving in opposite directions at the same speed, v. Assume the mass of one of the pucks is doubled and the procedure is repeated.
   a. From Newton's third law, derive an equation that shows how the final speed of the double-mass puck compares with the speed of the single puck.
   b. Calculate the speed of the double-mass puck if the single puck moves away at 0.4 m/s.

CHAPTER 5 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 5.1, 5.8, 5.9, 5.10, 5.11, 5.16, 5.22, 5.25

Tutorials

- Newton's Third Law
- Vectors

Videos

- Forces and Interaction
- Action and Reaction on Different Masses
- Action and Reaction on Rifle and Bullet
- Vector Representation: How to Add and Subtract Vectors
- Geometrical Addition of Vectors

Quizzes

Flashcards

Links