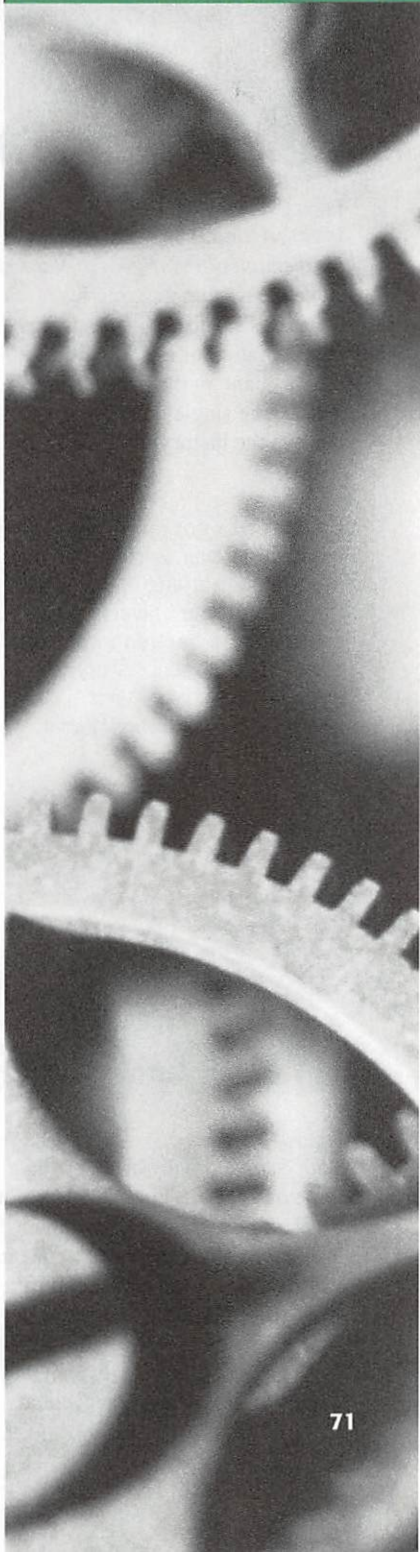
CHAPTER 4

Why Things Move as They Do



Nature and nature's laws lay hid in night;
God said, "Let Newton be," and all was light.

Alexander Pope, Eighteenth-Century British Poet

The world changed in 1687. In that year, Isaac Newton (**Figure 4.1**) published his *Mathematical Principles of Natural Philosophy.* To take just one example, by making Descartes's and Galileo's law of inertia the foundation of his work, Newton undermined our intuitive view of how things move, a view accepted by all educated people for 2000 years. The Newtonian world is surprisingly simple. Using only a few key principles, Newton was able to give quantitative explanations for all manner of things: planets, moons, comets, falling objects, weight, ocean tides, Earth's equatorial bulge, stresses on a bridge, and more. It was an unparalleled expansion and unification of our understanding of nature.

Newton's influence ranged far beyond physics and astronomy. Not only the sciences but also history, the arts, economics, government, theology, and philosophy were shaped by the general patterns of Newtonian physics. For example, the ideals of inalienable human rights that inspired the American and French revolutions stemmed largely from a populace steeped in a Newtonian culture of universal natural law that applied equally to all people, to commoners and kings alike.

Newtonian physics worked almost too well. Unchallenged for over two centuries, it was eventually regarded as absolute truth. The very word *understand* came to mean "to explain in terms of Newtonian physics." Most importantly, people eventually took for granted many subtle Newtonian habits of mind that had profound but unstated and unexamined implications having to do with determinism, cause and effect, the mechanical nature of the universe, and other philosophical conclusions.[1] Eventually, everyone from the laborer to the scholar assumed that Newton had laid the framework for all human knowledge.

