4 Newton's Second Law of Motion—Force and Acceleration

Kick a football and it moves. Its path through the air is not a straight line—it curves due to gravity. Catch the ball and it stops. Most of the motion we see undergoes change. Most things start up, slow down, or curve as they move. The last chapter covered objects at rest or moving at constant velocity. There was no net force acting on these objects. This chapter covers the more common cases, in which there is a change in motion—that is, accelerated motion.

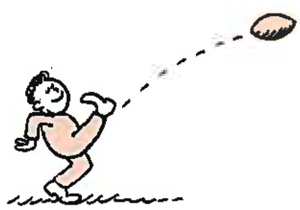

Fig. 4-1 Kick a football and it neither remains at rest nor moves in a straight line.

Recall from Chapter 2 that acceleration describes how fast motion is changing. Specifically, it is the change in velocity per certain time interval. In shorthand notation,

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time interval}}$$

This is the definition of acceleration.* This chapter focuses on the *cause* of acceleration: *force*.

4.1 Force Causes Acceleration

Consider an object at rest, such as a hockey puck on ice. Apply a force and it moves. Since it was not moving before, it has accelerated—changed its motion. When the stick is no longer in contact with the puck, it moves at constant velocity. Apply another force by striking it with the stick again, and the motion changes. Again, the puck has accelerated. Forces are what produce accelerations.

Fig. 4-2 Puck about to be hit.

* The Greek letter Δ (delta) is often used as a symbol for "change in" or "difference in." In "delta" notation, $a = \Delta v/\Delta t$, where Δv is the change in velocity, and Δt is the change in time (the time interval).

Most often, the force we apply is not the only force that acts on an object. Other forces may act as well. The combination of all the forces that act on an object is called the **net force**. It is the net force that accelerates an object.

We see how forces combine to produce net forces in Figure 4-3. If you pull horizontally with a force of 10 N on an object that rests on a friction-free surface, an air track for example, then the net force acting on it is 10 N. If a friend assists you and pulls at the same time on the same object with a force of 5 N in the same direction, then the net force will be the sum of these forces, 15 N (Figure 4-3 top). The object will accelerate as if it were pulled with a single force of 15 N. If, however, your friend pulls with 5 N in the opposite direction, the net force will be the difference of these forces, 5 N (Figure 4-3 center). The acceleration of the object would be the same as if it were instead pulled with a single force of 5 N.

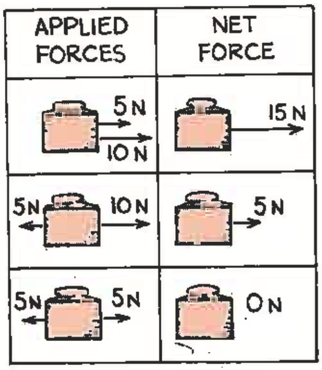

Fig. 4-3 When more than one force acts in the same direction on an object, the net force is the sum of the forces. When forces act in opposite directions, the net force is the difference of the forces.

We find that the amount of acceleration depends on the amount of the net force. To increase the acceleration of an object, you must increase the net force. This makes good sense. Double the force on an object, and you will double the acceleration. If you triple the force, you'll triple the acceleration, and so on. We say that the acceleration produced is directly proportional to the net force. We write:

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

The symbol ~ stands for "is directly proportional to."

4.2 Mass Resists Acceleration

Push on an empty shopping cart. Then push equally hard on a heavily loaded shopping cart, and you'll produce much less acceleration. This is because acceleration depends on the mass being pushed upon. For objects of greater mass we find smaller accelerations. Twice as much mass for the same force results in only half the acceleration; three times the mass results in one third the acceleration, and so forth. In other words, for a given force the acceleration produced is inversely proportional to the mass. We write:

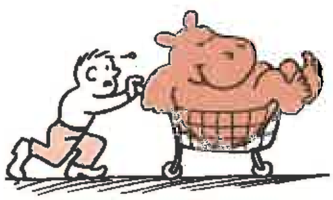

Fig. 4-4 The acceleration produced depends on the mass being pushed.

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

By **inversely** we mean that the two values change in opposite directions. (Mathematically we see that as the denominator increases, the whole quantity decreases. The quantity $\frac{1}{100}$ is less than the quantity $\frac{1}{10}$, for example.)

4.3 Newton's Second Law

Newton was the first to realize that the acceleration we produce when we move something depends not only on how hard we push or pull (the force) but on the mass as well. He came up with one of the most important rules of nature ever proposed, his second law of motion. **Newton's second law** states:

> The acceleration produced by a net force on a body is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the body.

Or in shorter notation,

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

By using consistent units such as newtons (N) for force, kilograms (kg) for mass, and meters per second squared (m/s^2) for acceleration, we get the exact equation.

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

In briefest form, where a is acceleration, F is net force, and m is mass:

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

The acceleration is equal to the net force divided by the mass. From this relationship we can see that if the net force that acts on an object is doubled, the acceleration will be doubled. Suppose instead that the mass is doubled. Then the acceleration will be halved. If both the net force and the mass are doubled, then the acceleration will be unchanged.

