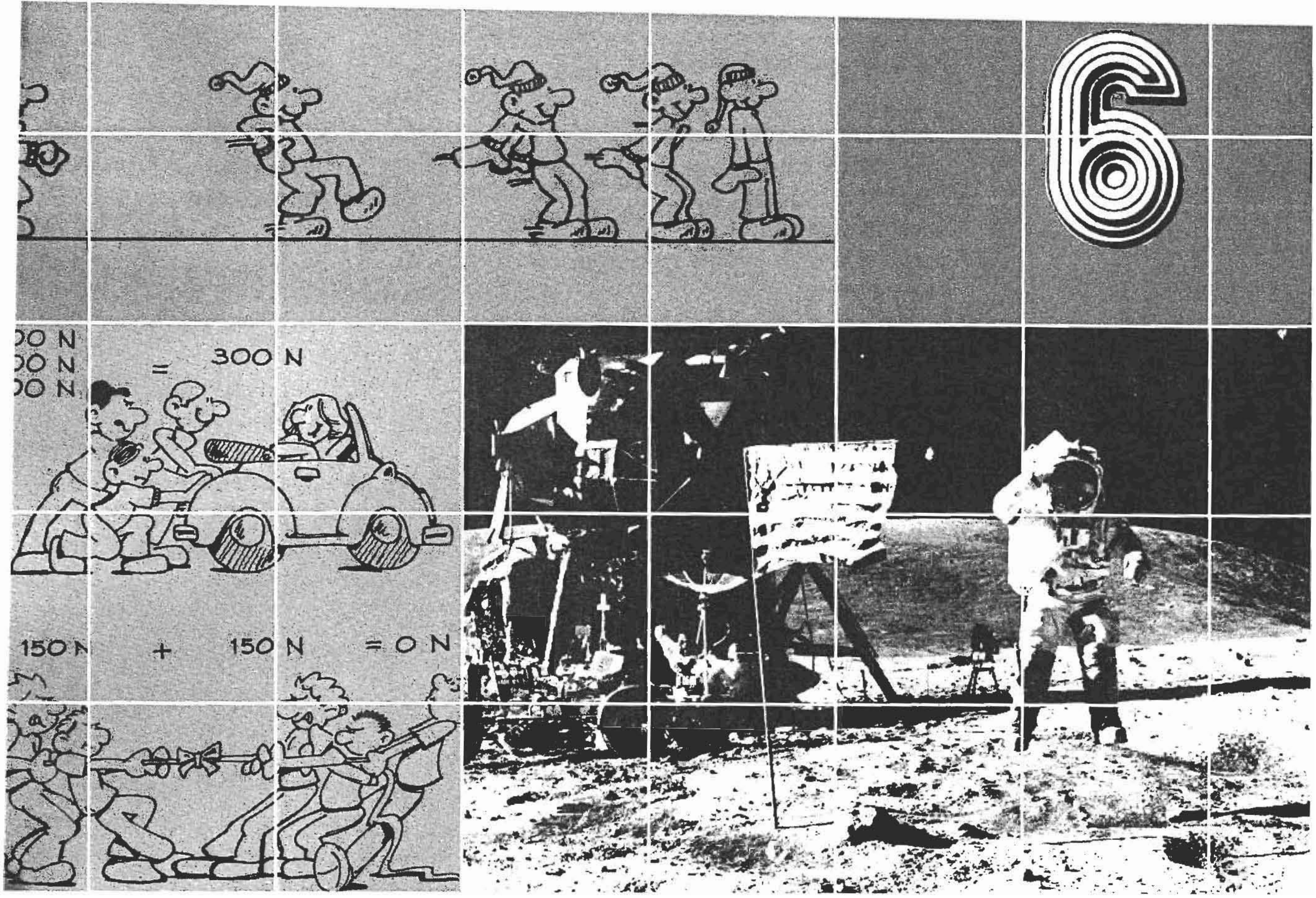


Interaction and Force

Your father graduated from West Point. Your grandfather graduated from Annapolis. The Army-Navy game is today. Where do you sit? Which side do you support? Aaaaaahhhhhh!

Your political science instructor has just assigned two chapters to be read by tomorrow. You have a quiz in history and a theme due in English composition. You cannot possibly get all this work done in one evening. Help!

Forces—pushes and pulls—are so much a part of the physical world around us that we use these words to describe social situations too. You are caught in the middle, pulled by your father's allegiance to West Point and your grandfather's allegiance to Annapolis. Too many instructors are pushing you to get things done. With all these forces pulling and pushing you in different directions, you are going crazy. In social as well as physical interactions, a force is something exerted by one interacting object on another—on you, in the situations just described.

In Chapter 5 we described physical interactions in terms of the concept of momentum. While the momentum of each object changes during an interaction, the total momentum of a closed system remains constant. In this chapter we shift our attention from the system to individual objects within the system. We introduce the concept of *force* to explain the change in momentum of an individual object. When more than one force acts on the object, these forces are combined to produce a *net force.* We discuss *Newton's second law,* which relates the net force acting on the object to the mass and acceleration of that object.

FORCES-A FIRST LOOK

We often build an intuitive understanding of concepts long before we encounter their more formal definition. A concept like momentum, for example, emerges while playing billiards. When the cue ball strikes the 10-ball, "something" is exchanged. People may describe this thing differently, but they share an intuitive understanding gained from a common experience. Eventually we agree on a concept, like momentum, that supplies the needed vocabulary. Physicists then develop a more formal definition consistent with other concepts or principles in their field. When faced with these more formal definitions, we have to modify our intuitive ideas.

Force, like momentum, is a concept for which we have an intuitive definition. Our bodies provide sensations that report both when we exert a force and when a force is exerted on us. Before tackling the formal definition of force, we examine these intuitive ideas.

Pushes and Pulls

Force is commonly defined as a push or a pull. Physiologically, we detect forces through contractions or extensions of our muscles. When you open a door, you pull on it. The contractions of your biceps let you know that you are exerting a force. When you lift a glass of water, push on a piano, or pull a sled, similar sensations contribute to your intuitive sense of force. Other pushes and pulls do not involve us. A tow truck pulls a stalled car; gravity pulls a rocket back to earth; socks just removed from the dryer cling (are pulled) to one another. All these objects are involved in pushing and pulling-in exerting forces.

Pushes and pulls enable us to measure force. The instrument most commonly used to measure force is the **spring scale.** Forces either compress or extend a spring, which, in turn, moves a dial. When you stand on a bathroom scale, the pull of gravity on your body (also called your weight) causes a spring to be compressed. This compression results in a change in the dial on the scale. The force of gravity on your body, measured in pounds, appears on the scale. In the metric system, force is measured in units called *newtons.* One **newton** (N) is roughly equivalent to the force of gravity on a stick of butter, or about one quarter of a pound. Figure 6-1 shows several common forces and their approximate size in newtons.