During the twentieth century, relativity and quantum physics superseded Newtonian physics. But Newtonian cultural habits remain, partly because there is no agreed-upon philosophical framework for the new physics and partly due to the failure of science educators to teach the new physics to all people. Thus, our culture remains largely Newtonian while our science is post-Newtonian...not a healthy situation. In order that

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[1] Two classic historical studies of physical science from the early Greeks through Newton examine the transition to the new worldview. The very title of Arthur Koestler's *The Sleepwalkers* (New York: Universal Library and The Macmillan Company, 1963) refers to the philosophically naive manner in which the Newtonian view developed. E. A. Burtt's *The Metaphysical Foundations of Modern Science* (originally published in 1932; reissued by Humanities Press, Atlantic Highlands, NJ, 1980) is a close examination of the history and implications of these unstated philosophical assumptions.

you may develop the tools to help pull all of us into the post-Newtonian age, I've chosen modern post-Newtonian physics and its significance as one of the themes of this book.

Newton's physics starts from only a few concepts and principles. You have already learned two concepts, velocity and acceleration, and two principles, the law of inertia and the law of falling. Newton's other key concepts are force and mass (Sections 4.1 and 4.2). His other key principles are the law of motion (Sections 4.3 and 4.4), the law of force pairs (Section 4.5), and the law of gravity (Chapter 5). Section 4.6 applies these ideas to the motion of a device that has, for better or worse, reshaped our cities, our landscapes, and our lives: the automobile. Section 4.7 presents another way of looking at Newtonian physics based on the concept of "momentum."

Figure 4.1
Isaac Newton, 1642–1727. His *Mathematical Principles of Natural Philosophy*, summarizing his, Descartes's, and Galileo's studies on the motion of material objects on Earth and in the heavens, may well be the single most important book in the history of science.

4.1 FORCE: WHY THINGS ACCELERATE

The preceding chapter used the word *force* synonymously with "external influence." Now I need to be more specific. Since the law of inertia says that bodies having no external influence (no force) on them are unaccelerated, it is natural to define a **force** as any external influence that causes a body to accelerate. So a body "exerts a force on" another body whenever the first body causes the second body to accelerate.

Newton was not only the greatest genius that ever existed, but also the most fortunate, inasmuch as there is but one universe, and it can therefore happen to but one man in the world's history to be the interpreter of its laws.
Pierre-Simon De Laplace, Scientist

Some examples: If a ball is at rest on a table and you push it with your hand, the ball will accelerate into motion. If the ball is already moving across a table and you push it briefly from behind, it will speed up. If you "pat" a moving ball lightly on the front side, toward the rear, it will slow down. If you pat it lightly sideways, it will change directions. In all four cases, your hand push accelerated the ball. In fact, a little experimentation shows that you cannot push the ball without accelerating it.[2] So every hand push is a force. When you use the word *force,* it is useful to remember that a force is like a push.

There are many misconceptions about the word *force.* Just like the word *push,* a force is an *action* rather than a *thing.* An object cannot *be* a force or *possess* force. Instead, force is something that one object does to another, just like "pushing." A body can "exert a force on" another body.

Pulling is another example. Starting with a ball at rest on the table, you can grasp it and pull it toward you, accelerating it into motion. So pulls are forces. Instead of pulling the ball with your hand, you could attach a string and pull the string, which pulls on the ball to accelerate the ball. So strings, when they pull, exert forces.

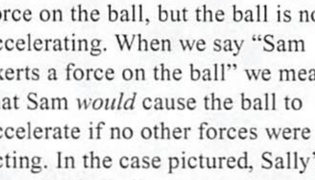

Figure 4.2
Both Sam and Sally are exerting a force on the ball, but the ball is not accelerating. When we say "Sam exerts a force on the ball" we mean that Sam *would* cause the ball to accelerate if no other forces were acting. In the case pictured, Sally's force on the ball prevents Sam's force from causing it to accelerate.

Now suppose that Sam and Sally both push on a ball in opposite directions (**Figure 4.2**). If they adjust their pushes, they can get them to balance so that the ball remains at rest. Yet both are pushing on the ball. Even though the ball is unaccelerated, we will say that Sam exerts a force on the ball and that Sally does, too. In cases involving more than one force, a body exerts a force on another body if, in the absence of the other forces, the first body *would* cause the second body to accelerate.

You could tap a ball with a hammer instead of pushing or pulling it with your hand. Since the hammer tap accelerates the ball, it exerts a force on the ball. Try

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[2] Assuming that there is only one push at a time. Two simultaneous pushes in opposite directions could cancel each other.

tapping a motionless or moving ball from various directions yourself, and observe it carefully. Exactly when is it accelerating?