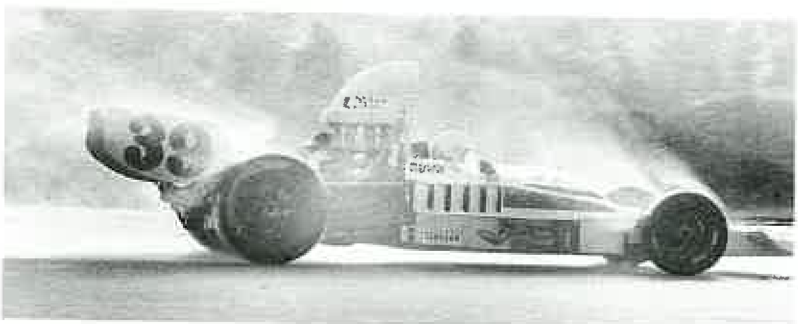

Fig. 4-5 The good acceleration of the racing car is due to its ability to produce large forces.

Problem Solving

If the mass of an object is measured in kilograms (kg), and acceleration is expressed in meters per second squared (m/s^2), then the force will be expressed in newtons (N). One newton is the force needed to give a mass of one kilogram an acceleration of one meter per second squared. We can arrange Newton's second law to read

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$1\ \text{N} = (1\ \text{kg}) \times (1\ \text{m/s}^2)$$

As you can see,

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

(The dot between "kg" and "m/s^2" means that the units have been multiplied together.)

If you know two of the quantities in Newton's second law, you can easily calculate the third. For example, how much thrust must a 30 000-kg jet plane develop to achieve an acceleration of 1.5 m/s^2? Thrust means force, so

$$\begin{aligned} F &= ma \\ &= (30\ 000\ \text{kg}) \times (1.5\ \text{m/s}^2) \\ &= 45\ 000\ \text{kg}\cdot\text{m/s}^2 \\ &= 45\ 000\ \text{N} \end{aligned}$$

Suppose you know the force and the mass and want to find the acceleration. For example, what acceleration will be produced by a force of 2000 N on a 1000-kg car? Using Newton's second law we find

$$a = \frac{F}{m} = \frac{2000\ \text{N}}{1000\ \text{kg}} = \frac{2000\ \text{kg}\cdot\text{m/s}^2}{1000\ \text{kg}} = 2\ \text{m/s}^2$$

If the force were 4000 N, what would be the acceleration?

$$a = \frac{F}{m} = \frac{4000\ \text{N}}{1000\ \text{kg}} = \frac{4000\ \text{kg}\cdot\text{m/s}^2}{1000\ \text{kg}} = 4\ \text{m/s}^2$$

Doubling the force on the same mass simply doubles the acceleration.

In traditional problem-solving physics courses, the problems are often more complicated than the ones given here. This book will not focus on solving complicated problems, but will instead concentrate on becoming acquainted with the equations as guides to thinking about the basic physics concepts. Mathematical problems can be an objective for follow-up study in physics. Most any other physics textbook will provide you with plenty of mathematical problems if you want them. But please—learn the concepts first!

▶ **Questions**

1. If a car is able to accelerate at 2 m/s², what acceleration can it attain if it is towing another car of equal mass?
2. What kind of motion does an unchanging force produce on an object of fixed mass?

4.4 Statics

How many forces act on your book as it lies motionless on the table? Don't say one, its weight. If that were the only force acting on it, you'd find it accelerating. The fact that it is at rest, and not accelerating, is evidence that another force is acting. The other force must just balance the weight to make the net force zero. The other force is the **support force** of the table (often called the **normal force***). To see that the table is pushing up on the book, imagine an ant underneath the book. The ant would feel itself being squashed from both sides, the top and the bottom. The table actually pushes up on the book with the same amount of force that the book presses down. If the book is to be at rest, the sum of the forces acting on it must balance to zero.

Hang from a strand of rope. Your weight provides the force which tightens the rope and sets up a tension force in it. How much tension is in the strand? If you are not accelerating, then it must equal your weight. The rope pulls up on you, and the gravitation of the earth pulls down on you. The equal forces cancel because they are in opposite directions. So you hang motionless.

Suppose you hang from a bar supported by two strands of rope, as in Figure 4-7. Then the tension in each rope is half your weight (if the weight of the bar is neglected). The total tension up ($\frac{1}{2}$ your weight + $\frac{1}{2}$ your weight) then balances your downward acting weight. When you do pullups in exercising, you use both arms. Then each arm supports half your weight. Ever try pullups with just one arm? Why is it twice as difficult?

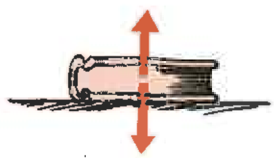

Fig. 4-6 The net force on the book is zero because the table pushes up with a force that equals the downward weight of the book.

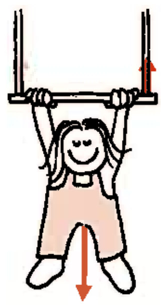

Fig. 4-7 The sum of the rope tensions must equal your weight.