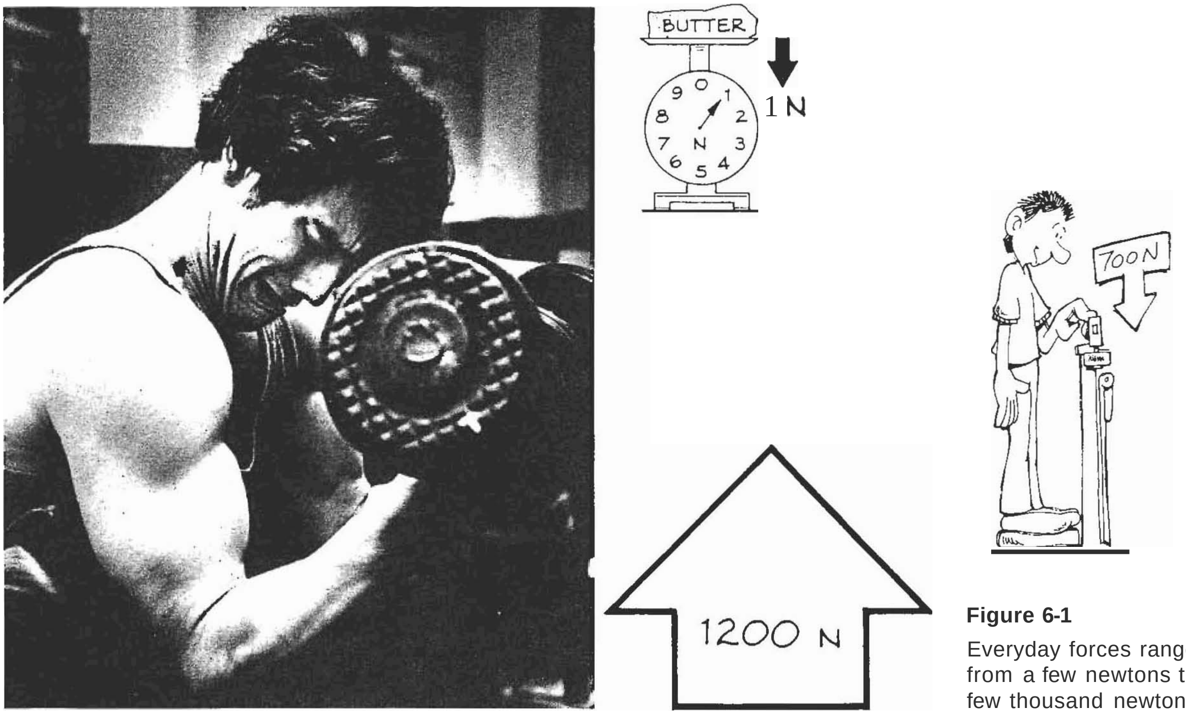


Figure 6-1

Everyday forces range from a few newtons to a few thousand newtons.

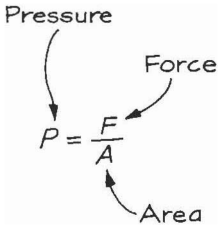
Pain, Pleasure, and Pressure

While muscular compressions and extensions provide the physiological sensations that we notice as we exert forces, nerve impulses from the skin tell us when forces are exerted on us. These impulses range from pleasure to pain-from the sense of loving communicated by a kiss to the sense of anger communicated by a slap.

A small force applied through a pin or needle is painful, while the same force applied by the touch of a hand is pleasurable. The difference between these two situations is the surface area of the skin over which the force is exerted. A pin applies a small force over a very small area, resulting in pain. A hand can apply the same force over an area 400,000 times greater, resulting in pleasure. Rather than sensing just the force, we feel a combination of force and area, called pressure.

Pressure is defined as the ratio of the applied force to the area over which it is applied:

$$\text{pressure} = \frac{\text{magnitude of force}}{\text{area of application}}$$



Pressure is measured in units of newtons per square meter, which is usually written N/m^2. The English unit of pressure is pounds per square inch Ob/in.^{2}).

Table 6-1 Some Common Pressures

Event	Approximate Pressure (N/m^2)
"Peck" on the cheek	300
Kiss	500
Pat on the back	600
Slap on the face	5000
Auto shoulder harness during quick stop	2 X 10^6
Hypodermic syringe as it punctures skin	5 X 10^6
Blow that fractures a skull	5 X 10^7

We can use the definition of pressure to compare sensations of pain and pleasure. The pressure exerted by a 10 N force applied over the area of a pinhead (8 X 10^{-7}) square meters (m^2) is (10 N)/(8 X 10^{-7} m^2) = 1.25 X 10^7 N/m^2. The pressure is enormous! The same force applied over the area of a hand (0.02 m^2) is (10 N)/(0.02 m^2) = 500 N/m^2. Spreading the force out over a larger area decreases the pressure substantially. Table 6-1 lists common pressures we experience.

SELF-CHECK 6A

Which will result in greater pressure: 5 N applied by the pointed end of a pencil (area, 7 × 10^{-7} m^2) or by the end containing the eraser (area, 2 X 10^{-4} m^2)? If you try it, **be careful.** High pressures will puncture your skin.

FORCE AND CHANGE IN MOMENTUM

The strobelike drawings in Figure 6-2 represent a man wearing shoes while sliding across an ice-covered lake. He slides easily, traveling about five meters before coming to a stop. Collisions between his shoes and thousands of small bumps in the ice surface gradually slow him down. When we apply momentum conservation to each collision, we conclude that the ice accelerates to the right as the man slows down. The mass of the ice-earth system is so large, however, that we simply do not notice this motion.

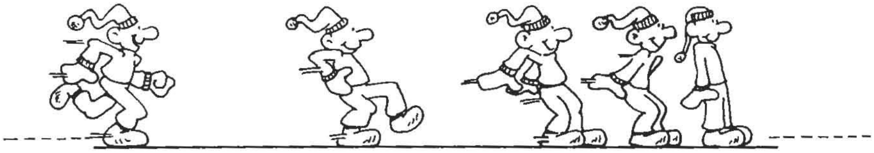


Figure 6-2

The ice exerts a force that slows the man to a stop.

Now, cover the bottom part of the figure by placing a piece of paper along the dotted lines on each side of the drawing. You can still see successive images of the man, but you can no longer see the contact between the man and the ice. Yet you still know that the man is interacting with something. As successive images of the man get closer together, you imagine something slowing him down. While we do not know what other objects are involved, we do know that an interaction has occurred.

By covering the ice with the paper, we focus our attention on just one part of the interaction-the man. We explain the change in his motion by saying that something is exerting a force on him. In so doing, we replace the many collisions between the man's shoes and the surface of the ice with a single abstract quantity-a force. Let's examine how force is defined in terms of the man's change in momentum.

Force and Time Interval Affect Change in Momentum

Figure 6-3 represents the same man sliding across an ice-covered lake and across a waxed tile floor. In each example the man wears the same shoes, begins with the same momentum, and eventually slides to a stop. The change in his momentum is identical on the two surfaces. Only the surface on which he slides is different. This, in turn, affects how long and how far he slides. On ice he slides further and longer than on tile.

We can use the concept of force and the stopping time to describe the man's change in momentum. Both the ice and the tile floor exert forces that slow the man down. From experience and our intuitive feeling for forces, we expect the force exerted by the tile floor to be greater than the force exerted

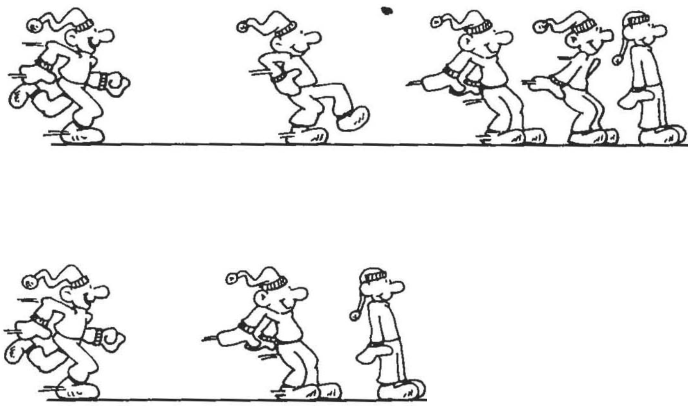
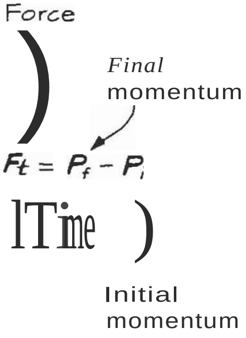


Figure 8-3

The tile floor exerts a greater force than the ice. The man slides for a shorter distance and a shorter time on the tile.

by the ice. As illustrated by Figure 6-3, the greater force exerted by the tile causes the man to slide a shorter time, and hence a shorter distance, than the lesser force exerted by the ice. Given identical starting momenta, a large force leads to a short stopping time, while a small force results in a long stopping time.



This relationship is generalized in an equation first suggested in the seventeenth century by Isaac Newton:

force X time = change in **momentum**

The change in momentum of an object is equal to the product of the force applied to it and the time interval during which the force is applied. When the force is measured in newtons and the time in seconds, the change in momentum is measured in kilogram-meters per second (kg· *m/s)*.