———This is a pause for finding a ball and a hammer and trying this.

Observe carefully. The ball accelerates only during the fraction of a second when the hammer is touching it. So the hammer exerts a force on the ball only during this fraction of a second. After the tap, the ball moves at an unchanging speed in a straight line, so there is no force exerted on it. Note that the moving ball does not "have force" and it does not "carry force along with it." A force is like a push. You wouldn't say that the ball "has push."

I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

Newton

Friction and air resistance are two more forces. If you briefly shove a book and let go so that it slides across a table, the book will slow down as it slides. Some force must cause this acceleration (recall that slowing down is one type of acceleration). This force results from the contact between the book and the tabletop, and is exerted by the tabletop on the bottom of the book. This force exists because both surfaces are rough or uneven at the microscopic level, as you can verify by sliding the book across a smoother surface and observing that the (de-)acceleration is reduced. Such a force, by one surface on another surface due to the roughness of the surfaces, is called **friction.**

A fast bullet moving horizontally through air slows a little, so there must be a force on the bullet. This force is caused by the bullet hitting air molecules as it travels. It is called **air resistance.** Air resistance is similar to friction: The bullet slides through the air in somewhat the same way that a book slides across a table.

You know from the preceding chapter that an apple falling freely to the ground accelerates all the way down. Since the apple accelerates, there must be a force on it, commonly called the **force of gravity.** But remember that forces are always actions by one object on another object. Gravity is a force *on* the apple, but what is this force exerted *by*? The answer is that it is exerted by planet Earth. The experimental evidence for this is that no matter where you go on Earth, a falling apple always accelerates downward, toward Earth's center. You can think of a **gravitational force** as a pull, although not a human, muscular pull. It's a pull by Earth on nearby bodies.

There's an interesting difference between gravitational forces and the other forces we've looked at. Hand pushes, hand pulls, hammer taps, string pulls, friction, and air resistance all are contact forces: forces exerted by an object that is touching another object. The gravitational force by Earth on a falling apple is different, because Earth is not actually touching the apple while it falls. Air is touching the apple, but you could imagine removing the air and the apple would still fall. The gravitational force acts at a distance, across empty space.

4.2 CONNECTING FORCE AND ACCELERATION

The crux of Newton's theory of motion is really simple: *forces cause accelerations.* It's a surprising idea, as you saw in Chapter 3. Our Aristotelian intuitions tell us that outside influences are needed to keep something moving, that is, that forces cause (or maintain) *velocities.* But Newton says no force is needed to keep a thing moving, and that forces instead cause *accelerations.*

Newton formulated the specific relation between force and acceleration. To follow his reasoning, suppose that you put a smooth ball on a smooth table and tap it once with a hammer. As you know, it accelerates during the tap. Experience shows that the more strongly you tap, the faster it will be moving after the tap. So stronger forces cause larger accelerations. When this kind of experiment is done quantitatively, it is found that as the force on an object increases, the object's acceleration increases in exactly the same proportion: A doubled force causes a doubled acceleration, a tripled force causes a tripled acceleration, and so forth. So an object's acceleration is proportional to the total force exerted on it. In symbols,

$$a \propto F$$

> **How do we know that acceleration is proportional to force?** The proportionality between acceleration and force can be demonstrated by using a setup such as **Figure 4.3**: A coaster (Figure 3.6) glides without friction, pulled by a spring. Measuring the coaster's acceleration with clocks and rulers, one finds that an unchanging pulling force (Figure 4.3a) causes an unchanging acceleration and that a doubled pulling force (Figure 4.3b) causes a doubled acceleration.

Now imagine exerting forces on a light ball and a heavy ball. You'll find that, if you give them equal taps, the light ball accelerates into faster motion than does the heavy ball. So the light ball has a larger acceleration during the tap. It's useful to extend the concept of inertia (Section 3.3) to this situation. Recall that an object's inertia is its ability to maintain its velocity. Since the heavier ball changes its velocity the least, we say that it has more inertia than the light ball, using the word **inertia** to mean a body's resistance to acceleration.