▶ **Answers**

1. When the engine produces the same force on twice the mass, the acceleration will be half. It will be 1 m/s².
2. Motion at a constant acceleration, in accord with Newton's second law.

* This force acts at right angles to the surface; "normal to" means "at right angles to," which is why the force is called a normal force.

► **Question**

When you step on a bathroom scale, the downward pull of gravity and the upward support force of the floor compress a spring which is calibrated to give your weight. In effect, the scale shows the support force. If you stand on two scales with your weight equally divided between each scale, what will each scale read? How about if you stand with more of your weight on one foot than the other?

4.5 Friction

Even when a single force is applied to an object, it is usually not the only force affecting the motion. This is because of friction. Friction is a force that always acts in a direction to oppose motion. It is due in large part to irregularities in the two surfaces that are in contact. Even very smooth surfaces are bumpy when viewed with a microscope. When an object slides against another, it must either rise over the irregular bumps or else scrape them off. Either way requires a force.

The force of friction between two surfaces depends on the kinds of material and how much they are pressed together. Rubber against concrete, for example, produces more friction than steel against steel. That's why concrete road dividers are replacing steel rails (Figure 4-8). Notice that the concrete divider is wider at the bottom, so that the tire of a sideswiping car rather than the steel body makes contact with it. The greater friction between the rubber tire and the concrete is more effective in slowing the car than the contact between the steel body of the car with the steel rail of the other design.

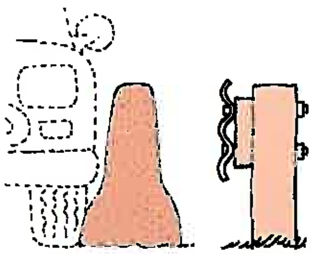

Fig. 4-8 Cross-section view of concrete road divider, and steel road divider. Which design is best for slowing an out-of-control, sideswiping car?

Friction is not restricted to solids sliding over one another. Friction occurs also in liquids and gases, which are called **fluids** (those which flow). Fluid friction occurs when an object moving through a fluid pushes aside some of the fluid. Have you ever tried running a 100-m dash through waist-deep water? The fric-

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► **Answer**

The reading on both scales must add up to your weight. This is because the sum of the scale readings, which equals the support force of the floor, must counteract your weight so the net force on you will be zero. If you stand equally on each scale, each will read half your weight. If you lean more on one scale than the other, more than half your weight will be read on that scale but less on the other, so they will still add up to your weight. For example, if one scale reads two-thirds your weight, the other scale will read one-third your weight. Get it?

tion of liquids is appreciable, even at low speeds. **Air resistance**, the friction that acts on something moving through air, is a very common case of fluid friction. You don't notice it when walking or jogging, but you'll notice it for higher speeds as in skiing downhill or skydiving.

When there is friction, an object may move at constant velocity while a force is applied to it. In this case, the friction force just balances the applied force. The net force is zero, so there is no acceleration. For example, in Figure 4-9 the crate will move at constant velocity when it is pushed just hard enough to balance the friction. The sack will fall at constant velocity when the air resistance balances its weight.

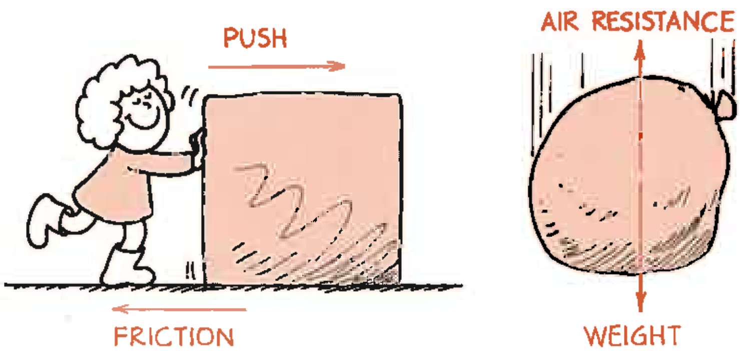

Fig. 4-9 Push the crate to the right, and friction acts toward the left. The sack falls downward, and air friction acts upward. The direction of the force of friction always opposes the direction of motion.

▶ Questions

1. Figure 4-6 shows only two forces acting on the book: its weight and the support force from the table. Doesn't the force of friction act as well?

2. Suppose a high-flying jumbo jet cruises at constant velocity when the thrust of its engines is a constant 80 000 N. What is the *acceleration* of the jet? What is the *force* of air resistance acting on the jet?

▶ Answers

1. No, not unless the book tends to slide or does slide across the table. For example, if it is pushed toward the left by another force, then friction between the book and table will act toward the right. Friction forces occur only when an object tends to slide or is sliding.

2. The acceleration is zero because the velocity is constant, which means not changing. Since the acceleration is zero, it follows from $a = F/m$ that the net force is zero. This implies that the force of air resistance must just equal the thrusting force of 80 000 N but must be in the opposite direction. So the air resistance is 80 000 N.

