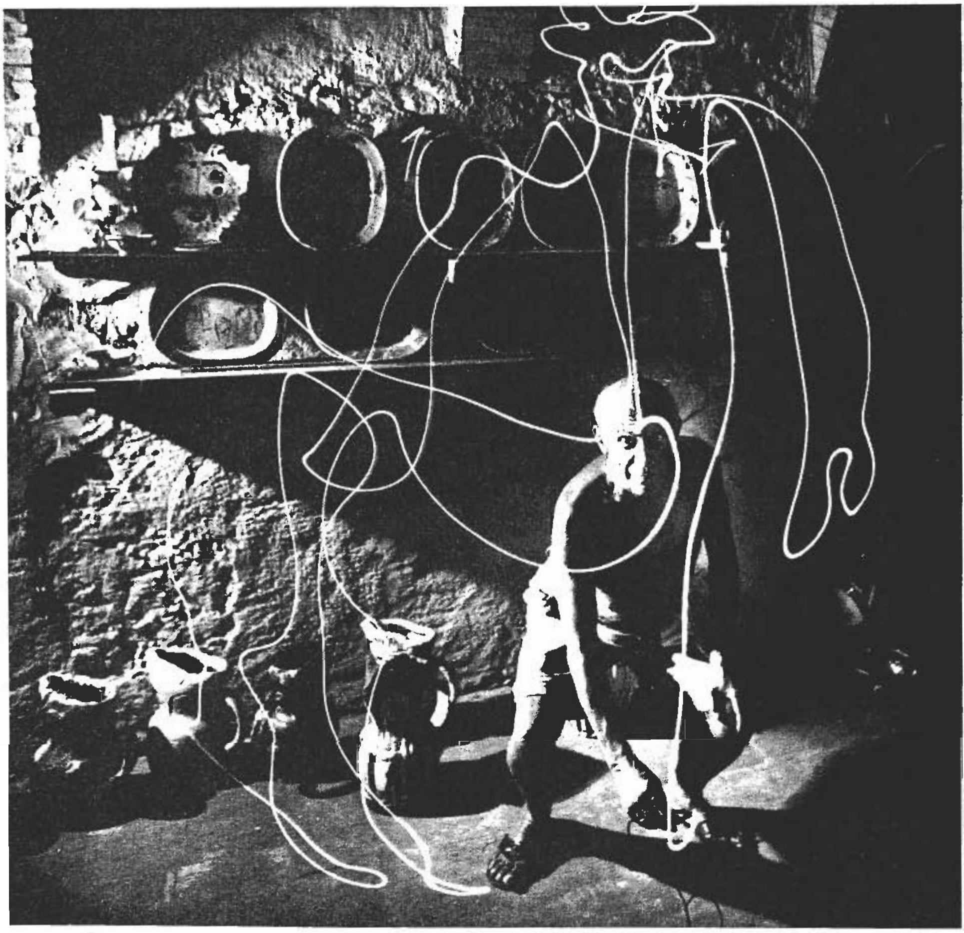
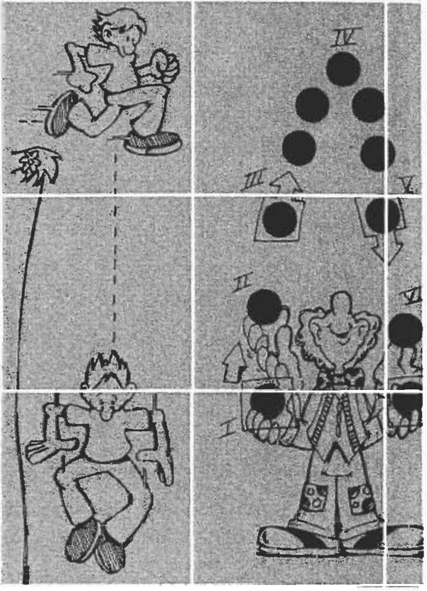


Gjon Mili, Life Magazine, © Time Inc.

Figure 7-1



7

Newton's Three Laws

While standing in front of a camera with its shutter held open, the late Pablo Picasso experimented with drawing in air. As he drew, Picasso applied a variety of forces to the penlight—pushing it upward, downward, to the left, and to the right. At the same time, gravitational forces alternately opposed or augmented his efforts. Frictional forces continuously opposed any motion. Though it would be difficult, we could use the concept of force to analyze the creation of each and every line. Such an analysis would tell us little about the creation of art, but it would demonstrate the role of forces in the world of motion around us.

Though motion can be complex and forces are numerous, the relationship between motion and force can actually be described quite simply. In Chapter 6 we began to consider this relationship in terms of our everyday experiences. In this chapter we examine it in terms of three laws of motion—simple but profound descriptions developed by Isaac Newton in the late seventeenth century. Newton's *first law* describes what occurs when there is no net force action on an object. His *second law*, which we introduced in Chapter 6, relates accelerated motion to a net applied force. The *third law* of motion describes the symmetrical relationship between two interacting bodies. These three laws, brief as they seem, provide a single theory with which to explain an enormous range of observations.

NEWTON'S FIRST LAW

Intuitively, we relate force to motion. Whether we push on the bike pedals to get up the hill, push on the ground to walk to class, or pull on a stuck drawer to make it open, the force we exert makes things move. As you saw in Chapter 6, however, motion can occur without force. Unless restrained by a seat belt, you keep moving when your car stops suddenly. Forces are acting on the car but not on you—until you hit the windshield. Forces can also act without motion, as you saw. Any architect will tell you that a variety of forces act on a high-rise building, but fortunately it does not move. Forces without motion and motion without force are the subjects of Newton's first law.

When Forces Disappear

In Chapter 6 we compared a man's motions as he slid on ice and on a waxed tile floor. He wore the same shoes, began with the same initial velocity, and slid to a stop on both surfaces. But there was one difference—his momentum changed over a longer time interval on ice than on tile. We explained this in terms of the size of the frictional force exerted by the two surfaces. The tile surface exerts a larger force than the ice. Large force, short time interval; small force, long time interval.

This trade-off between the size of the force and the length of the time interval allows us to imagine what would happen if the frictional force were to disappear. Suppose we could make the frictional force exerted by the ice even smaller—for example, by putting ice skates on the man. We would expect him to slide even longer. If we could continue to reduce the frictional force all the way to zero, our ice skater would be doomed to slide at a constant speed along a straight line forever. His momentum would never change.

Newton's First Law and Inertia

This argument is such a fundamental part of our concept of force that it is considered a major principle, called **Newton's first law:**

> When the net force acting on an object is zero, the object's momentum does not change.

In most interactions an object's mass remains constant, so that any change in momentum arises from a change in velocity. Consequently, Newton's first law tells us that when zero net force acts, the object's velocity must remain constant. If the object is standing still, it continues to stand still. If it is moving initially, it continues to move in a straight line at a constant speed. Neither the magnitude nor the direction of the velocity can change.