Design Affects Force

To see how well this relationship among force, time, and momentum fits our experiences, we apply it to catching a baseball, first barehanded, then with a catcher's mitt, and finally with a net like that used to protect the fans behind home plate. The ball moves in one direction; you or the net exert a force in the opposite direction to stop it. Suppose a 0.15 kg ball moves at a velocity of 33.3 *mis,* east, before it is stopped. Its initial momentum is (0.15 kg) *(33.3 mis,* east) = 5 kg . *mis,* east. Its final momentum is a kg . *m/s.* Consequently the change in momentum is −5 kg . *mis,* east. We could just as easily say that the change in momentum is 5 kg . *mis,* west.

Table 6-2 lists the force exerted and the time interval required to stop the ball. Comparing these quantities confirms our experiences. The pain is much smaller with a catcher's mitt because the force we must exert is much less. The padding sinks when struck by the ball, increasing the time interval over which the ball's momentum must be decreased to zero. This, in turn, decreases the force we need to exert. The net, because it sinks back even

Table 6-2 Force and Stopping Time in Catching a Baseball

Method	Change in Momentum of Baseball	Time Interval	Force
Bare hand	5 kg· *mis,* W	0.0006 s	8333 N, W
Catcher's mitt	5 kg· *mis,* W	0.003 s	1667 N, W
Net screen	5 kg· *mis,* W	0.03 s	167 N, W

Courtesy Insurance Institute for Highway Safety.

Figure 6-4

Air bags increase the stopping time, thus decreasing the force exerted in stopping the passenger's forward motion.

further when struck by the ball, must exert an even smaller force. As the time interval required to stop the ball increases, the force that must be exerted decreases.

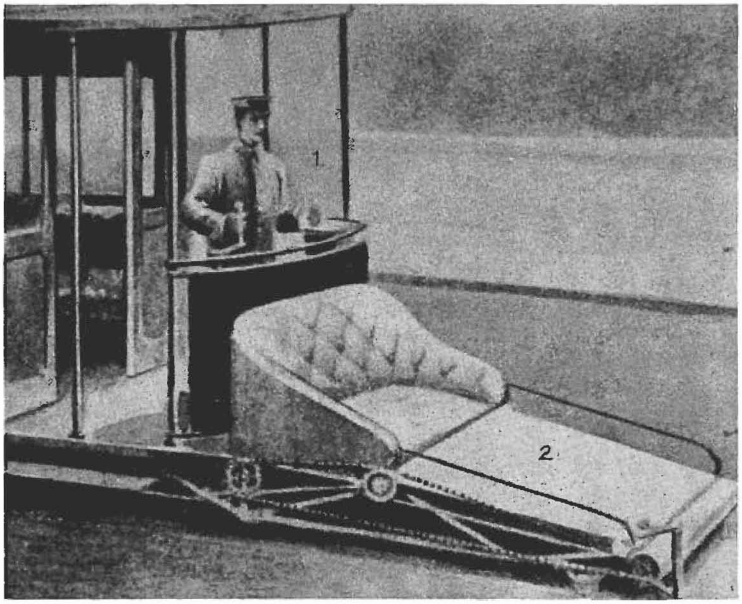
As another example, try dropping an egg on the floor. The hard floor "gives" very little, so the momentum of the egg must change in a very short time interval. Short time interval, large force: scrambled egg. If, on the other hand, we wrap foam rubber around the egg and then drop it, the egg does not break. The foam gives quite a bit, increasing the time interval in which the momentum of the egg must go to zero. Long time interval, small force: whole egg.

Air bags used in some automobiles are designed with the same concept in mind. When an automobile collides with some obstacle, its momentum is abruptly brought to zero. Passengers who are not wearing seat belts or shoulder harnesses collide with the dashboard, windshield, or steering wheel. The forces these objects exert depend on the time during which the collision takes place. Padding added to dashboards increases the stopping time (and safety) slightly, but passengers often collide with the windshield anyway. The air bag (Figure 6-4) is designed to provide additional protection. As soon as a switch on the automobile senses a sudden change in momentum, the air bag inflates and the partially filled bag provides a soft place to stop the passenger's motion gradually. Because a long stopping time decreases the force that must be exerted on the passenger, fewer broken bones result.

SELF-CHECK 68

Use the relationship between force and stopping time to explain why the Post Office recommends using lots of padding for packages containing fragile objects.

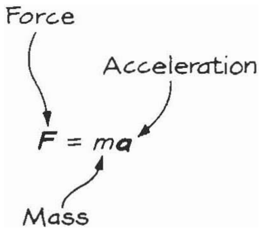
LENGTHENING THE COLLISION TIME WITH PEDESTRIANS



At the end of the nineteenth century, the accident rate between pedestrians and street cars was quite high. Since the pedestrians seemed uninterested in getting out of the way of the trams, an alternative solution was invented. The tram (1) would push a padded couch (2) in front af it. When an unobservant walker wandered in front of the moving tram, the person would collide with the front of the couch and fall into it. Because af the padding, the interaction time with the couch would be large. Thus, the momentum of the person would change gradually, keeping the force small. This device was tested in Los Angeles. Unfortunately far the inventor, the first test case fell and missed the couch. Instead, he struck the pavement, where the interaction time was very small and the force quite large. After that, Los Angeles pedestrians were on their own and eventually learned to watch out for trams and other horseless vehicles.

A Formal Definition of Force

The relationship between force, mass, and momentum first suggested by Newton provides us with a definition of force that is a bit more specific than the pushes or pulls with which we opened the chapter. This definition can be expressed in several different ways (see the box on page 115), but the most common form relates force to acceleration. The **force** exerted on an object is equal to its mass times its acceleration:



force = mass X **acceleration**

When the mass is measured in kilograms and the acceleration in (meters per second) per second ((mjs)j s), the force is given in newtons. (We define 1 N to e 1 kg . (m/s)/s). Force is a vector whose direction is the same as the direction in which the object accelerates. A force that acts in the same direction as he object's motion produces a positive acceleration-the object speeds up. A orce that acts in the opposite direction produces a negative acceleration-he object slows down. Forces in other directions can cause changes in both he magnitude and direction of the velocity.

To see how to apply this definition, look back at the man who slides to a stop (Figure 6-3). On ice, the man slows down at a rate of 0.625 (m/s)/s; his acceleration is 0.625 (m/s)/s to the left. Given that the man's mass is 70 kg, the force exerted by the ice is (70 kg)(0.625 (m/s)/s, left) = 43.75 N to the left. On the tile floor, the man's acceleration is greater-about 1.25 (m/s)/s to the left. Again applying the definition of force, we find that the tile floor exerts a force of (70 kg)(1.25 (m/s)/s, left) = 87.5 N to the left. The force exerted by the tile floor is twice that exerted by the ice. A concrete sidewalk would exert an even greater force-the man would slide to a stop even sooner.

In applying the concept of force, it is important to remember that mass and acceleration describe characteristics of the object itself, while force de-

A STEP FURTHER-MATH

A FORCE IS A FORCE IS A FORCE

When a law is broad enough to explain diverse phenomena, it is often written in several different ways to suit a variety of purposes. Newton's relationship can be used to describe force in at least three different ways. We begin with:

$$\textbf{force} \times \text{time} = \text{change in } \textbf{momentum}$$

We can rearrange this to isolate force on one side of the equation:

$$\textbf{force} = \frac{\text{change in } \textbf{momentum}}{\text{time}}$$

This was the expression with which Isaac Newton actually introduced the concept of force. Since the momentum of an object depends on its mass and velocity, either or both can change as a result of the force exerted on the object. Most of the time, however, the mass of an object remains constant and only its velocity changes. This allows us to write Newton's relationship in yet a third way:

$$\textbf{force} = \text{mass}\,\frac{\text{change in } \textbf{velocity}}{\text{time}}$$

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

All three describe the relationship between force and the motion of the object upon which the force acts. A force is a force is a force!

Figure 6-5

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scribes an interaction that occurred with some other object. Objects do not accelerate by exerting forces on themselves (Figure 6-5). Other objects exert forces on them, causing them to accelerate in predictable ways. Sometimes these other objects are obvious, and we are able to associate forces directly with the objects involved. In other situations we see an object accelerating and infer that a force must be present-even when it is not at all obvious what object exerts that force.