4.6 Applying Force—Pressure

You can put a book on a table, and no matter how you place it—on its back, upright, or even balancing on a single corner—the force of the book on the table is the same. This can be checked by doing this on a bathroom scale, where you'll read the same weight in all cases. Balance the book different ways on the palm of your hand. Although the force will be the same, you'll note differences in the way the book presses against your palm. This is because the area of contact is different in each case. The force *per unit of area* is called **pressure**. More precisely,

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

where the force is perpendicular to the surface area. In equation form,

$$P = \frac{F}{A}$$

where P is the pressure and A is the area against which the force acts. Force, which is measured in newtons, is different from pressure, which is measured in newtons per square meter [called a **pascal** (Pa), a relatively new unit, adopted in 1960].

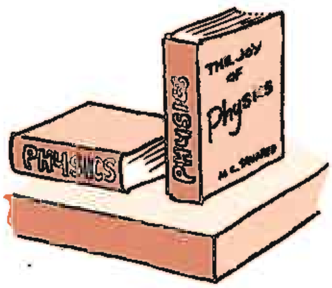

Fig. 4-10 The upright book exerts the same force but a greater pressure against the supporting surface.

Many people mistakenly believe that the wider tires of drag-racing vehicles produce more friction. But the larger area reduces only the pressure. The force of friction is independent of the contact area. Wide tires produce less pressure, and narrow tires produce more pressure. The wideness of the tires reduces heating and wear.

Fig. 4-11 Friction between the tire and the ground is the same whether the tire is wide or narrow. The purpose of the greater contact area is to reduce heating and wear.

You exert more pressure against the ground when you are standing on one foot than when standing on both feet. This is because your area of contact is less. Stand on one toe, like a ballerina, and the pressure is huge. The smaller the area that supports a given force, the greater is the pressure on that surface.

You can calculate the pressure you exert on the ground when you are standing. One way is to moisten the bottom of your foot with water and step on a clean sheet of graph paper marked with squares. Count the number of squares contained in your footprint. Divide your weight by this area and you have the average pressure you exert on the ground while standing still on one foot. How will this pressure compare with the pressure when you stand on two feet?

A dramatic illustration of pressure is shown in Figure 4-12. The author applies appreciable force when he breaks the cement block with the sledge hammer. Yet his friend, who is sandwiched between two beds of sharp nails, is unharmed. This is because much of this force is distributed over the more than 200 nails that make contact with his body. The combined surface area of this many nail points results in a tolerable pressure that does not puncture the skin. CAUTION: This demonstration is quite dangerous. Do not attempt it on your own.

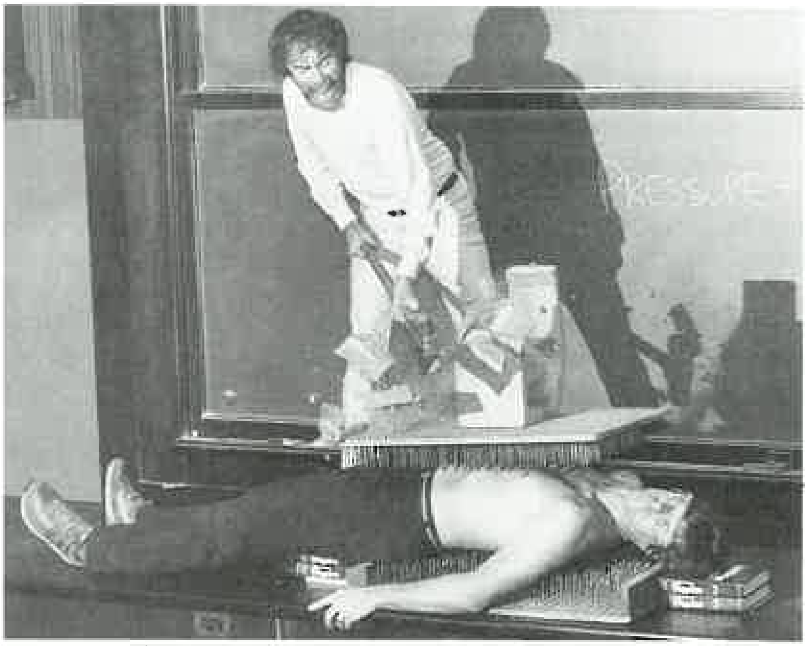

Fig. 4-12 The author applies a force to fellow physics teacher Paul Robinson, who is bravely sandwiched between beds of sharp nails. The driving force per nail is not enough to puncture the skin. CAUTION: Do not attempt this on your own!

▶ **Questions**

1. In attempting to do the demonstration in Figure 4-12, would it be wise to begin with a few nails, and work upward to more nails?
2. The massiveness of the cement block plays an important role in this demonstration. Which provides more safety—a less massive or more massive block?

▶ **Answers**

1. No, no, no! There would be one fewer physics teacher if the demonstration were performed with fewer nails, because of the resulting greater pressure.
2. The greater the mass of the block, the smaller is the acceleration of the block and bed of nails toward the friend. Much of the force wielded by the hammer goes into moving this block and *breaking* it. It is important that the block be massive and that it break upon impact.