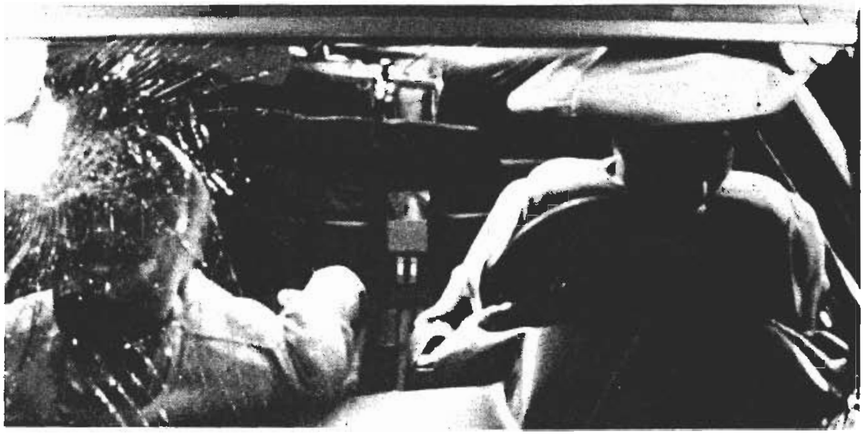


Figure 7-2
In an automobile collision, unrestrained passengers continue to move forward as the car stops. Seat belts safely transfer the force exerted on the car to the passengers.

Newton's first law was originally stated in somewhat different terms by Galileo in the early seventeenth century. Galileo introduced the term **inertia** to describe the tendency of an object to keep moving in a straight line at a constant speed or to remain stationary when zero net force acts on it. The greater the inertia of an object, the greater the force needed to cause a noticeable change in its motion. Consequently, Newton's first law is often referred to as the *law of inertia.*

Both inertia (a characteristic of an object) and Newton's first law (a statement about motion) express what occurs when a net force is absent. For systems in which no forces act, Newton's first law seems almost trivial. If no forces act, no interactions can occur. Of course, an object's momentum does not change. However, for systems in which forces act but their effects sum to zero, Newton's first law changes people's intuitive ideas about the relationship between force and motion.

On earth, all moving objects experience friction. To keep a bicycle moving at a constant velocity, you must apply a force by pushing on the pedals. For centuries, scientists made this rather natural link between force and motion at a constant velocity, believing that a force was always necessary to maintain a state of motion. Most of us develop this same sort of intuitive link between force and motion; it seems to us that we exert a force on the bicycle to keep it moving. In fact, we push on the pedals to overcome yet another force—friction. The two forces—our pushing and friction—sum to zero, enabling the bicycle to continue to move at a constant velocity. On earth, most situations in which the net force is zero arise because two or more forces act on the object simultaneously. It is rare that objects experience no force.

Newton's First Law and Seat Belts

Automobile accidents involve two collisions. The first occurs when the automobile strikes an object, such as a telephone pole. The pole provides the force needed to change the car's momentum, eventually bringing it to rest. A second collision, which occurs shortly after the first, involves the passengers. If they are not in some way attached to the car, the passengers do not experience the force exerted by the telephone pole. The car may stop, but the passengers continue moving forward at a constant velocity. According to Newton's first law, their forward motion will continue until they experience a force. Unfortunately, this force is usually exerted by the dashboard or windshield, and serious injuries result.

Car manufacturers conduct a great deal of research and testing aimed at reducing the severity of the injuries that result from this second collision. Padded steering wheels, padded dashboards, steering columns recessed from the wheel, and head rests are a few of the modifications made as a result of this research. Ultimately, however, seat belts offer one of the best solutions. In simulations conducted at automobile testing grounds, the role of seat belts in reducing injury was explored extensively. Figure 7-2 shows a car that had dummies used as passengers. The dummies did not wear seat belts. The photograph shows the continuing forward motion of the dummies until the second collision occurred. You can contrast this to the motion that occurred when seat belts were worn. When car and passenger are connected, their motion is stopped by the same force at the same time.

SELF-CHECK 7A

Lap belts restrain passengers' lower bodies but not their shoulders. Use Newton's first law to describe the motion of the lower body, head, and shoulders of a passenger who is wearing only a lap belt while involved in an automobile accident.

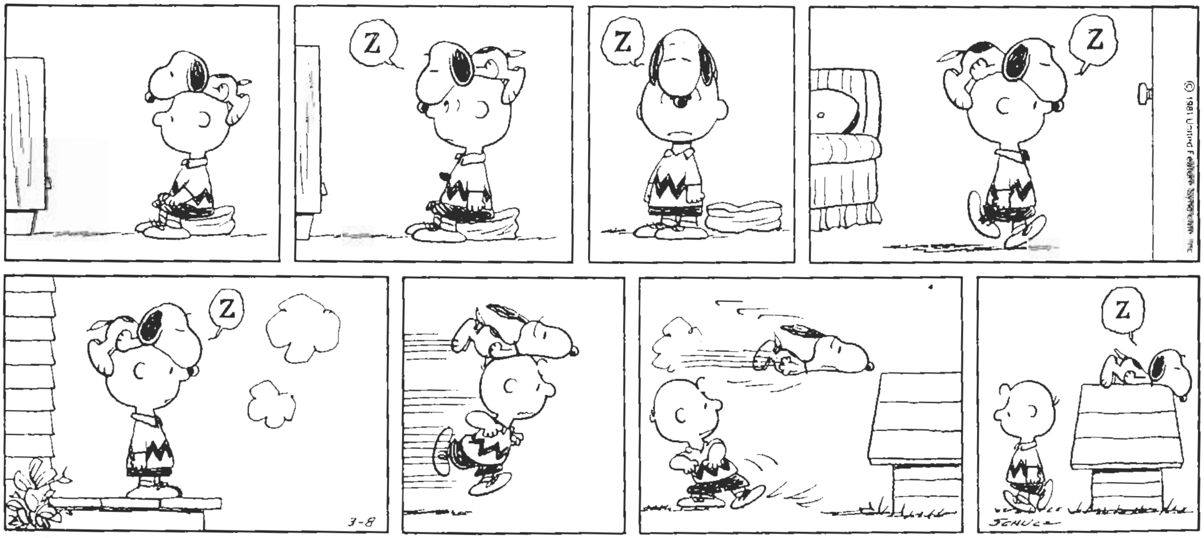


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Figure 7-3

AP/Wide World Photos

Equilibrium

Towers that transmit television signals frequently have many cables attached to them. Each cable applies a force to the tower. In addition, wind, gravity, and the ground exert forces on the tower. Despite the action of all these forces, the tower usually does not move. This lack of acceleration is called **equilibrium,** a state in which the net force acting on an object is zero.

In designing structures that remain in equilibrium, architects are generally concerned with gravitational forces. Buildings must be designed so that the upward forces exerted by the skeletal structure balance the downward force due to gravity. When equilibrium is not maintained, disaster can occur. During a severe storm, the roof of Kemper Arena in Kansas City collapsed. A study of the design later revealed that water, which had accumulated on the flat roof during the storm, had caused the collapse. The building design had been adequate to support the weight of the roof but clearly not adequate to support the weight of the roof and the water. Figure 7-3 shows the collapsed roof of the Kemper Arena.