Force due to Gravity

Force due to gravity

Acceleration due to gravity

$F=mg$

(Mass

The most common application of our definition of force is the calculation of the force due to gravity acting on an object near the earth's surface. As described in Chapter 2, all objects experience an acceleration due to gravity near the surface of the earth. In the absence of other forces, this acceleration has been measured to be 9.8 (m/s)/s, down. We can use the definition of force to calculate the force due to gravity acting on a mass of 1 kg:

$$\begin{aligned} \textbf{Force} \text{ due to gravity} &= \text{mass X } \textbf{acceleration} \text{ due to gravity} \\ &= (1 \text{ kg})(9.8 \text{ (m/s)/s, down}) \\ &= 9.8 \text{ N, down} \end{aligned}$$

An object with mass of 1 kilogram experiences a gravitational force of 9.8 N, down, near the surface of the earth. An object with mass 2 kg experiences twice the gravitational force, or 19.6 N, down.

We can use this same procedure to determine the gravitational forces exerted by other planets or moons. For example, we can contrast the force due to gravity on the earth with the force due to gravity on the moon. On the earth, the acceleration due to gravity near the surface is 9.8 (m/s)/s, down. On the moon the acceleration due to gravity near the surface is 1.6 (m/s)/s, down. On the earth, an astronaut with a mass of 70 kg experiences a force due to gravity of

$$\textbf{force} = mg = (70 \text{ kg})(9.8 \text{ (m/s\}/s, down}) = 686 \text{ N, down}$$

Table 6-3 Acceleration Due to Gravity on Various Planets and the Moon

Solar Body	Acceleration Due to Gravity (m/s)/s, down
Moon	1.6
Mercury	3.3
Venus	8.1
Earth	9.8
Mars	3.6
Jupiter	24.3
Saturn	10.3

When the astronaut reaches the moon, the force due to gravity is:

$$\textbf{force} = mg = (70\ \text{kg})(1.6\ (mjs)js,\ \text{down}) = 112\ \text{N, down}$$

Table 6-3 lists the acceleration due to gravity for several different planets in the solar system, as well as the moon.

The force with which gravity acts on an object is called the object's **weight.** As illustrated in the example, an object's weight depends on the acceleration due to gravity on the planet on which the object is located. The astronaut has the same mass (70 kg) on both the earth and the moon. By contrast, the astronaut weighs 686 N on the earth but only 112 N on the moon. Even on the same planet an object's weight can vary slightly due to variations in the acceleration due to gravity. On the earth, for example, the acceleration due to gravity varies from 9.78243 (mjs)js, down, near the equator to 9.82534 *(mjs)js*, down, in Greenland. The astronaut's weight on the earth can vary from 684.8 N to 687.8 N. Admittedly small, such variations remind us that weight depends on location, while mass does not. Consequently, most physical laws are described in terms of mass.

Figure 6-6

On the moon the force due to gravity is one-sixth that on the earth.

SELF·CHECK 6C

The acceleration due to gravity on the surface of Jupiter is 24.3 (m/s)/s, down. What is the weight of the 70 kg astronaut on Jupiter?

KINDS OF FORCES

At any given moment, literally billions and billions of forces are acting. Some, like those you exert when you push or pull on something, are relatively simple to identify. Others, like the force the floor exerts on you, become obvious only when they are no longer present. Stepping through a rotten floorboard reminds you that there is usually something pushing back as you walk along the floor. Still other forces, like gravity, seem almost magical, since they need not involve any contact between objects at all. We now examine the general kinds of forces present in our environment.

Contact Interactions

The **forces from contact interactions** include pushes, pulls, and friction. Normally we are able to identify pushes and pulls simply by looking at the situation. When you open a door, the contact between your hand and the door allows you to identify a pull acting on the door. When a bulldozer pushes the dirt, the contact between the shovel and the dirt allows us to identify the push. When a person stands on the ice, the contact between the ice and the person allows us to identify the upward push exerted by the ice.

Friction also involves contact between objects, but it is more easily overlooked. Whenever two objects are in direct contact, either while moving or stationary, a frictional force acts between them. These forces always oppose any motion.

Frictional forces can be divided into two categories: static friction and kinetic friction. **Static friction** arises when two objects are stationary relative to each other. When you stand on a steep hill, for example, the ground exerts a frictional force along the surface that keeps you from sliding down the hill. When you push a car, the force you need to exert to get the car started rolling is more than the force you exert to keep it moving. Static friction opposes any start of motion. **Kinetic friction** arises when one object slides relative to another. When the man slides across the ice, the ice exerts a frictional force that eventually brings him to a stop, though this force is much smaller than the frictional force exerted by the tile. Kinetic friction is also present as objects move through gases or liquids. The most common example is the air resistance which acts to slow all moving objects in the earth's atmosphere. As the man slides across the ice, he is slowed by the kinetic friction of the air as well as that of the ice.

Interaction at a Distance

A second category is **forces that act at a distance.** So far, we have discussed only one such interaction, gravity. The force due to gravitational interactions is present between all masses, but the magnitude of the force depends on the size of the masses and their distance from each other. On the earth, we notice only gravitational interactions between a small mass (like ourselves) and a large mass (like the earth). Gravitational interactions between two small masses (such as yourself and a desk) are much too small to notice. On earth,

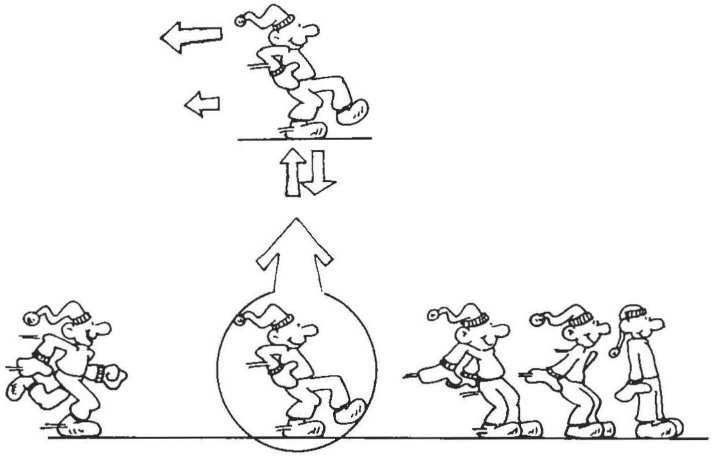


Figure 6-7

Four forces act on the man. The force due to gravity pulls the man downward. The ice exerts an upward force that balances the force due to gravity. The ice surface and surrounding air both exert frictional forces to the left.

the gravitational force always acts downward, pulling the small mass toward the earth's surface.

Three other kinds of interactions at a distance exist: electrical forces, strong nuclear forces, and weak nuclear forces. We discuss each of these in some detail in Chapter 8 and look at situations in which they act in later chapters dealing with electromagnetic, atomic, and nuclear interactions.

Identifying Forces

In analyzing interactions in terms of force, we are faced with the task of identifying the forces acting on an object. The two kinds of forces, contact forces and forces due to interaction at a distance, provide us with a two step process for accomplishing this task. Let's apply the process to the man sliding across the ice.

Although we described the man's motion in terms of a single force exerted by the ice, several kinds of forces are actually present, some of them exerted by the ice and some not. We first look for contact forces. The man is in direct contact with the ice and the surrounding air. His contact with the ice leads to the exertion of two forces-one to the left and a second upward. The ice exerts a frictional force that opposes the man's motion-as he slides to the right, the ice pushes back to the left. The ice also exerts a force upward to support the man. (As in the case of the broken floorboard, we often become aware of this upward force only when it is no longer present. We discuss the nature of this force in the next chapter.) The man is also in direct contact with the surrounding air, so air resistance acts to the left as he slides to the right. The only force due to interaction at a distance is the force due to gravity. The earth pulls the man downward toward its surface with a force equal to the man's weight.

As illustrated in Figure 6-7, four forces act on the man-the force due to gravity pulling downward, a force exerted by the ice pushing upward, and two frictional forces acting to the left. As you will see in Chapter 7, the force due to gravity is balanced by the upward force exerted by the ice, so the man does not move up or down. The two frictional forces, that due to air resistance and that exerted by the ice, slow the man down.

SELF-CHECK 6D

Identify the forces acting on an apple when it:

a. hangs from a limb on the tree

b. falls downward

MORE THAN ONE FORCE

Suppose you are standing by a fence. You see the tops of two refrigerators move by. as shown in Figure 6-8. Using only the information contained in the drawings. can you state which refrigerator is interacting with other objects?