4.7 Free Fall Explained

Fig. 4-13 Galileo's famous demonstration.

Galileo showed that falling objects will accelerate equally, regardless of their masses. This is *strictly* true if air resistance is negligible, that is, if the objects are falling freely. It is *approximately* true when air resistance is very small compared to the weight of the falling object. For example, a 10-kg cannonball and a 1-kg stone dropped from an elevated position at the same time will fall together and strike the ground at practically the same time. This experiment, said to be done by Galileo from the Leaning Tower of Pisa, demolished the Aristotelian idea that an object that weighs ten times as much as another should fall ten times faster than the lighter object. Galileo's experiment and many others that showed the same result were convincing. But Galileo couldn't say *why* the accelerations were equal. The explanation is a straight-forward application of Newton's second law and is the topic of the cartoon "Backyard Physics" (next page). Let's treat it separately here.

Recall that mass (a quantity of matter) and weight (the force due to gravity) are proportional. A 2-kg bag of nails weighs twice as much as a 1-kg bag of nails. So a 10-kg cannonball has 10 times the force of gravity (weight) of a 1-kg stone. Followers of Aristotle believed that the cannonball should therefore accelerate ten times as much as the stone because they considered only the greater weight. But Newton's second law tells us to consider the mass as well. A little thought will show that ten times as much force acting on ten times as much mass produces the same acceleration as one-tenth the force acting on one-tenth the mass. In symbolic notation,

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

where $\mathbf{F}$ stands for the force (weight) acting on the cannonball, and $\mathbf{m}$ stands for the correspondingly large mass of the cannonball. The small F and m stand for the smaller weight and mass of the stone. We see that the *ratio* of weight to mass is the same for these or any objects. All freely falling objects undergo the same acceleration at the same place on earth. This acceleration, which is due to gravity, is represented by the symbol g.

We can show the same result with numerical values. The weight of a 1-kg stone (or 1 kg of *anything*) is 9.8 N at the earth's surface. The weight of 10 kg of matter, such as the cannonball, is 98 N. The force acting on a falling object is the force due to gravity, or weight of the object. The acceleration of the stone is


BACKYARD PHYSICS
IF I DROP THE BAG OF CLOTHESPINS AND THE SINGLE PIN AT THE SAME TIME, WHICH WILL FALL TO THE GROUND FIRST ?
THAT'S EASY! THE BAG OF CLOTHESPINS IS HEAVIER, WHICH MEANS GRAVITY PULLS ON IT WITH MORE FORCE. SO THE BAG OF PINS WILL ACCELERATE MORE AND HIT THE GROUND FIRST!
PHYSICS PHYSICS PHYSICS
NOT TRUE! THE BAG OF CLOTHESPINS HAS MORE MASS, WHICH IS TO SAY, HAS MORE INERTIA ... IT WILL BE LESS RESPONSIVE TO GRAVITY AND LAG BEHIND THE SINGLE PIN!
SO THE SINGLE PIN WILL HIT THE GROUND FIRST?
SIGH
SORRY GANG ... A TIE SCORE
HOW COME???
PLUNK!
PLINK!
SINCE THE BAG HAS BOTH A GREATER WEIGHT AND A GREATER INERTIA, ONE OFFSETS THE OTHER!
(WEIGHT / MASS)BAG = (WEIGHT / MASS)PIN = g
THE ACCELERATION IS EQUAL FOR BOTH!
OF COURSE
HEWITT DEWITT!

$$a = \frac{F}{m} = \frac{\text{weight}}{m} = \frac{9.8 \text{ N}}{1 \text{ kg}} = \frac{9.8 \text{ kg·m/s}^2}{1 \text{ kg}} = 9.8 \text{ m/s}^2 = g$$

and for the cannonball,

$$a = \frac{F}{m} = \frac{\text{weight}}{m} = \frac{98 \text{ N}}{10 \text{ kg}} = \frac{98 \text{ kg·m/s}^2}{10 \text{ kg}} = 9.8 \text{ m/s}^2 = g$$

The famous coin-and-feather-in-a-vacuum-tube demonstration was discussed in Chapter 2, but not the *reason* for the equal accelerations. Now we know that the reason both fall with the same acceleration (g) is because the net force on each is only its weight, and the ratio of weight to mass is the same for both.

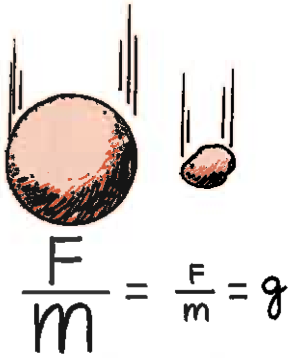

Fig. 4-14 The ratio of weight (F) to mass (m) is the same for the 10-kg cannonball and the 1-kg stone.

> ▶ **Question**
>
> If you were on the moon and dropped a hammer and a feather from the same elevation at the same time, would they strike the surface of the moon together?