NEWTON'S SECOND LAW

Newton's second law, presented in the last chapter, tells us that a net force results in an acceleration.

> The net force acting on an object is equal to the product of the object's mass and its acceleration.
>
> **net force** = mass × **acceleration**

We see a variety of accelerations—cars as they move away from a stop sign, balls as they fall toward the earth, grocery carts as they gradually coast to a stop. These examples involve only a change in speed; the objects continue to move in a straight line. Motion along a curved path, such as traveling around on a merry-go-round, also involves acceleration. Here the speed of the object might remain constant, but its direction changes. In examining Newton's second law, we consider examples of acceleration along both straight-line and curved paths.

Hammer and Feather

In Chapter 2 we described the classic physics experiment in which Apollo Astronaut David Scott dropped a hammer and feather simultaneously on the moon's surface. The hammer and feather reached the lunar surface at the same time—their accelerations were identical. This seems strange to us because the same experiment performed on the earth's surface gives a different result. The hammer always reaches the ground before the feather. We can use Newton's second law to understand the two different results.

If we rearrange Newton's second law, we find that the acceleration that any object experiences is equal to the net force acting on it divided by its mass:

$$\textbf{acceleration} = \frac{\textbf{net force}}{\text{mass}}$$

The net force acting on a falling object is the force due to gravity, or the weight of the object. We have defined weight as the product of the object's mass and the acceleration due to gravity at its location. On the moon, the acceleration due to gravity is 1.6 (meters per second) per second [(m/s)/s], down. A 1 kilogram (kg) hammer will weigh (1 kg)[1.6 (m/s)/s, down], or 1.6 Newtons (N), down. A 0.001 kg feather will weigh (0.001 kg)[1.6 (m/s)/s, down], or 0.0016 N, down. The force due to lunar gravity is the only force on each object, so both accelerate at 1.6 (m/s)/s, down. Both hit the ground at the same time.

On the surface of the earth, two forces act on the hammer and feather. As on the moon, a force due to gravity acts downward, pulling objects toward the surface of the earth. But the earth's atmosphere adds a frictional force, called *air resistance,* that acts upward. Consequently the net force acting on each object is the vector addition of the force due to gravity and the contact force due to air resistance. This second force, the air resistance, leads to the difference between the results on the earth and those on the moon.

Unlike the force due to gravity, the force exerted by the surrounding air varies with the speed at which the object falls. As an object begins to fall, the force exerted by the surrounding air begins to increase. It continues to increase until the object no longer accelerates—that is, until the force exerted by the surrounding air equals the force due to gravity. The net force is then zero and the object stops accelerating. From then on the object continues to fall at a constant velocity—the velocity it reached the instant before the net force became zero.

Table 7-1 lists the forces acting on the hammer and feather, as well as the net force and acceleration at several times during the fraction of a second after each is released. The force due to air resistance is quite small compared to the force due to gravity acting on the hammer. This means that the hammer's acceleration decreases very little and the hammer accelerates rapidly to the ground. By contrast, the force due to air resistance is initially one-third the force due to gravity acting on the feather, and within a few hundredths of a second, the two forces on the feather are equal. The net force acting on the feather is zero, and it floats gently to the ground. The velocity at which the feather falls is the velocity it reached within that first few hundredths of a second after it was released.

Motion in a Circle: or How David Slew Goliath

We applied Newton's second law to motion along a straight line. Now we look at motion along a curved path. The simplest curved motion is that of a small rock as it is being twirled at a constant speed on the end of a string. As shown

Table 7-1 Hammer and Feather

Hammer				
Time (s)	Force due to Gravity (down) (N)	Force due to Air Resistance (up) (N)	Net Force (down) (N)	Acceleration (down) (m/s)/s
0.00	9.8	0.000	9.8000	9.8000
0.01	9.8	0.0003	9.7997	9.7997
0.03	9.8	0.003	9.7970	9.7970
0.05	9.8	0.009	9.7910	9.7910

Feather				
Time (s)	Force due to Gravity (down) (N)	Force due to Air Resistance (up) (N)	Net Force (down) (N)	Acceleration (down) (m/s)/s
0.00	0.0098	0.000	0.0098	9.8
0.01	0.0098	0.0003	0.0095	9.5
0.03	0.0098	0.003	0.0068	6.8
0.05	0.0098	0.009	0.0008	0.8

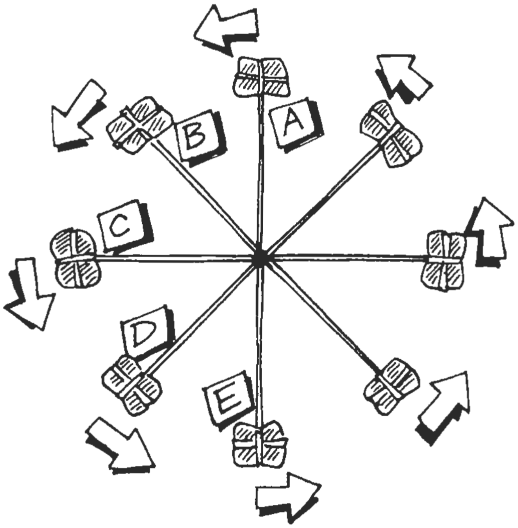


Figure 7-4

A strobe drawing of the motion of a rock shows it moving at a constant speed. Its direction, however, changes constantly. The rock accelerates.

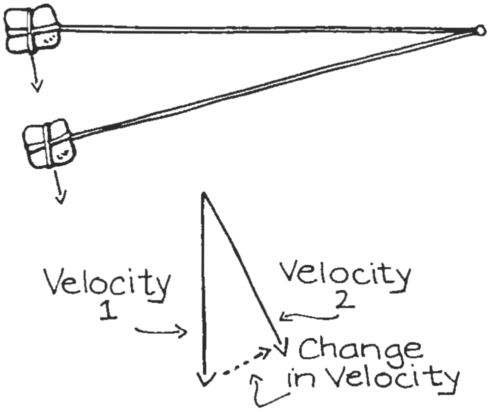


Figure 7-5

The change in velocity lies toward the center of the circular motion. Both the acceleration and the net force are directed toward the center.

in the strobelike drawing in Figure 7-4, the images of the rock are equally spaced. The rock's speed is constant throughout its motion around the circle. The direction in which the rock moves, however, changes constantly. At A, the rock moves to the left; at C, it moves downward; and so forth. This change in direction means that the rock is accelerating—that a net force must be acting on it.