If you use only these drawings and the ideas we have discussed so far. you must conclude that refrigerator B is interacting with another object, while refrigerator A is not. The images of refrigerator B become more closely spaced over time. Its momentum is decreasing. so something must be exerting a force to slow it down. The images of refrigerator A are equally spaced. Its momentum remains constant, suggesting that no force acts on it. Of course, your common sense tells you otherwise. Refrigerators don't just float down the street!

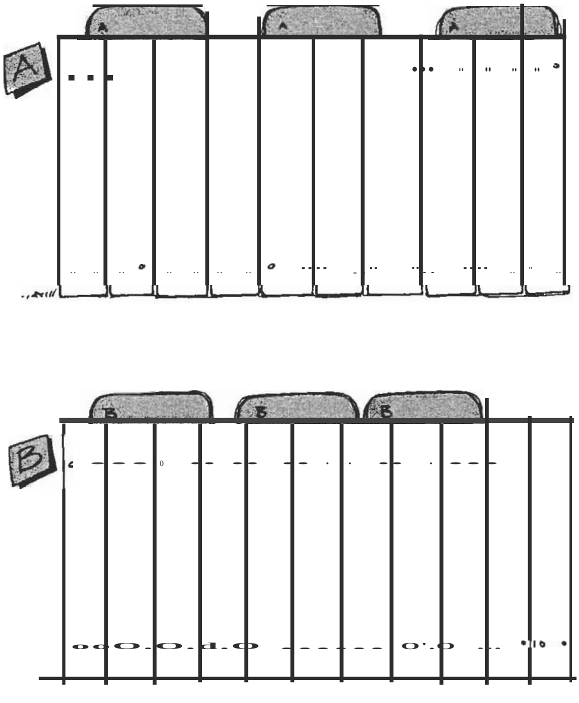


Figure 6-8

Based only on the drawings, which refrigerator is interacting with other objects?

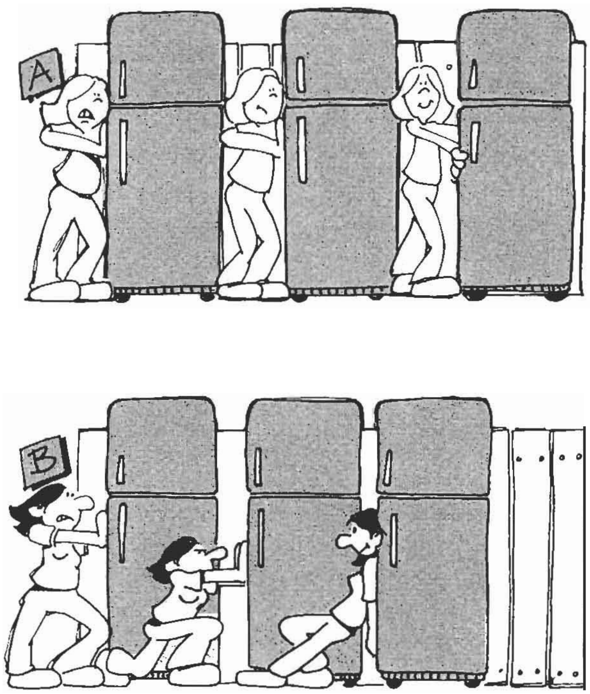


Figure 6-9

Both refrigerators are interacting with a number of different objects-the woman, the floor, and the surrounding air. In (a) the forces sum to zero. In (b) the net force acts to the left, so the refrigerator slows down.

From experience, we know that any moving refrigerator has someone pushing on it. As shown in Figure 6·9, people are pushing both refrigerators. To understand how forces can lead to no change in momentum as well as to some change in momentum, we must examine what happens when more than one force acts on the same object.

What Forces Act?

We can identify the forces acting on both refrigerators using the process described in the last section. First look for contact forces-pushes, pulls, and friction; then look for forces due to interaction at a distance.

As shown in Figure 6-9, five forces act on each refrigerator. Four contact forces exist: one force (a horizontal push) due to the contact provided by the person pushing the refrigerator, two forces (an upward push and friction) due to the contact between the refrigerator and the ground, and one force (friction) due to the contact between the refrigerator and the surrounding air. The fifth force, which acts at a distance, is the force due to gravity exerted by the earth. We can look at the way these forces combine by considering the forces that act vertically separately from those that act horizontally.

Looking at the forces that act vertically, we have the force due to gravity pulling the refrigerator downward and the contact force between the refrigerator and the ground pushing back upward. As in the case of the man on the ice, these vertical forces cancel. The refrigerator does not move vertically. Looking at the forces that act horizontally, we have the woman pushing to the right and two frictional forces, that of the ground and that of the air, pushing to the left. For refrigerator B, the woman pushes to the right with a force that is less than the two frictional forces exerted to the left. The refrigerator gradually slows down, much as the man sliding along the ice did. For refrigerator A, however, the woman pushes to the right with a force that is equal to the two frictional forces exerted to the left. Refrigerator A continues to move at a constant velocity.

When more than one force acts on an object, the combination of forces can produce motion at a constant velocity, motion with acceleration, or no motion at all. For both refrigerators, the two vertical forces combined to produce no vertical motion. For refrigerator A, the horizontal forces combined to produce motion at a constant velocity. For refrigerator B, the horizontal forces combined to produce a deceleration.

Net Force

To describe situations in which more than one force acts, we introduce the concept of *net force.* When we talked about the force that the ice exerts on the man, we really meant the net force—the sum of all the forces exerted by the ice. We can modify our definition of force accordingly, substituting net force for force:

$$\overset{\text{Net force}}{F_{net}} = \underset{\text{Mass}}{m}\overset{\text{Acceleration}}{a}$$

net force = mass X **acceleration**

Known as **Newton's second law,** this relationship can be used to predict the acceleration that results from one or several forces acting on an object.

The net force is the sum of all forces acting on an object. Since force is a vector quantity, we must keep track of directions as well as magnitudes. The concepts of vector addition introduced in Chapter 1 can be applied to forces as well as displacements. The net force that results from two or more forces acting in the *same* direction, Figure 6-10(a), is the sum of the magnitudes of the vectors. Three forces of 100 N, east, combine to exert a net force of 300 N, east. The magnitudes of forces that act in *opposite* directions must be subtracted, as shown in Figure 6-10(b). Forces of 150 N, east, and 150 N, west, exert a net force of 0 N. Forces that act at angles relative to one another, as in Figure 6-10(c), can be added using the tail-to-tip method. While the tail-to-tip method provides an excellent strategy for adding vectors, it is always a good idea to put your past experience to work in estimating the net force exerted. In Figure 6-10(c), for example, most people predict that a force of 10 N, north, and a force of 10 N, east, combine to exert a net force to the northeast.

To see how to apply Newton's second law, we return to the motion of the two refrigerators in Figure 6-9. No net force is acting on the refrigerators vertically. The upward force exerted by the ground just equals the downward force due to gravity. The net vertical force is zero; the refrigerators experience no vertical acceleration.