It might seem, offhand, that "inertia" means pretty much the same thing as "weight," because the heavier or "weightier" ball has more inertia. And in fact an object's inertia and its weight are pretty much the same thing so long as the object is near Earth's surface. However, *weight and inertia are actually different things.* Convincing evidence of this key fact comes from the study of objects in outer space, objects such as the many isolated rocks moving through our solar system. If you were in distant space holding such a rock in your hand, and then released it, the rock wouldn't "fall"; it would instead remain "floating" in front of you. But if you

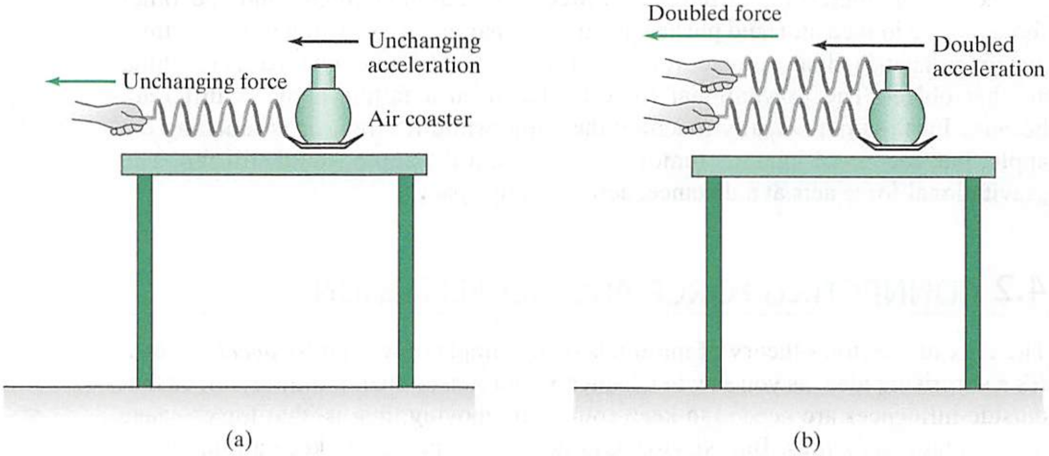

Figure 4.3
Quantitative demonstration that acceleration is proportional to force. (a) An unchanging pulling force causes an unchanging acceleration of a frictionless coaster along a horizontal surface. (b) If the pulling force is doubled, the acceleration is also doubled.

push it with your hand, you'll find that it resists your push. A huge push is needed to get a large boulder moving at even a slow speed. *A rock in space has inertia, even though it has no weight.* As you'll see in the next chapter, such an object has no weight because weight is the force of gravitational attraction and is too small to notice in deep space.

It's useful to define inertia quantitatively. When inertia is made quantitative, it's called *mass*. That is, *the* **mass** *of an object is its amount of inertia.* To establish a measurement scale for mass, scientists choose one particular object, called the **standard kilogram,** and define its mass to be one **kilogram,** abbreviated kg (**Figure 4.4**). There are good duplicates of it in most physics laboratories. Any object having the same inertia as the standard kilogram is said to have a mass of 1 kilogram. And any object having the same inertia as 2 kilograms bundled together has a mass of 2 kilograms. The mass of any object is defined in this way, by comparing its inertia with that of 1 or more kilograms (or with half a kilogram or some other fraction).

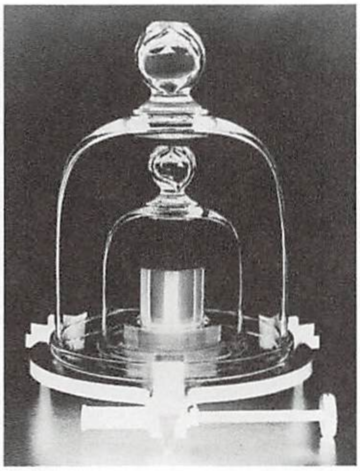

Figure 4.4
The U.S. National Standard Kilogram no. 20, an accurate copy of the International Standard Kilogram kept at Sèvres, France. It is stored inside two bell jars from which air has been removed.