Newton's second law states that the net force acts in the direction in which the object accelerates. When the object moves in a straight line, it is relatively simple to see the direction in which the object accelerates—it either slows down or speeds up. When the object moves in a circle, however, the situation is more difficult. We can determine the direction in which the rock accelerates by looking at the change in its velocity over a very short time interval. Figure 7-5 shows the rock initially moving downward. A short time later it is moving down and slightly to the right. Subtracting these two vectors shows that the change in velocity is a vector that points toward the center of the circle. This acceleration is called a **centripetal acceleration.** (The word *centripetal* is derived from a Greek word meaning center-seeking.)

The net force that leads to a centripetal acceleration is called, naturally enough, a **centripetal force.** A centripetal force is a force that acts toward the center of the circle, causing the object to move about in a circle at a constant speed. When you throw a rock, it moves in a straight line in the direction it was traveling at the moment you released it, in accordance with Newton's first law. But if you then apply a force by pulling on an attached string, the rock will continuously be deflected from its straight-line path, in accordance with Newton's second law. The rock's inertia—its tendency to keep moving in

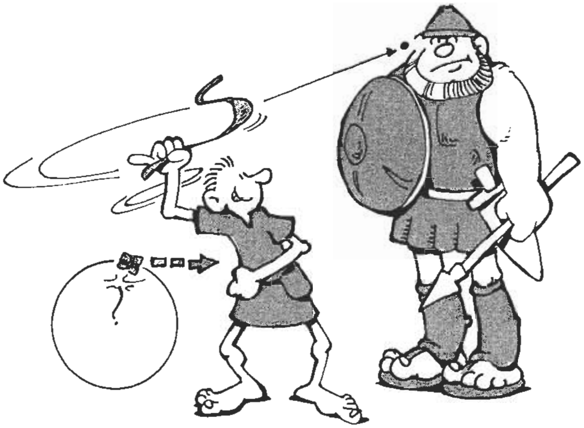


Figure 7-6
When David released his stone, it moved off along a straight line in accordance with Newton's first law. By choosing the right release point, David slew Goliath.

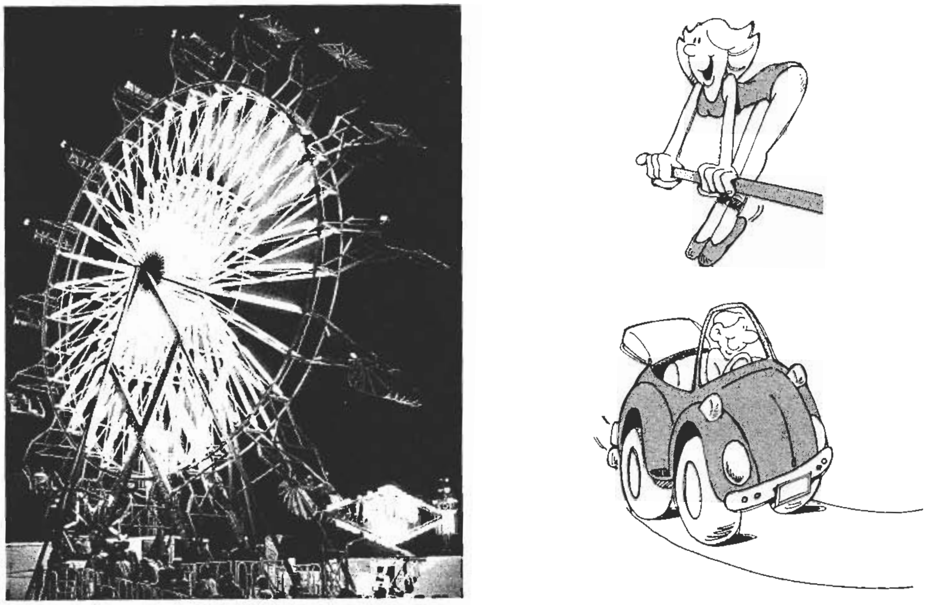
a straight line—keeps it from being pulled back to you, but the centripetal force prevents it from moving farther away from you. The result is that the rock moves in a circle. If you have ever twirled something on a string, your first impression might be that the force you exert is not centripetal. In order to keep the object moving, you usually have to flip your hand. This flip is actually doing more than providing a centripetal force. It also provides the force necessary to balance gravity and air resistance as the object moves about in a circle. To feel just the centripetal force, let the string attached to the object wrap around your finger. As it does so, your finger will constantly provide a centripetal force to maintain the circular motion.

If a centripetal force suddenly disappears, as when the string on your rock breaks, Newton's first law continues to operate and the object continues to move in a straight line. When David slew Goliath, he used a slingshot that consisted of a small pouch on the end of a string. After placing a rock in the pouch, David applied a centripetal force to the string. In accordance with Newton's second law, the rock began moving in a circle at a constant speed. When David released the string that held the pouch shut, the rock no longer had any centripetal force acting on it. Newton's first law took over, and the rock moved off in a straight line in the direction it had at the time of release (Figure 7-6). By selecting the release point carefully, David was able to direct the rock so that it hit Goliath's head.

A modern example occurs with automobiles. In order to travel around a curve, a car must have a centripetal force acting on it. This force is usually supplied by the frictional interactions between the tires and the road. But if the road is icy or the tires are bald, the frictional force is decreased and cars sometimes cannot make the curve. In the absence of a centripetal force, the car continues to move in a straight line—right off the road!

ACCELERATED REFERENCE FRAMES

Sometimes we are in reference frames that are accelerating while we are not. As a car goes quickly around a tight curve, passengers not wearing seat belts often slide across the seat. Or, when a car stops suddenly, passengers not



Robert J. Bennett, Bridgeville, Del.

Figure 7-7

SELF-CHECK 7B

The gymnast, Ferris wheel, and car in Figure 7-7 each move at a constant speed. What is the direction of the net force and acceleration in each case? What object provides the centripetal force?

wearing seat belts continue to move forward. The car accelerates, but the passengers do not. Because the passengers use the car as a reference frame, they describe their motion relative to this accelerating reference frame.

Straight-Line Accelerated Reference Frames

If the car in which you are riding suddenly stops, you continue moving forward until your seat belt stops you. You might describe yourself as being "thrown forward." If the car suddenly accelerates forward, you say you were "thrown backward." The word *thrown* implies a force acting on you, and in these situations you often use words implying a force to describe what happened to you. Because no force really acts on you, such a description refers to what are called *fictitious forces.*

Fictitious forces are not real forces, but they arise from the acceleration of the reference frame. The real force in the case just described acts on the car; it is due to friction between the tires and road or to collisions with another object. The car accelerates; the passengers do not. However, the passengers treat the car as if it were a stationary reference frame and describe their motions in terms of a fictitious force. The fictitious force always acts in a direction opposite to the direction in which the real force acts on the reference frame. When the car accelerates forward, the passengers describe a "force" acting to throw them backward. When the car stops suddenly, the passengers report that a "force" has thrown them forward.

Fictitious forces also arise when everything in a reference frame accelerates together, producing events that seem abnormal. Suppose, for example, that someone puts you in a closed box, takes the box up in an airplane, and drops it. If you drop an object while in the box, the object will accelerate downward at the same rate as you and the box. It will seem to float in front of you. Normally objects do not float in front of us, so we say that a force pushes upward on the object. Such a force arises from the motion of the reference frame and not from any real interaction with other objects.