4.8 Falling and Air Resistance

The feather and coin fall with equal accelerations in a vacuum, but quite unequally in the presence of air. When air is let into the glass tube and it is again inverted and held upright, the coin falls quickly while the feather flutters to the bottom. Air resistance diminishes the net forces—a tiny bit for the coin and very much for the feather. The downward acceleration for the feather is very brief, for the air resistance very quickly builds up to counteract its tiny weight. The feather does not have to fall very long or very fast for this to happen. When the air resistance of the feather equals the weight of the feather, the net force is zero and no further acceleration occurs. Acceleration terminates. The feather has reached its **terminal speed**. If we are concerned with direction, down for falling objects, we say the feather has reached its **terminal velocity**.

The air resistance on the coin does not have as much effect. At small speeds the force of air resistance is very small compared to the weight of the coin, and its acceleration is only slightly less

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▶ **Answer**

Yes. On the moon's surface they would weigh only one-sixth their earth weight, which would be the only force acting on them since there is no atmosphere to provide air resistance. The ratio of moonweight to mass for each would be the same, and they would each accelerate at $\frac{1}{6}g$.

than the acceleration of free fall, g. The coin might have to fall for a few minutes before its speed would be great enough for the air resistance to increase to its weight. Its speed at that point, perhaps 200 km/h or so, would no longer increase. It would have reached its terminal speed.

The terminal speed for a human skydiver varies from about 150 to 200 km/h, depending on weight and position of fall. A heavier person will attain a greater terminal speed than a lighter person. The greater weight is more effective in "plowing through" the air. A heavy and light skydiver can remain in close proximity if the heavy person spreads out like a flying squirrel while the light person falls head or feet first. A parachute greatly increases air resistance, and terminal speed can be cut down to an acceptable 15 to 25 km/h.

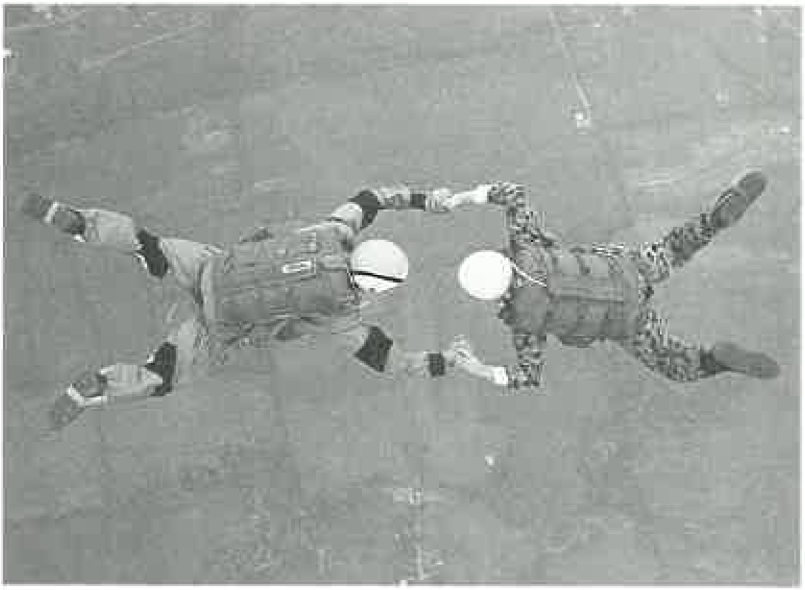

Fig. 4-15 Terminal speed is reached for the skydiver when air resistance equals weight.

Fig. 4-16 The flying squirrel increases its area by spreading out. This increases air resistance and decreases the speed of fall.

▶ **Question**

If a heavy person and a light person parachute together from the same altitude, and each wears the same size parachute, who should reach the ground first?

▶ **Answer**

The heavy person reaches the ground first. This is because the light person, like the feather, will reach terminal speed sooner while the heavy person continues to accelerate until a greater terminal speed is reached. So the heavy person moves ahead of the light person, who is unable to catch up.

If you hold a baseball and tennis ball at arm's length and release them together, you'll note they strike the floor at the same time. But if you drop them from the top of a high building, you'll notice the heavier baseball strikes the ground first. This is because of the buildup of air resistance with higher speed (like the parachutists in the check question). For low speeds, air resistance may be negligible. For higher speeds, it can make quite a difference. Air resistance is more pronounced on the lighter tennis ball than the heavier baseball, so acceleration of fall is less for the tennis ball. The tennis ball behaves more like a parachute than the baseball does.

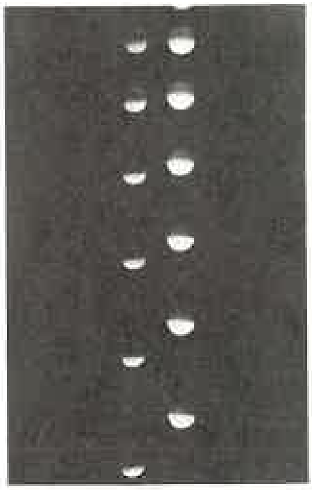

Fig. 4-17 A stroboscopic photo of a golf ball and a Styrofoam ball falling in air. The weight of the heavier golf ball is more effective in overcoming air resistance, so its acceleration is greater. Will both ultimately reach a terminal speed? Which will do so first? Why?