Each of the refrigerators has three forces acting on it horizontally. However, the net force acting on refrigerator A is zero, while that on refrigerator B is not zero. The force of friction exerted by the ground and surrounding air

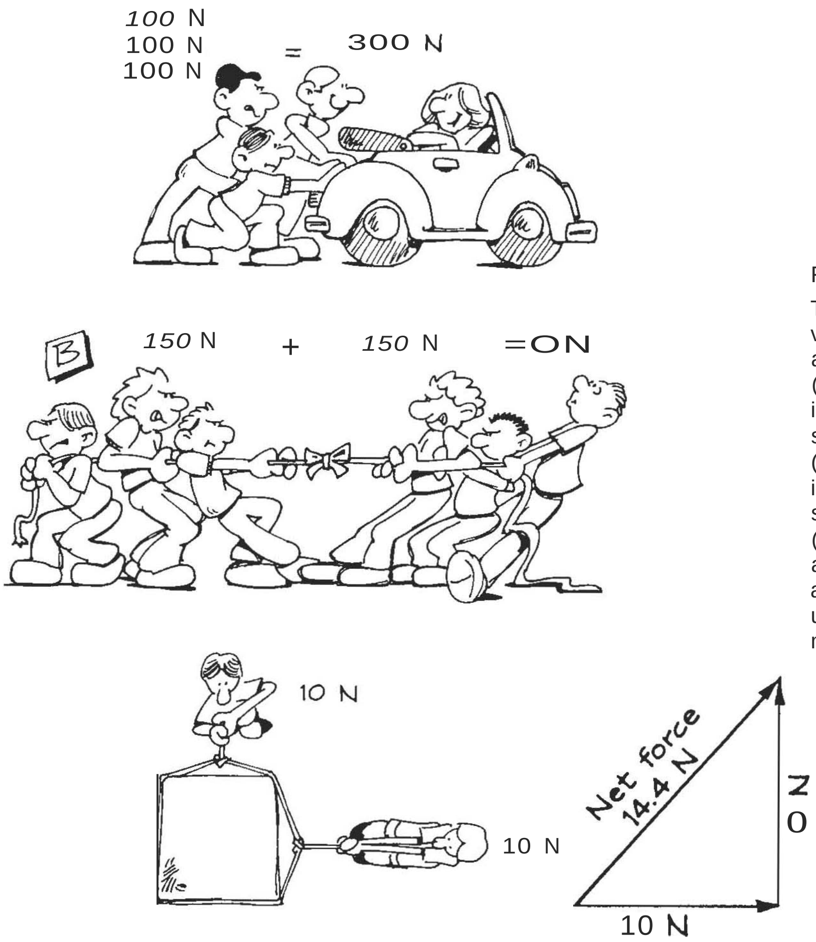


Figure 6-10

The net force is the vector sum of all forces acting.
(a) Forces that act in the same direction simply add.
(b) Forces that act in opposite directions subtract.
(e) Forces that act at right angles to one another can be added using the tail-to-tip method.

exceeds the force with which the woman pushes refrigerator B. The net force acts to the left, and refrigerator B slows down. By contrast, the woman pushes refrigerator A with a force that equals the force due to friction exerted by the ground and the surrounding air. The net force acting on the refrigerator is zero, and refrigerator A continues to move at a constant velocity.

Zero Net Force

As is evident from the two refrigerators, zero net force can result in either no motion or motion at a constant velocity. Intuitively, we know that no net force results in no motion. The cartoon in Figure 6-11 is funny because it seems absurd to us that the characters do not grasp this fact. The idea that zero net force can also result in motion at a constant velocity is not so obvious. From experience, most of us associate motion at a constant velocity with a force. We have to push a refrigerator in order to keep it moving at a constant velocity, and we generally assume that no other force is acting on it. What we have ignored, of course, is the frictional force against which we are actually pushing. The force we exert is balanced by the frictional force exerted by the

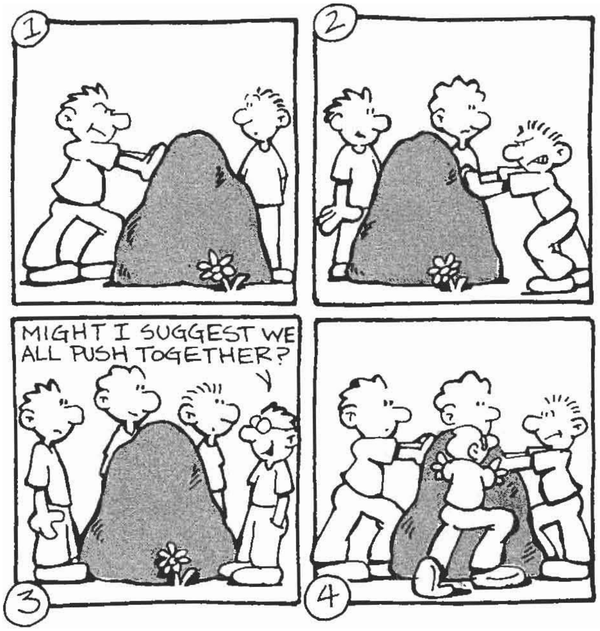


Figure 6-11

Why doesn't the rock move?

ground and the surrounding air, so that the net force on the refrigerator is zero.

Of course, to start a refrigerator moving we must exert a net force greater than zero. Each woman in our example must have initially exerted a force to the right greater than the net frictional force exerted to the left. When the refrigerators were not moving horizontally, a zero net force in the horizontal direction resulted in no motion. A zero net force in the horizontal direction also results in motion at a constant velocity. To keep a refrigerator moving once it has started, we need only balance the opposing forces.

You learned earlier in the chapter that the net force on an object equals the object's mass times its acceleration. A zero net force results in zero acceleration. This results either in no motion or motion at a constant velocity.

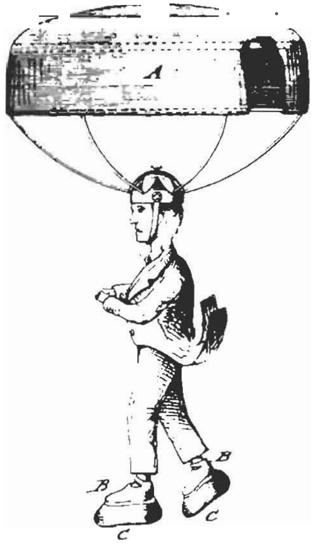
SELF-CHECK 6E

A child pushes a 10 kg wagon with a force of 10 N. The force of friction exerted by the ground and the surrounding air is 8 N. What is the net force acting on the wagon? What is the wagon's acceleration?

FORCE, ACCELERATION, AND THE SPEED OF LIGHT

Our definition of force must be modified somewhat to describe motion at speeds near the speed of light. If we apply a net force in the same direction as

OFF TALL BUILDINGS IN A SINGLE, SAFE BOUND



Net force and its relationship to momentum change and time were foremost in the mind of Thomas M. Prentiss when he designed the personal fire escape in 1873. When trapped by a fire in the upper levels of a multistory building, the owner of a personal fire escape could simply jump out the window. A parachute *(A)* attached to the head would act to slow the fall. The upward force of the air as it tried to move through the parachute would cancel some of the downward pull of gravity. Thus the net force downward on the person escaping the fire would be less than the force due to gravity. The acceleration would result in a sufficiently small speed to cause little harm on landing. To assure a safe landing, Mr. Prentiss included a pair of elastic padded overshoes *(B* and *C)*. These shoes would increase the time of the collision with the ground and, thus, decrease the force applied on the person by the ground.

an object moves, the object's velocity will increase. In most everyday situations, forces act for just a short time. But what if the force continues to act for a long time—say days or months? For example, if we push continuously on a 1 kg mass with a net force of 100 N (approximately the force you exert to hold a bowling ball), the low-speed definitions of force and acceleration tell us that the mass would be moving at the speed of light after 34 days. However, according to the special theory of relativity, objects cannot exceed the speed of light. Consequently, our definition of force must be altered somewhat to place a limit on the extent to which an object can be accelerated by a constant force.

The modification we make is in our concept of mass. At ordinary speeds, we imagine the mass of an object to be independent of the object's speed. A 10 kg wagon has a mass of 10 kg at rest, at 10 *m/s*, or at 100 *m/s*. Einstein suggested that such a concept simply does not work, although its limitations are not apparent until the object's speed nears the speed of light. He proposed that the mass of an object does depend on the speed at which it moves. The mass of a moving object, called the **relativistic mass,** increases as the object's speed increases.

This new definition of mass produces results that are consistent with our low-speed experiences but that alter our concepts at high speeds. Table 6-4 compares the low-speed and high-speed definitions of mass as an object moves at higher and higher speeds. At everyday speeds, the difference in mass is not noticeable. At around half the speed of light, however, we could start detecting the difference. The mass of a 1 kg object increases substantially as the object approaches the speed of light and becomes almost 71 kg at 0.9999 the speed of light. As objects travel at higher speeds, their masses increase.