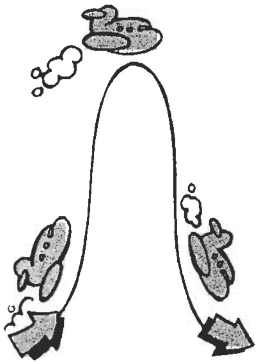


Figure 7-8

Using the path shown, NASA's reduced-gravity airplane can provide future astronauts with about 15 seconds of apparent weightlessness.

Being placed inside a box and dropped toward the earth may seem absurd, yet astronauts are prepared for space travel in a similar way. A large airplane is flown along the path shown in Figure 7-8. The airplane moves up and down rapidly, creating segments of the trip in which the airplane and astronauts are "falling" downward together. This creates an apparent weightlessness and approximates the experience which the astronauts will have in space. During this time, astronauts practice the tasks they are assigned to complete in space. (They also feel side effects. NASA calls the airplane the "reduced gravity environment"; the astronauts refer to it as the "vomit comet.")

Rotating Reference Frames

As a car goes around a curve, passengers often slide across the seat. Barrel rides at amusement parks provide much the same sensation. As the barrel rotates faster and faster, people say they are pressed against the side of the barrel. Such forces are often called *centrifugal* (center-fleeing) forces.

Centrifugal forces are fictitious forces that arise from the rotation of the reference frame. Like the fictitious forces that act in straight-line accelerated reference frames, centrifugal forces appear to act in a direction opposite to that of the real force that is causing the reference frame to accelerate. As a car goes around a curve, friction between the tires and the road provides the centripetal force needed to cause the change in direction. Passengers, however, report a centrifugal force pushing them outward, away from the center of the circle. They reach this conclusion because the reference frame accelerates while they do not. Using the accelerating car as the reference frame, the passengers conclude that a force has been applied to them (Figure 7-9).

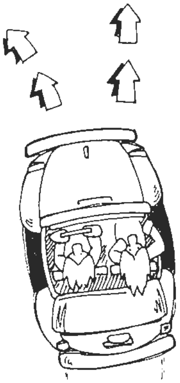


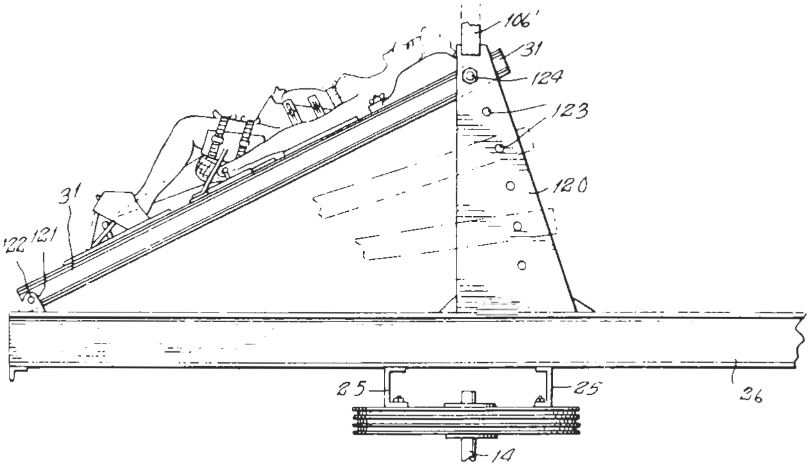
Figure 7-9

As the car turns the corner, an unrestrained passenger continues to move along a straight line in accordance with Newton's first law. Using the car as a reference frame, the passenger reports that a centrifugal force pushes her outward.

SELF-CHECK 7C

Suppose you are holding a drink while riding in a car with a seat belt on. The car suddenly turns to your left. What happens to the liquid in the glass? Explain this result in terms of fictitious forces.

HELPING "MOM"



Giving help in the delivery of a baby was of concern to George B. and Charlotte E. Blonsky when they invented the Spinnet, a device that takes advantage of fictitious forces in accelerating reference frames. The woman who is about to deliver is strapped to a platform (31), which is rotated by a shaft (14) connected to a motor. During rotation, the mother and baby are in an accelerated reference frame in which a centrifugal force acts outward—in the same direction the soon-to-be mother needs to push. The two forces add, so the woman can exert less force than she would if the platform were not rotating. Seen from the nonrotating (hospital) reference frame, Mom's help comes from Newton's first law. While rotating, the baby will tend to move in a straight line rather than turn with the acceleration of its mother. A straight line brings the baby right out into the world.

Invented in 1965, the Spinnet has not been widely accepted by modern hospitals. However, the Blonskys did anticipate another practice that is being used in the Western world today—and has been used for centuries throughout the world. When they tilted the expectant mother downward, they let gravity lend a hand!

NEWTON'S THIRD LAW

Newton's first and second laws completely define force and describe the motion that results when a net force acts on a single object. Forces arise from interactions, however, and our discussion would not be complete without a look at the entire interaction. Newton's third law describes the forces on all objects involved in an interaction.

Action and Reaction

A skydiver is plummeting toward earth. At a certain altitude she opens a parachute to increase air resistance and reduce her acceleration. When she hits the ground, the ground exerts an upward force on her, abruptly reducing her downward momentum to zero. This force can be quite large—large enough to break bones if the skydiver is falling too quickly. But what about the ground? Just as the earth exerts a force on the skydiver, the skydiver exerts a force on the earth. The earth is so massive, we do not see its momentum change; but we see a small dent or a bit of mashed grass. Both objects involved in the interaction experience a force.

As a more subtle example, suppose you push on a wall while standing on a skateboard. You exert a reasonably large force on the wall, but the wall does not budge perceptibly. Instead you accelerate backward. We can only explain your motion by saying that the wall exerts a force on you. Both objects—you and the wall—exert forces during the interaction.

Forces Appear in Pairs

These two examples illustrate an important, yet subtle, characteristic of force. The skydiver exerts a force on the ground and the ground exerts a force on the skydiver. The skateboarder exerts a force on the wall and the wall exerts a force on the skateboarder. Forces occur in pairs. Newton stated this characteristic of force in his **third law:**

> Every applied force results in a reaction force on the applier.
> This reaction force is equal in magnitude but opposite in direction
> to the applied force.

The skydiver pushes downward on the ground; the ground pushes upward on her. The skateboarder pushes to the right on the wall; the wall pushes to the left on him. Both objects involved in the interaction exert forces.

Newton's third law seems at once both simple and perplexing. The cliché "for every action there is an opposite and equal reaction" is a common expression of this principle. Yet many people will, after a little thought, ask the natural question: If for every applied force a reaction force of equal magnitude and opposite direction occurs, how can motion ever happen? Don't the two forces just cancel?