Now, suppose you conducted further "coaster" experiments such as those shown in Figure 4.3, but that this time you maintained an unchanging pulling force while varying the amount of material being pulled (**Figure 4.5**). Figure 4.5a shows a single coaster being pulled, and Figure 4.5b shows a double coaster (two identical coasters linked together) being pulled by the same force. The acceleration should be smaller in case (b), because the greater amount of material has greater inertia. But how much smaller? The experimental answer turns out to be that the doubled coaster has *half* as much acceleration as the single coaster. And three coasters would have *one-third* as much acceleration, and so forth. We express this by saying that an object's acceleration is **proportional to the inverse** of its mass. Since the inverse of a number is 1 divided by that number, this is abbreviated as $a \propto 1/m$.

You learn something else from this experiment: *An object's mass (its inertia) is a measure of the "quantity of matter" (amount of material, number of atoms) it contains.* For example, there is twice as much matter in the doubled coaster as in the single coaster, and also twice as much mass.

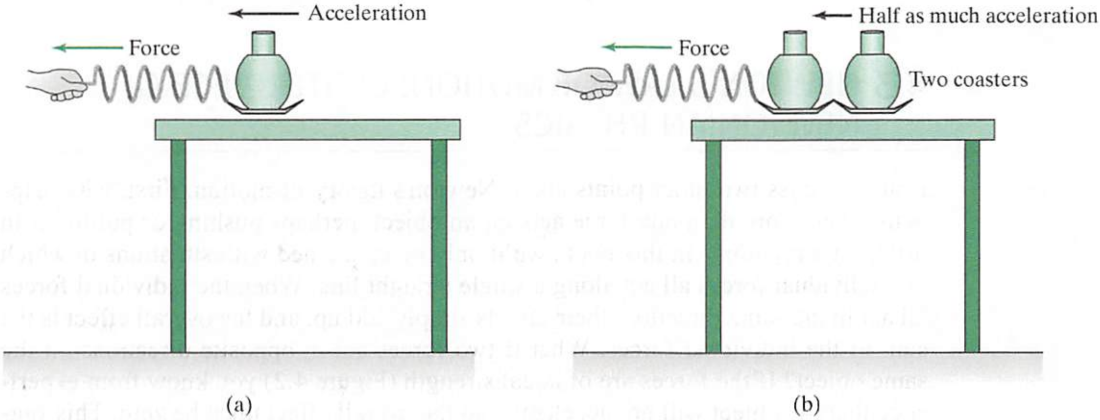

Figure 4.5
Quantitative demonstration that acceleration is inversely proportional to mass. (a) Pulling on an air coaster causes the coaster to accelerate, as in Figure 4.3. (b) Pulling on two air coasters (twice as much mass), with the same force as in (a), causes half as much acceleration.

Our two proportionalities, $a \propto F$ and $a \propto 1/m$, can be put together to read

$$\text{acceleration} \propto \text{force/mass}; \qquad a \propto F/m$$

In words: An object's acceleration is proportional to the force exerted on it divided by its mass.

We need a measurement scale for force. The unit of force, called the **newton** (abbreviated **N**), is defined as the amount of force that can give a 1 kg mass a 1 m/s^2 acceleration. So the proportionality becomes an equality:

$$\text{acceleration} = \text{force/mass}; \qquad a = F/m$$

This formula gives the acceleration in m/s^2, provided the force is in N and the mass in kg. In the U.S. system of units, force is measured in pounds. One newton is a little less than a quarter of a pound. Think of a quarter-pound (a single stick) of butter.

CONCEPT CHECK 1 A giant rock several kilometers across is at rest in outer space, far from all outside influences. A small, slow-moving pebble lightly "taps" the rock and bounces off. What does the rock do? (a) It accelerates up to a slow speed during the tap, and then comes quickly back to rest. (b) It accelerates up to a slow speed during the tap, and then comes gradually back to rest. (c) It accelerates up to a slow speed during the tap, and then continues moving at that speed. (d) It doesn't accelerate at all. (e) It accelerates up to a high speed during the tap, and then continues moving at that speed. (f) It turns into a frog.

CONCEPT CHECK 2 Imagine you are in space and so far from all astronomical bodies that gravity is negligible, with two blocks of metal in front of you. They look identical, but you have been informed that one is made of aluminum and the other of lead (which, on Earth, would be much heavier than aluminum). You could determine which one is which by (a) giving them equally strong hammer taps—the one that then moves more slowly is aluminum; (b) giving them equally strong hammer taps—the one that then moves more slowly is lead; (c) holding them in your two hands—the heavier one is aluminum; (d) holding them in your two hands—the heavier one is lead; (e) actually, none of these methods would work.