▶ **Question**

If the force of air resistance is the *same* for a falling baseball and a falling tennis ball, which will have the greater acceleration?

When Galileo reportedly dropped the objects of different weights from the Leaning Tower of Pisa, the heavier one *did* get to the ground first—but only a split second before the other, rather than the pronounced time difference expected by the followers of Aristotle. The behavior of falling objects was never really understood until Newton announced his second law of motion.

Isaac Newton truly changed our way of seeing the world.

▶ **Answer**

Don't say the same! It's true the air resistance is the same for each, but this doesn't mean the net force is the same for each, or that the ratio of net force to mass is the same for each. The heavier baseball will have the greater net force, and greater net force per mass, just like the heavier parachutist in the previous question. (Convince yourself of this by considering the upper limit of air resistance—when it is equal to the weight of the tennis ball. What will be the acceleration of the tennis ball then? Do you see that the baseball has a greater acceleration at that point? And with more thought, do you see that the baseball has the greater acceleration even when the air resistance is less than the weight of the tennis ball?)

4 Chapter Review

Concept Summary

An object accelerates—changes speed and/or direction—when there is a net force that acts on it.

- The acceleration of an object is directly proportional to the net force that acts on it.
- The acceleration of an object is inversely proportional to the mass of the object.
- Acceleration equals net force divided by mass, and is in the same direction as the net force.

An object remains at rest or continues to move with constant velocity when the net force on it equals zero.

- When an object is at rest, its weight is balanced by a support force of equal amount.
- When an object is moving at constant velocity while an applied force acts on it, that force must be balanced by an equal amount of resisting force (usually friction).

The application of a force over a surface produces pressure.

- Pressure equals force divided by area of application, where the force is perpendicular to the surface area.

A falling object is acted on by gravity, which pulls downward with a force equal to the weight of the object.

- In free fall (no air resistance), the acceleration of all objects is the same, regardless of mass.
- When there is air resistance, a falling object will accelerate only until it reaches its terminal speed.
- At terminal speed, the force of air resistance balances the force of gravity.

Important Terms

air resistance (4.5)
fluid (4.5)
inversely (4.2)
net force (4.1)
Newton's second law (4.3)
normal force (4.4)
pascal (4.6)
pressure (4.6)
support force (4.4)
terminal speed (4.8)
terminal velocity (4.8)

Review Questions

1. Distinguish between the relationship that defines acceleration, and the relationship that states how it is produced. (4.1)

2. What is meant by the *net force* that acts on an object? (4.1)

3. Forces of 10 N and 20 N in the same direction act on an object. What is the net force on the object? (4.1)

4. If the forces exerted on an object are 50 N in one direction and 30 N in the opposite direction, what is the net force exerted on the object? (4.1)

5. Suppose a cart is being moved by a certain net force. If the net force is doubled, by how much does its acceleration change? (4.1)

6. Suppose a cart is being moved by a certain net force. If a load is dumped into the cart so its mass is doubled, by how much does the acceleration change? (4.2)

7. Distinguish between the concepts of *directly proportional* and *inversely proportional*.

Support your statement with examples. (4.1–4.2)

8. State Newton's second law in words, and in the form of an equation. (4.3)

9. How much force must a 20 000-kg rocket develop to accelerate 1 m/s²? (4.3)

10. How much support force does a table exert on a book that weighs 15 N when the book is placed on the table? What is the *net* force on the book in this case? (4.4)

11. When a 100-N bag of nails hangs motionless from a single vertical strand of rope, how many newtons of tension are exerted in the strand? How about if the bag is supported by four vertical strands? (4.4)

NO 12. What is the cause of friction, and in what direction does it act with respect to the motion of a sliding object? (4.5)

13. If the force of friction acting on a sliding crate is 100 N, how much force must be applied to maintain a constant velocity? What will be the net force acting on the crate? What will be the acceleration? (4.5)

NO 14. Distinguish between force and pressure. (4.6)

NO 15. Which produces more pressure on the ground—a narrow tire or a wide tire of the same weight? (4.6)

16. The force of gravity is twice as great on a 2-kg rock as on a 1-kg rock. Why then, does the 2-kg rock not fall with twice the acceleration? (4.7)

17. How can a coin and a feather in a vacuum tube fall with the same acceleration? (4.7)

18. Why do a coin and a feather fall with different accelerations in the presence of air? (4.8)

19. How much air resistance acts on a 100-N bag of nails that falls at its terminal speed? (4.8)

20. How do the air resistance and the weight of a falling object compare when terminal speed is reached? (4.8)

21. All things being equal, why does a heavy skydiver have a greater terminal speed than a lighter skydiver? What can be done so that both terminal speeds are equal? (4.8)

22. What is the net force acting on a 25-N freely falling object? What is the net force when it encounters 15 N of air resistance? When it falls fast enough to encounter 25 N of air resistance? (4.7–4.8)

Activities

1. If you drop a sheet of paper and a book side by side, the book will fall faster due to its greater weight compared to the air resistance. If you place the paper against the lower surface of the raised horizontally held book and again drop them at the same time, it will be no surprise that they will hit the surface below at the same time. The book has simply pushed the paper with it as it falls. If you repeat this, only with the paper on *top* of the book, which will fall faster? Try it and see!