The answer lies in the relationship between the concept of force and the concept of interaction. When the skateboarder pushes against the wall, he interacts with it. The very nature of the interaction requires that the wall do something to the skateboarder. Newton's third law reminds us that this single interaction results in two forces. The two forces, however, act on different objects. The wall pushes the skateboarder, and the skateboarder accelerates. The skateboarder pushes on the wall, and the wall accelerates. Generally, the wall is so much more massive than the skateboarder that we do not see its ac-

Figure 7-10

The two forces are more obvious when both objects are of about the same mass. The boy pushes on the box; the box pushes on the boy. Both move apart.

celeration. If we replaced it with a box on another skateboard (Figure 7-10), the box would accelerate visibly.

Essentially, Newton's third law reminds us that momentum is conserved in a closed system. If we ignore the friction between the skates and the ground, the skateboarder and the box, along with their skateboards, form a closed system. Before the interaction, the skateboarder and the box are stationary. The total momentum of the closed system is zero. After the skateboarder pushes on the box, both are moving. Conservation of momentum requires that the total momentum of the system remain zero. As the skateboarder moves to the left, the box must move to the right. Newton's third law predicts the same result. As the skateboarder pushes on the box, the box pushes back.

Either Action Can Be the Reaction

The wall applied a force to the skateboarder when the skateboarder applied a force to it. This sounds strange, because we think of pushing as a voluntary act. The skateboarder decides to push the wall in order to accelerate backward. You might well ask how the wall "knows" when to push back. The answer lies in what happens to an object during an interaction. If you step on a bed, you see and feel a change in it. As you sink down, the springs compress until they create a force that balances your weight. It is easy to see that a very flexible object like a spring pushes back on you as you push on it. On a soft, plush carpet you feel a similar, but smaller, compression as you walk. On a wooden floor you barely feel the compression, but compression forces are still present, pushing back on you. Whenever an object is compressed or stretched, it pushes or pulls on whatever is compressing or stretching it. The wall pushes back on the skateboarder because it is being compressed slightly.

When two objects interact, the forces they exert on each other occur at the same time. Newton's third law does not specify which of the two is the action force and which is the reaction force—as far as Newton's third law is concerned, there is no difference. We ordinarily describe forces exerted by people as action forces because this fits our image that forces arise from voluntary acts. However, when calculating the effects forces have, we could just as well say that the wall pushing on the skateboarder is the action and the skateboarder pushing on the wall is the reaction. Action-reaction pairs are symmetrical.

Walking Away

Newton's third law explains the process by which we walk. Every time you take a step, your foot exerts a force on the floor. When you push on the floor to the left, the floor distorts slightly and pushes you to the right. If this is the only force acting on you, you accelerate to the right. The floor is quite massive, so its acceleration to the left is too small to be noticed. However, if you have ever walked on a treadmill or stepped on a loose roller skate, you know how difficult motion is when the floor does accelerate!

The force that the floor exerts on your foot arises from frictional interactions. We can push on the floor and the floor can push back because friction causes our foot to "stick" to the floor and, thus, push back on it. When you walk on waxed surfaces or ice, the importance of friction becomes more apparent. If friction is small, our foot just keeps moving backward as we try to step forward rather than compressing the surface.

SELF-CHECK 7D

In Chapter 6 we used conservation of momentum to describe what occurs when a person tries to step from a boat. Use Newton's third law to describe the same event.

ALL THREE LAWS

While we have discussed each of Newton's laws separately, realistically we must combine them when we analyze most interactions. As an example, consider a common event—throwing a ball up and catching it.

The first step is to identify all the forces acting on the ball. There are three: (1) contact interaction between the ball and your hand, (2) contact interaction between the ball and the air, and (3) interaction at a distance between the ball and the earth. While all three forces act at some point during the ball's motion, at no point do all three forces act simultaneously. The force due to gravity acts on the ball continuously. The contact force you exert with your hand acts only while the ball is in direct contact with your hand—while you are holding it, throwing it up, or catching it. The third force, air resistance, acts only while the ball is actually moving through the air. Figure 7-11 and Table 7-2 summarize the various stages of the ball's motion and which forces act during each stage.

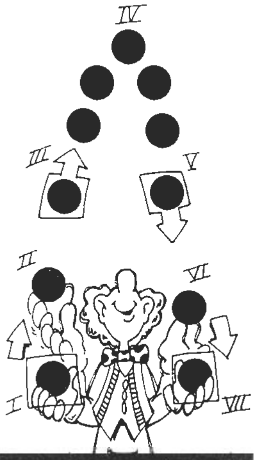
Newton's first law tells us that when the net force acting on an object is zero, the object does not accelerate. This occurs at two points—right before you throw the ball up and right after you catch it. As you hold the ball in your hand, your hand pushes up with just enough force to balance the downward force due to gravity. The net force is zero and the ball remains at rest.

Newton's second law tells us that when a net force acts on an object, the object accelerates. The ball accelerates as it is thrown upward, as it moves through the air, and as it is caught. Each of these stages involves a different set of forces, so we examine each stage separately.

While holding the ball (I), your hand exerts an upward reaction force which balances the downward force on the ball due to gravity. To throw the ball up (II), you use your muscles to increase the force you exert with your hand, so that the upward force is greater than the downward force. The ball accelerates upward because a net force acts upward. When you catch the ball, the same forces are involved. In order to stop its downward motion, a net force again must be applied upward. When the downward-moving ball touches your hand (VI), it pushes your hand down, a small distortion occurs, and your hand exerts a reaction force upward on the ball. This upward force exceeds the downward force due to gravity. Since a net force that opposes the motion of an object will cause it to decelerate, the ball slows to a stop. Then, the force supplied by your hand once again balances the force due to gravity (VII).

Once the ball leaves your hand, the only forces acting on it are the force due to gravity and the force of air resistance. As the ball moves upward (III), both forces act downward. The net force opposes the motion of the ball and it gradually slows down. In fact, it stops momentarily at the top of its path (IV). Once the ball starts moving downward, the force of air resistance acts upward, while the force due to gravity acts downward. The downward force due to gravity is greater than the upward force of air resistance. The net force is still downward and the ball accelerates downward (V).

Figure 7-11
We can look at the forces acting during several stages in the ball's motion.



SELF-CHECK 7E

We can add some numbers to our discussion of the ball's motion. Let the mass of the ball be 2 kg; the force due to gravity be 19.6 N; and the force of air resistance be 0.5 N. What is the ball's acceleration as it moves upward? Downward? Why are these two values different?

Table 7-2 Summary of Ball's Motion

Stage	Interaction Force(s) up	 Force(s) down	Net Force	Acceleration	Description of Motion
I Resting in hand	Contact (hand)	Gravity	None	None	Ball has no motion.
II During throw	Contact (hand)	Gravity	Up	Up	Ball accelerates upward as it leaves your hand.
III Moving up	None	Gravity Air resistance	Down	Down	Ball's upward velocity decreases.
IV At top of flight	None	Gravity	Down	Down	Ball's velocity is momentarily zero as it stops moving upward and begins to move downward.
V Moving down	Air resistance	Gravity	Down	Down	Ball's downward velocity increases.
VI During catch	Contact (hand)	Gravity	Up	Up	Ball's velocity decreases to zero.
VII Resting in hand	Contact (hand)	Gravity	None	None	Ball has no motion.