4.3 NEWTON'S LAW OF MOTION: CENTERPIECE OF NEWTONIAN PHYSICS

I must discuss two other points about Newton's theory of motion. First, what happens when more than one force acts on an object, perhaps pushing or pulling it in different directions? In this book, we'll only be concerned with situations in which the individual forces all act along a single straight line. When the individual forces all act in the same direction, their effects simply add up, and the overall effect is the sum of the individual forces. What if two forces act in opposite directions on the same object? If the forces are of equal strength (Figure 4.2) you know from experience that the object will not accelerate, so the overall effect must be zero. This suggests subtracting the two forces. This suggestion is correct.

So two or more forces acting in the same direction have the same overall effect as a single force equal to their sum, while two forces acting in opposite directions have an overall effect equal to their difference and acting in the direction of the larger force. We call this overall effect the **net force.**

For instance, if you push your book along a tabletop with a force of 10 N and the tabletop exerts a 3 N frictional force on the book (Figure 4.6), the net force on the book is 7 N. These 7 newtons represent the net, overall effect of the external environment pushing and pulling on the book. It is this 7 N net force, and not just your 10 N pushing force, that accelerates the book.

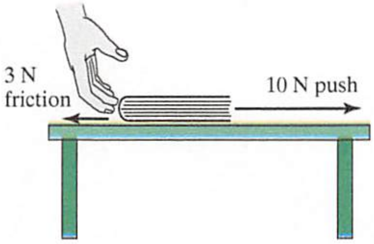

Figure 4.6
How strong and in what direction is the net force on the book?

The second point is the direction of the acceleration. Since forces have directions, and since acceleration is proportional to force, it is not surprising that acceleration should have a direction, too. So far, the only accelerations I have discussed quantitatively were ones in which an object was speeding up along a straight line. In this case, the direction of the acceleration is forward, because the change in velocity is in the forward direction (Figure 4.7). What about an object slowing down along a straight line? Since the velocity gets smaller, the change in velocity is backward (Figure 4.8). This means that the acceleration is backward, opposite to the velocity. The next chapter discusses the direction of the acceleration in cases where the object does not move along a straight line.

Since an object's acceleration is determined by the net force on it, it seems plausible that the acceleration's direction should be the same as the net force's direction. Simple experiments verify this: If you give a motionless ball a brief hammer tap, it will accelerate into motion along the direction in which you tapped, so the acceleration is along the direction of the force. If the ball is already moving and you tap it from behind, it will speed up; the acceleration is forward, again along the direction of the force. And if you tap a moving ball lightly from in front, the ball will slow down; this is a backward acceleration, which again is along the direction of the force. I'll save the case of a sideways force, which is neither forward nor backward, for the next chapter.

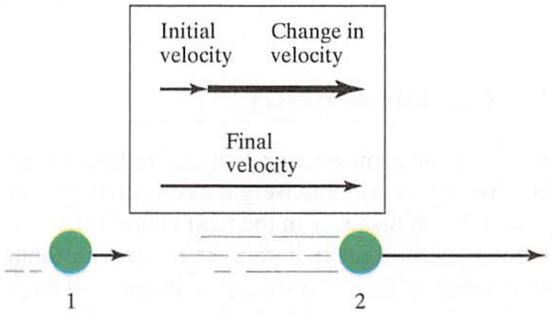

Figure 4.7
When an object speeds up along a straight line, its change in velocity is along the direction of the motion.

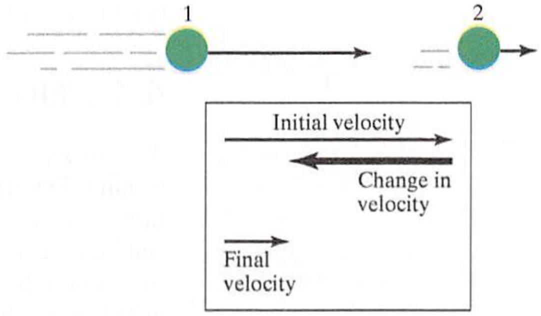

Figure 4.8
When an object slows down along a straight line, its change in velocity is opposite to the direction of the motion.