This definition of mass places a natural limit on the extent to which an object can be accelerated. If a constant force, say 10 N, acts on an object, the object will accelerate. As the object's speed increases, however, its mass increases. Since the force is constant, an increase in mass must cause the acceleration of the object to decrease. As the object begins to move at speeds approaching the speed of light, its mass increases at an ever greater rate, and its acceleration becomes increasingly small. This means that though the velocity gets closer and closer to that of light, it never quite equals it. The relativistic definition of mass establishes a natural limit to the extent to which we can accelerate objects. No object can be accelerated to speeds that exceed the speed of light.

Table 6-4 Relativistic Mass at Various Speeds

Speed of Moving Frame			
Fraction of Light Speed	(m/s)	Rest Mass (kg)	Relativistic Mass (kg)
0.0001	3×10^4	1.00	1.000000005
0.001	3×10^5	1.00	1.0000005
0.01	3×10^6	1.00	1.00005
0.1	3×10^7	1.00	1.005
0.2	6×10^7	1.00	1.02
0.4	1.2×10^8	1.00	1.09
0.6	1.8×10^8	1.00	1.25
0.8	2.4×10^8	1.00	1.67
0.9	2.7×10^8	1.00	2.29
0.99	2.97×10^8	1.00	7.09
0.999	2.997×10^8	1.00	22.37
0.9999	2.9997×10^8	1.00	70.71

$$\text{mass} = \frac{\text{rest mass}}{1 - \frac{(\text{speed of mass})2}{(\text{speed of light})2}}$$

CHAPTER SUMMARY

The concept of force is used to describe situations in which we wish to focus our attention on just one of the objects involved in an interaction. A force is a description of the effect of an interaction on an object. Intuitively we define *force* as a push or a pull. When we exert forces, we feel the extensions and contractions in our muscles. When forces are exerted on us, we sense the pressure exerted on our skin. Force is measured in units called newtons; pressure is measured in units of newtons per square meter. *Pressure* is defined as the force exerted divided by the area over which the force acts.

When we focus our attention on just one of the objects involved in an interaction, the force times the time interval during which the force acts equals the object's change in momentum. More formally, *force* is the product of the mass of an object and its acceleration. Force is a vector quantity whose direction is the same as the direction of the object's acceleration.

Forces can be divided into two categories: contact forces and forces that act at a distance. *Contact forces* include pushes and pulls that arise from contact between objects, as well as frictional forces that oppose motion. *Forces that* act *at* a *distance* include gravitational and electrical forces and strong and weak nuclear forces. All objects exert gravitational forces on each other, but the gravitational pull exerted by small masses is too small to be noticed. A large mass, such as the earth, exerts a noticeable gravitational force downward on small objects near its surface. This force is called an object's *weight*.

We use the concept of net force to describe situations in which more than one force act. The *net force* acting on an object is the vector sum of all forces acting on it. When the mass of the object remains constant, the net force acting on it is the product of its mass and its acceleration: F_{net} = mao This relationship is known as *Newton's second law*. When the net force acting on an object is zero, the object experiences no acceleration. It either remains stationary or continues to move at a constant velocity. When the net force is not zero, the object accelerates.

At speeds near the speed of light, the mass of an object does not remain constant. The mass of a moving object, called its *relativistic mass,* equals its rest mass divided by a quantity that depends on the object's speed compared to the speed of light. As objects move faster, their relativistic masses increase to the extent that no object can be accelerated beyond the speed of light.

ANSWERS TO SELF-CHECKS

6A. The smaller the area, the greater the pressure. The pointed end exerts a greater pressure.

Pointed end: $(5\ \text{N})/(7.0 \text{ X } 10^{-7}\ \text{m}^2) = 7.1 \text{ X } 10^{6}\ \text{N/m}^2$

Eraser end: $(5\ \text{N})/(2 \text{ X } 10^{-4}\ \text{m}^2) = 2.5 \text{ X } 10^{4}\ \text{N/m}^2$

68. When a box is thrown into a truck, the box experiences a change in momentum. According to the definition of force, the greater the time interval in which the momentum changes, the less the force exerted on the object. The padding will increase this time interval.

6C. **Weight** = (70 kg)(24.3 (m/s)/s, down) = 1701 N, down

6D. When the apple is hanging from a limb on the tree, two forces act on it. The contact between the apple and the limb gives rise to an upward force that keeps the apple from falling. The other force is the force due to gravity pulling the apple downward toward the ground. When the apple is falling toward the ground, two forces act on it. The force due to gravity is pulling the apple downward toward the ground. The surrounding air exerts a frictional force upward, slowing the rate at which the apple falls.

6E. **net force** = 10 N, right - 8 N, left = 2 N, right;
acceleration = (2 N, right)/(10 kg) = 0.2 (m/s)/s, right

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the following terms:
Force
Contact interaction
Interaction at a distance
Net force
Pressure
Static friction
Kinetic friction
Rest mass
Relativistic mass

A2. We defined force formally in terms of momentum and in terms of acceleration. State these two definitions. Which is more general? Why do we introduce two definitions?

A3. How do we intuitively define force?

A4. How does the concept of force enable us to concentrate on one object in an interaction?

AS. Describe how the change in momentum of an object depends on the force applied to it and on the time during which the force is applied.

A6. Use the definition of force to describe how air bags protect passengers in automobile collisions.

A7. List the two categories of force we encounter in most everyday situations.

A8. If more than one force acts on an object, how do you combine them to determine the net force?

A9. An object moves along at a constant velocity. What two possibilities exist for explaining this motion?

AlO. Describe how you would calculate the force due to gravity on an object when you know its mass.

A11. Why must our concept of mass be changed at speeds near the speed of light?

B. Using the Chapter Material

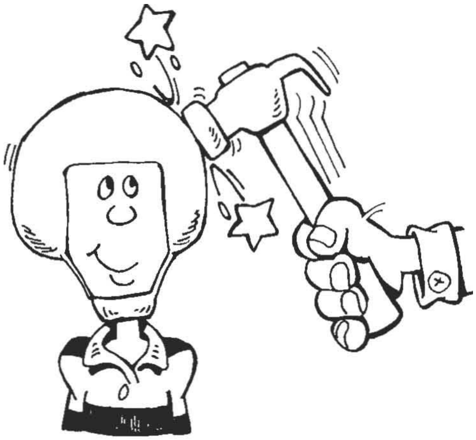
81. In the early 1960s women wore high-heeled shoes, called spike heels, which had a very small area at the heel. Typically, they had an area of 0.0001 m^2. What pressure could a force of 600 N apply on one heel? On two heels? (While spike heels were difficult to walk in, they were great for self-defense.)

82. A bicycle brake applies a 20 N force for 10 s.
 a. What is the change in momentum of the bicycle?
 b. How much force would be needed to make the same change of momentum in 2 s?

83. Helmets are used in a variety of situations to protect people from head injuries. As illustrated in Figure 6-83, the wearer can endure forces that could normally kill a person. The protection offered by a helmet arises from two sources:
 a. Without a helmet, the force exerted by the hammer is simply exerted on the skull over the area of the hammerhead.

The helmet spreads this force over the entire area of the helmet. Estimate the area of the hammerhead and the area of the helmet. How does this reduce the pressure exerted on the skull?

b. The interior of most helmets is padded. How does this padding add further protection?



84. Calculate the force acting:
   a. when a 1000 kg drag racer accelerates from zero to 170 *mls* in 5 s
   b. when a 50 kg runner accelerates from zero to 12 *mls* in 6 s

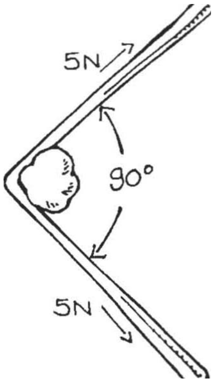
85. Identify all forces acting on the rock in the first and last frames of the cartoon in Figure 6-11.
   a. Why does the rock not accelerate if only one person pushes on it?
   b. Why does the rock not accelerate when all four people push on it?

86. While you hold a book motionless in your hand, what are the forces acting on it? Which are due to contact interactions and which are due to interaction at a distance?

87. Three children are pulling on a toy. Kim pulls with a force of 30 N, north; Kevin, with a force of 30 N, south; and Julie with a force of 15 N, east. What is the acceleration of the toy?

88. A 500 N force acts on a 2000 kg car in the direction in which the car is moving. Air resistance and friction supply a 300 N force in the opposite direction. What is the net force acting on the car? What is the car's acceleration?