So far we have looked at a variety of interactions that could be described in terms of force. All the interacting objects exerted forces. But we have avoided an important question—just what causes these forces? Cement floors, rugs, tile floors, grass—all exert frictional forces on moving objects, but just what is friction? Are there as many forces as there are objects to exert them or can we categorize these forces into just a few major kinds? The attempt to simplify the classification of observed forces is centuries old. It is also the subject of Chapter 8.

CHAPTER SUMMARY

Newton's three laws describe the motion of any object upon which a force acts. *Newton's first law* states that when the net force acting on an object is zero, the object's momentum does not change. If the object is stationary, it remains stationary. If the object is moving, it continues to move in the same direction at a constant speed. This behavior is sometimes called *inertia,* which is a property of an object. Objects which have more than one force acting on them but a net force of zero are said to be in *equilibrium.*

Newton's second law states that the net force acting on an object is equal to the product of the object's mass and its acceleration. This means that when the net force is not zero, the object must accelerate. A net force can result in a change in speed as the object moves along a straight-line path. A net force can also produce motion along a curve—that is, a change in the direction of motion. A *centripetal force* is a net force that acts toward the center of a circle, causing an object to move at a constant speed along a circular path.

Because we experience motion in terms of a reference frame, the acceleration of a reference frame can make us feel that forces are exerted when in reality no force exists. These forces, called *fictitious forces,* arise from the acceleration of the reference frame without acceleration of the object in the reference frame. When a car stops suddenly, we say that we are "thrown" forward. The real force acts on the reference frame, the car. The "force" on us is fictitious—we continue moving forward because of inertia, or Newton's first law. A fictitious force is always perceived as acting in the opposite direction to the real force. *Centrifugal force* describes the fictitious forces we feel when a centripetal force actually acts on the reference frame.

Newton's third law states that forces always occur in pairs. When you push on the wall, the wall pushes back on you. An applied force is always accompanied by a reaction force equal in magnitude but in the opposite direction. The applied force and the reaction force always act on different objects.

ANSWERS TO SELF-CHECKS

7A. The seat belt enables the force that stopped the car to be transmitted to your lap. Your head and shoulders, however, have no net force acting on them. According to Newton's first law, they continue to move forward until a net force acts on them, typically when your head strikes the dashboard.

7B. In all three cases, the net force and the acceleration are toward the center of their circular motion. The force exerted on the gymnast is applied by the bar. The force exerted on the Ferris wheel is supplied by the axle. The force exerted on the car is supplied by the friction between the tires and the road.

7C. When the car suddenly turns left, the drink moves to the right relative to the car. In a reference frame attached to the road, the drink continues to move forward while the car turns to the left. Observers in the car will report that a centrifugal force pushes the drink away from the center of the turn.

7D. In stepping from the boat, the person applies a force that pushes the boat backward. According to Newton's third law, the boat exerts a force of equal magnitude, but in the opposite direction, on the person. The person moves forward while the boat moves backward.

7E. Moving upward: **Net force** = 19.6 N, down, + 0.5 N, down, **Net force** = 20.1 N, down = (m)(**a**); **a** = (20.1 N, down)/(2 kg) = 10.05 (m/s)/s, down. Moving downward: **Net force** = 19.6 N, down, + 0.5 N, up, **Net force** = 19.1 N, down = (m)(**a**); **a** = (19.1 N, down)/(2 kg) = 9.55 (m/s)/s, down. The acceleration is different because the force due to air resistance acts with the force due to gravity as the ball moves upward and against the force due to gravity as the ball moves downward.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the following terms:
Inertia
Equilibrium
Centripetal acceleration
Centripetal force
Centrifugal force
Fictitious force

A2. State each of Newton's three laws.

A3. How are inertia and Newton's first law related?

A4. What is the acceleration of an object that is in equilibrium?

A5. Must an object's velocity be zero if no forces are applied to it? Why or why not?

A6. Why must an object moving in a circle be accelerating even if its speed is not changing?

A7. Why do people say that they are thrown to the outside of a car traveling around a curve?

A8. What must be happening to a reference frame if a fictitious force is present?

A9. If Newton's third law is correct, why is every force not canceled by its reaction force?

A10. How is Newton's third law related to momentum conservation?

B. Using the Chapter Material

B1. A loose item on the shelf behind the back window of a car can become a deadly missile in a collision. Explain why in terms of one or more of Newton's laws.

B2. As you are turning a corner on a bicycle, a strap holding a package on the back breaks. Draw and explain the path of the package after it leaves the bicycle.

B3. A spaceship is motionless relative to a nearby star. The engines on the rear of the spaceship are fired for 3 minutes and then turned off. Describe in words the forces on the spaceship, the acceleration of the spaceship, and the changes in velocity that the spaceship experiences while the rockets are being fired and immediately after they are turned off.

B4. If the spaceship in Problem B3 has a mass of 2000 kg and its engines apply a force of 8000 N to the rocket, what is the acceleration of the rocket during the first 3 minutes? What is its acceleration after the first 3 minutes?

B5. To study the effects of weightlessness on equipment to be used in space, NASA drops it down a six-story shaft near Cleveland. While the equipment is falling, experiments are performed. Why does this procedure allow NASA to evaluate how the equipment will perform in space?

B6. One of the authors of this book was eating a meal on an airplane when the airplane suddenly dropped about 500 m. When describing the event later, the author said, "The plate flew up in the air." Describe the reference frame he used and its motion.

B7. When fuel is expelled from a rocket, interactions inside the rocket push the exhaust out the back of the rocket. Use Newton's laws to explain why the rocket moves forward.

B8. When you are standing on the floor, you are being pulled downward by gravity. What is the size of the force pulling down? However, you are not accelerating. What is the size of the force pushing up? What object applies this force?

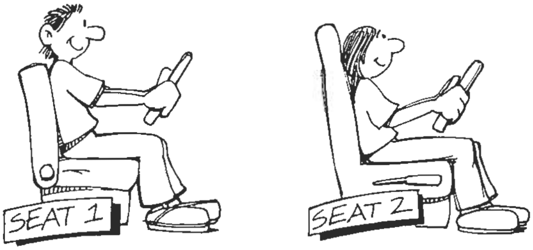
B9. Momentum conservation tells us that a direct collision between a stationary and moving billiard ball will result in momentum exchange. The stationary ball begins to move and the moving billiard ball stops. Apply Newton's laws (particularly the third law) to this interaction to explain the observation.