In summary:

Newton's Law of Motion[3]

An object's acceleration is determined by its mass and by the net force exerted on it by its environment. The direction of the acceleration is the same as the direction of the net force. Quantitatively, the acceleration is proportional to the net force divided by the mass:

$$\text{acceleration} \propto \frac{\text{net force}}{\text{mass}}; \quad a \propto \frac{F}{m}$$

If force is measured in newtons, mass in kilograms, and acceleration in m/s^2, the proportionality becomes an equality:

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}; \quad a = \frac{F}{m}$$

CONCEPT CHECK 3 A slow car moves at a steady 10 km/hr down a straight highway while another car zooms past at a steady 120 km/hr. Which car has the greater net force on it? (a) The slower one. (b) The faster one. (c) The one having the greater air resistance and rolling resistance. (d) None of the above.

CONCEPT CHECK 4 You push your 2 kg book along a tabletop, pushing it with a 10 N force. If the book is greased so that friction is negligible, the book's acceleration (a) is 5 m/s^2; (b) is 10 m/s^2; (c) is 20 m/s^2; (d) is 0.2 m/s^2; (e) keeps getting larger and larger as long as you keep pushing; (f) keeps getting smaller and smaller as long as you keep pushing.

CONCEPT CHECK 5 Follow-up on Concept Check 4: A nongreased book also has a mass of 2 kg and is pushed with a 10 N force, but now there is a 4 N frictional force. The book's acceleration is (a) 12 m/s^2; (b) 20 m/s^2; (c) 28 m/s^2; (d) 3 m/s^2; (e) 5 m/s^2; (f) 2 m/s^2.

4.4 WEIGHT: GRAVITY'S FORCE ON A BODY

As you know, Earth exerts a gravitational force on objects that are falling to the ground. This force is called "weight." An object still has weight even when it's not falling, as when it's at rest on the ground. We'll discover in the next chapter that the sun, moon, planets, stars, and all other astronomical bodies exert gravitational forces, too. It's useful to extend the meaning of the word *weight* to include all such possibilities. In other words, the **weight** of an object refers to the net gravitational force exerted on it by all other objects. Since weight is a force, it can be measured in newtons. In U.S. units, weight is measured in pounds.

Weight and mass are related concepts, but they certainly are not the same thing. An object's weight is the force on it due to gravity, whereas its mass is its quantity of inertia. Weight is measured in newtons (or pounds, in U.S. units) while mass is measured in kilograms. An object's weight depends on its environment; for

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[3] Often called, boringly, Newton's second law.

instance, an object's weight is less when it is on the moon than when it is on Earth, because the force of gravity is smaller on the moon than on Earth. But an object's mass is a property of the object alone and not of its environment, so its mass is the same on the moon as on Earth. For example, a kilogram has a mass of 1 kilogram regardless of whether it is on Earth or on the moon or in distant space, but its weight is about 10 N (or 2.2 pounds) on Earth, only 1.6 N on the moon, and essentially zero in distant space.

If you drop a stone and a baseball, Galileo's law of falling tells us that their accelerations will be the same (neglecting air resistance). If the stone and baseball happen to have the same mass, Newton's law of motion tells us that the forces on them are the same. But this force is just the force of gravity, which means that their weights are equal. This is a plausible and important conclusion: *Two objects of equal mass also have equal weight,* so long as you measure both weights at the same place (you wouldn't want to measure one on Earth and the other on the moon). So you can compare masses by comparing weights, for instance on a balance beam (**Figure 4.9**). Any object that balances a kilogram has a mass of 1 kilogram, for example.

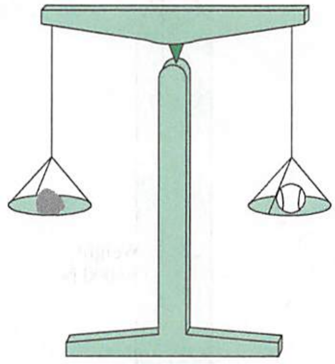

Figure 4.9
You can compare masses by comparing weights, for instance on a balance beam. Since they balance, the stone and the baseball have equal masses.