89. Shooting paper wads with rubber bands is a common pastime among junior high students. The force on the paper wad is applied through the rubber band. What are the net force and acceleration of a 0.01 kg paper wad in the situation illustrated in Figure 6-89?



810. The brakes on a small truck are designed to apply a force that uses the tires to stop the truck. The force results in an acceleration that stops the truck in a safe distance. Adding a camper body to the truck can increase its mass by 50%. The camper is frequently added without changing the brake system. In this situation, why may the truck no longer be able to stop within a safe distance?

811. A small spaceship has a rest mass of 2000 kg. What mass would you measure for the ship when it moves by you at 50% the speed of light? 60% the speed of light? 90% the speed of light?

C. Extensions to New Situations

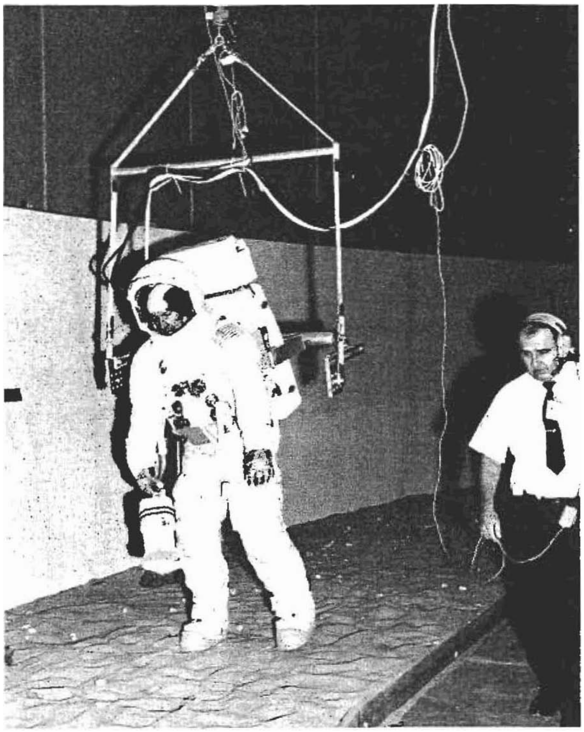
C1. Unpleasant forces on the human body occur in accidents in which the body changes its momentum from some value to zero. Determine the forces acting in each situation.
   a. People have survived falls in which their momentum changed from 210 kg . *mls* to 0 kg . *mls* in 0.02 s.
   b. A typical fall into a fireman's net gives a momentum change from 150 kg . *mls* to 0 kg . *mls* in 0.1 s.

   c. If a standing person just fell over and hit his or her head on a hard surface, he or she could be killed. The momentum change of the person's head in this situation is from 120 kg . *mls* to 0 kg . *mls* in 0.004 s.
   d. During an accident, momentum changes of a head protected by a motorcycle helmet are typically from 80 kg . *mls* to 0 kg . *mls* in 0.02 s.

C2. During World War II the Soviet Union decided to attempt a surprise raid on the German Army by dropping soldiers onto battlefields without parachutes. Each soldier was placed in a large sack filled with straw and then dropped into snowdrifts from heights ranging from 5 to 15 m.
   a. Why would anyone think that such an operation would work?
   b. In terms of the change in momentum, what is the purpose of the straw and snow? (Only about one-half of the soldiers were able to fight after landing, so this type of air-to-ground delivery was stopped.)

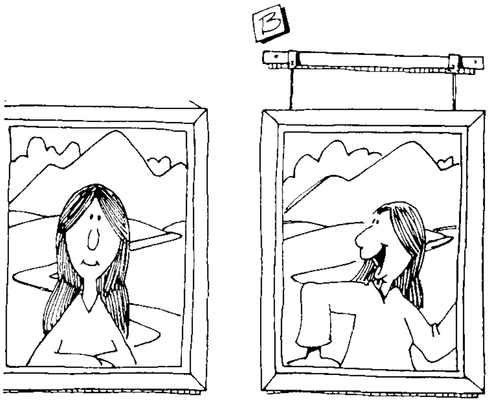
C3. Frictional interactions between tires and the road cause vehicles to stop when the brakes are applied. The friction can occur with rolling tires or sliding ones (a skid). To see which stopping method works better, we consider measurements on identical cars of mass 1000 kg. One stops by rolling with its brakes applied; the other skids. Both cars are initially moving at a city speed limit of 15 m/s.
   a. Guess which one will stop more quickly.
   b. The car with rolling tires stops in 1 s. What is its acceleration? What force is applied to it?
   c. The skidding car stops in 1.5 s. What are its acceleration and the applied force?
   d. Which way is a better way to stop in an emergency?

C4. Apollo astronauts needed to learn to move under the lower gravitational force of the moon while still on earth. One method of training was to attach a cable to the astronauts, as shown in Figure 6-C4.
   a. Why could such a cable pulling up be used to simulate situations in lunar gravity?
   b. What force due to gravity acts on an 80 kg astronaut on the earth? On the moon?
   c. With what force must the cable pull upward on the 80 kg astronaut to simulate lunar gravity?



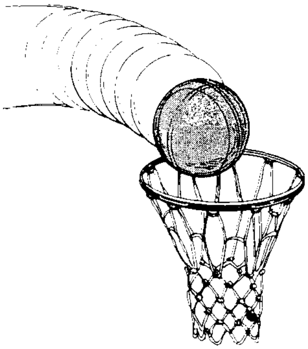
C5. One way of teaching people to ski is the Graduated Length Method (GLM). Novices begin on very short skis (usually 1 m in length). As they learn the various techniques, they graduate to longer lengths. Proponents of this method state that on short skis, beginners travel more slowly. Use the ideas of pressure, sinking into snow, and contact interactions to argue that this statement is correct. (While the skis change in length, they do not change in width.)

C6. In homes, paintings are frequently hung from the walls with wires, as shown in Figure 6-C6(a). However, art museums usually attach wires as shown in (b).
   a. For a 2 kg painting, what is the magnitude of the gravitational force acting downward on it?
   b. If the painting is to remain hanging, with what force must the wires pull upward?



c. What is the force applied by each wire in (b)?
d. To have this force acting up in (a), an equal force must act horizontally. With what force must the wire pull in (a) to achieve the same vertical force as in (b)?
e. Why can art museums use wire that is less strong than homes?

When you take a shot in basketball, the ball follows the path illustrated in Figure 6-C7.



a. What contact forces act on the ball after it leaves the player's hand and before it strikes the basket?
b. What forces from interaction at a distance act on the ball?
c. In what direction does the ball accelerate?
d. Use the answers in (a)-(c) to describe why the ball follows the motion shown in the figure.

See if you can figure this out for yourself before we discuss it in the next chapter.

The force on a car moving around a curve is toward the center of the curve. That means that the car is being pulled inward. Yet guardrails to prevent cars from leaving the road are placed on the outside. Can you determine why?
a. Using the concept of force, guess why the guardrails are on the outside.
b. What would happen to a car's momentum if no force acted on it as it entered the curve?
c. Sketch a road with a curve on it. Now, remembering that momentum is a vector, show the path followed by a car if no force acts on it when it reaches the curve.
d. If no force acts as the car enters the curve, why will it interact with the guardrail?
e. If your guess is different from your answers to (c) and (d), try to explain the differences. If you are still uncertain, wait until we finish Chapter 7.

C9. A bicycle and rider with a total mass of 80 kg apply a force of 240 N to the road. The bicycle accelerates at 2 (m/s)/s, W.
a. What is the size of the force applied in the forward direction on the bicycle by the road?
b. What is the net force acting on the bicycle?
c. Why is the net force different from the 240 N?
d. What is the force of friction acting on the bicycle?

CIO. Use the concept of relativistic mass to discuss:
a. how momentum varies as a particle approaches the speed of light
b. why the equation force = (change in momentum)/time is valid at all speeds

D. Activities

01. Design a package for a fresh egg which can be dropped three stories without breaking the egg (no parachutes allowed.) Explain your design in terms of momentum change and force. Try it.

02. Find locations on highways where accidents, and thus injuries, could result from rapid changes in momentum. Use the concepts of force and change in momentum to suggest improvements.