2. Drop two balls of different weights from the same height, and for small speeds they practically fall together. Will they roll together down the same inclined plane? If each is suspended from the same size string and each is made into a pendulum, and displaced through the same angle, will they swing to and fro in unison? Try it and see.

3. The net force that acts on an object and the resulting acceleration are always in the same direction. You can demonstrate this with a spool. If the spool is pulled toward you, which way will it roll? Does it make a difference if the string is on the bottom or the top? Try it and maybe you'll be surprised.

Think and Explain

1. What is the difference between saying that one quantity is proportional to another and saying it is equal to another?

2. If a four-engine jet accelerates down the runway at 2 m/s^2 and one of the jet engines fails, how much acceleration will the other three produce?

3. If a loaded truck can accelerate at 1 m/s^2 and loses its load so it is only ¾ as massive, what acceleration can it attain for the same driving force?

4. A rocket fired from its launching pad not only picks up speed, but its acceleration increases significantly as firing continues. Why is this so? (*Hint*: About 90% of the mass of a newly launched rocket is fuel.)

5. What is the mass and what is the weight of a 10-kg object on the earth? What is its mass and weight on the moon, where the force of gravity is ⅙ that of the earth?

6. The little girl in Figure A hangs at rest from the ends of the rope. How does the reading on the scale compare to her weight?

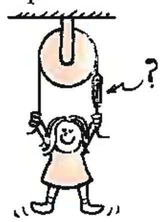

Fig. A

7. In football-team blocking, why does a defending lineman often attempt to get his body under that of his opponent and push upward? What effect does this have on the friction force between the opposing lineman's feet and the ground?

8. Why is the force of friction no greater for a wide tire than for a narrow tire?

9. Why does a sharp knife cut better than a dull knife?

10. Harry the painter swings year after year from his bosun's chair. His weight is 500 N and the rope, unknown to him, has a breaking point of 300 N. Why doesn't the rope break when he is supported as shown in Figure B left? One day Harry is painting near a flagpole, and for a change, he ties the free end of the rope to the flagpole instead of to his chair (Figure B right). Why did Harry end up taking his vacation early?

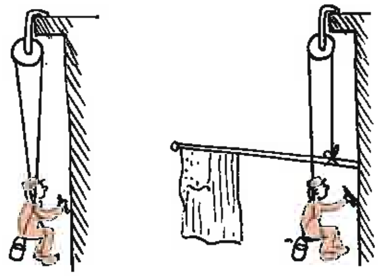

Fig. B

11. What is the advantage of the large flat sole on the foot of an elephant? Why must the small foot (hoof) of an antelope be so hard?

12. When a rock is thrown straight upward, what is its acceleration at the top of its path? (Is your answer consistent with $a = F/m$?)

13. As a skydiver falls faster and faster through the air, does the net force on her increase, decrease, or remain unchanged? Does her acceleration increase, decrease, or remain unchanged? Defend your answers.

14. After she jumps, a skydiver reaches terminal speed after 10 seconds. Does she gain more speed during the first second of fall or the ninth second of fall? Compared to the first second of fall, does she fall a greater or a lesser distance during the ninth second?

15. A regular tennis ball and another filled with heavy sand are dropped at the same time from the top of a high building. Your friend says that even though air resistance is present, they should hit the ground together because they are the same size and "plow through" the same amount of air. What do you say?

5 Newton's Third Law of Motion—Action and Reaction

Fig. 5-1 When you push on the wall, the wall pushes on you.

If you lean over too far, you'll fall over. But if you lean over with your hand outstretched and make contact with a wall, you can do so without falling. When you push against the wall, the wall pushes back on you. That's why you are supported. Ask your friends why you don't topple over. How many will answer, "Because the wall is pushing on you and holding you in place"? Probably not very many people (unless they're physics types) realize that walls can push on us every bit as much as we push on them.*

5.1 Interactions Produce Forces

Fig. 5-2 The interaction that drives the nail is the same as the one that brings the hammer to a halt.

In the simplest sense, a force is a push or a pull. Looking closer, however, we find that a force is not a thing in itself, but is due to an interaction between one thing and another. For example, a hammer hits a nail and drives it into a board. One object interacts with another. Which exerts the force and which receives the force? Newton thought about questions like this, and the more he thought, the more he came to the conclusion that neither object has to be identified as the "exerter" or "receiver." He reasoned that nature is symmetrical and concluded that both objects must be treated equally. The hammer exerts a force against

* The terms *push* or *pull* usually invoke the idea of a living thing exerting a force. So strictly speaking, to say "the wall pushes on you" is to say "the wall exerts a force as though it were pushing on you." As far as the balance of forces is concerned, there is no observable difference between the forces exerted by you (alive) and the wall (nonliving).