C. Extensions to New Situations

C1. Whiplash is a serious neck and back injury which occurs in rear-end collisions. This injury usually happens to people who are in a stationary car that is hit from behind by another car.

a. When a car is hit from behind, what are the directions of the net force and acceleration on it?

b. Suppose a person is sitting in seat I (Figure 7-C1) during the collision. How does the force on the head differ from the force on the rest of the body?



c. How will the motion of the head differ from the motion of the rest of the body? (This difference causes the injury.)

d. Use Newton's laws to describe how whiplash injuries are decreased for passengers in seat II.

C2. During the spin-dry cycle of a washing machine, water leaves the clothes as they spin at a very high speed.

a. What is the direction of the force acting on the spinning clothes? What object applies this force?

b. If the clothes were not spinning, in which direction would they move?

c. The washing machine tub contains holes large enough to let water out but too small to allow the clothes out. Use Newton's laws to explain why the water separates from the clothes.

C3. The best way to use Newton's laws in analyzing two-dimensional motion is to treat each dimension independently. As an example, consider a bale of hay dropped from an airplane to cattle stranded by bad weather. The airplane travels horizontally at a constant velocity of 20 m/s, east. The bale has a mass of 20 kg.

a. While the bale is attached to the plane, what are the magnitudes of the net horizontal and vertical forces acting on it?

b. What are the horizontal and vertical

speeds of the bale just before it is released?

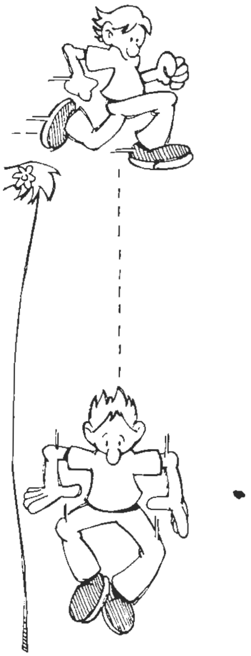
c. After the bale has been released, does a horizontal force act on it? A vertical force?

d. If we neglect air resistance, what will be the bale's horizontal speed throughout its flight? Explain why.

e. In what direction will the bale accelerate?

f. Use your answers to sketch the path of the bale as it moves from the airplane to the ground.

C4. On Saturday morning cartoons, characters frequently run off cliffs. Usually the animator shows a character running horizontally until it notices that it has no support. Then, the character falls straight down, as shown in Figure 7-C4. Use Newton's laws to explain why this motion is impossible.



C5. The questions below ask you to apply Newton's laws to see if you could "pull yourself up by your own bootstraps." (Ignore the downward pull of gravity because it is balanced by the reaction force of the floor.)

a. Suppose that you grab the shoes you are wearing and pull upward with a force of 50 N. What is the force up?

b. What is the reaction force down?

c. What is the net force on your shoes?

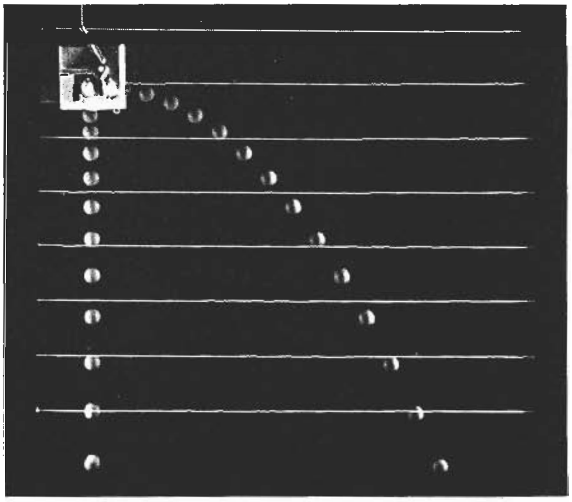
d. Why do you not move?

C6. Figure 7-C6 shows the motion of two balls. One is dropped straight down; the other is given a push to the right at the start of its motion. Once the balls leave the table, gravity is the only force acting on them.

a. After the balls leave the table, what is the net force on each ball in the horizontal direction?

b. Why does the ball on the right keep moving to the right?

c. Why do the two balls accelerate downward at the same rate even though the ball on the right was given a little push to the right?



C7. Instead of being a perfect sphere, the earth bulges near the equator. That is, the distance from the earth's center to the poles is slightly less than the distance from the earth's center to the equator. Use Newton's laws to explain why.

C8. Rotating reference frames are considered the most likely way to simulate gravity in future space stations. In one design, the space station would be a big, spinning donut.

a. Use Newton's laws to describe the motion of objects inside the space station.

b. Which direction relative to the center of the space station would be up? Explain your answer.

C9. One of life's small frustrations is that an empty beverage glass is likely to remain intact when dropped. However, a full one almost always breaks. To explain why, consider two identical glasses, each with a mass of 1 kg. One glass is empty; the other one contains 1 kg of water. Suppose both glasses are dropped so that they are in the air for 0.5 s.
   a. Use the equation speed = magnitude of acceleration × time to determine the speed of each glass just as it reaches the floor. What is the momentum of each glass just as it reaches the floor?
   b. What object applies the force to stop the glasses?
   c. If the glasses are stopped in 0.01 s, what force is applied to each? (Give both the magnitude and direction of the net force.)
   d. Why is the full glass more likely to break?

C10. To see the connection between momentum conservation and Newton's third law, consider once again the collision between moving and stationary billiard balls. For the purposes of this question, assume that each ball has a mass of 0.5 kg and that they are in contact for 0.01 s. Before the collision, ball A has a velocity of 1 m/s, east; ball B has a velocity of 0 m/s.
   a. Describe the horizontal forces on each ball before, during, and after the collision.
   b. What is the momentum of ball A before and after the collision?
   c. What is the momentum of ball B before and after the collision?
   d. What is the magnitude and direction of the force applied to ball B during the interaction? What object applies this force?
   e. What is the magnitude and direction of the force applied to ball A during the interaction? What object applies this force?
   f. In terms of Newton's third law, why must the decrease in momentum of ball A always equal the increase in momentum of ball B?

C11. When you jump off a chair and land on the earth, you could apply a force of 1000 N to the earth. In return the earth pushes back with a force of 1000 N. To see why you do not notice the earth moving backward, answer the questions below.
   a. If your mass is 60 kg, what acceleration do you experience when the earth pushes on you with a force of 1000 N?
   b. The mass of the earth is 6×10^{24} kg. What is its acceleration when you push on it with a force of 1000 N?
   c. Suppose all 5×10^{9} people on earth jumped right now. What would be the earth's acceleration?
   d. If, somehow, we moved all these people to one side of the earth and they all jumped together, what would the earth's acceleration be?

D. Activities

D1. How must realistic stage or movie fight scenes include Newton's laws? Develop a set of stage directions for a fight scene that includes proper accelerations for each force.

D2. Stand on a bathroom scale in an elevator. Describe and explain the changes in your weight as the elevator starts and stops.

D3. The force due to gravity has an effect on the evolution of life. For example, a hopping animal such as a kangaroo would require smaller leg muscles on the moon than on the earth. Design animals or plants that could live in the gravitational environment of Jupiter and those that could live on the moon. Explain your designs in terms of Newton's laws.