The **metric ton,** or **tonne** (it's always spelled this way), equal to 1000 kilograms, is useful for measuring larger masses. The similar U.S unit—the ton—is 2000 pounds. On Earth, the mass of a ton is about 900 kilograms, so a ton is a little less massive than a tonne. As you can see, the U.S system gets needlessly confusing, so you'll perhaps be glad to hear that I'll henceforth dispense with it entirely.

For example, consider this book resting on a table. Suppose it weighs 12 N, meaning that the gravitational force by Earth on the book is 12 N. This force has a downward direction. But the book is obviously not accelerating downward through the table. Since the book's acceleration is zero, Newton's law of motion tells us that the net force on it must also be zero. So there must be an upward force of 12 N acting on the book to balance the downward weight. The table must exert this force, because if the table vanished the book would fall.

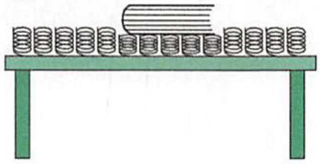

Figure 4.10
As an explanation of the normal force by a table on a book, imagine that the tabletop is covered with small springs. When the book rests on the table, it squeezes the springs, causing the springs to push back against the book.

It may seem strange that an inanimate object could exert a force. Why should a table push on a book? The tabletop doesn't seem to be doing anything. A microscopic view is enlightening. The upward force is exerted by the atoms in the tabletop on the atoms in the book's bottom.[4] When the book presses against the tabletop, the tabletop is squeezed down and slightly deformed. And like a squeezed spring, the atoms then push upward against the book (**Figure 4.10**). The direction of this force by the tabletop is directly away from the surface, perpendicular to it. A force similar to the upward force by the table on the book is exerted when any object touches a solid surface. Physicists call any such force a **normal force,** because "normal" means perpendicular.

Figure 4.11 shows the forces exerted on the book. Each force is represented by an arrow. A **force diagram** like this can help in analyzing forces and motion. When you draw a force diagram, show every one of the individual forces acting on whatever object is of interest. Show each force as an arrow pointing in the direction in which that force pushes or pulls on the object, and name each force.

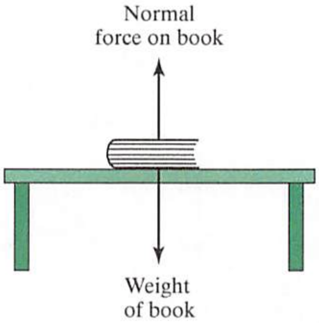

Figure 4.11
The forces exerted on a book at rest on a table.

As another example, suppose that a rocket at liftoff weighs 150,000 N and has a mass of 15,000 kg and that the rocket engines exert a 210,000 N "thrust" force on

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[4] More precisely, this force is an electric force by the electrons in the table's atoms on the electrons in the book's atoms. Electrons repel one another strongly when they get very close together.

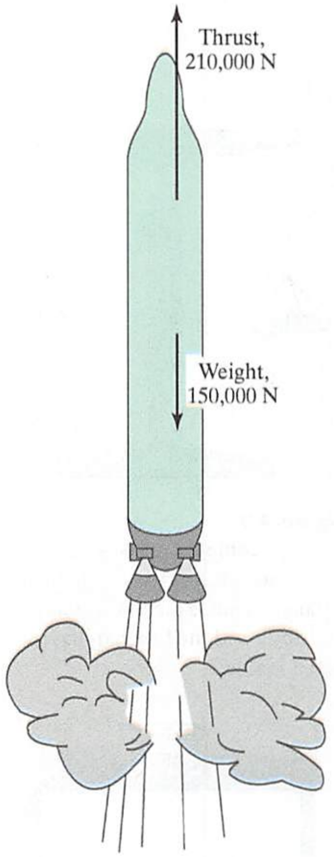


Figure 4.12
The forces exerted on a rocket during liftoff. Note that the diagram shows only the individual forces and not the 60,000 N net force. The 60,000 N net force is not an individual force (it is the sum of all the individual forces) and hence is not shown.

the rocket (**Figure 4.12**). (You'll learn more about the thrust force in the next section.) How large is the net force on the rocket, and how big is the rocket's acceleration? Solution: The net force is 210,000 N – 150,000 N = 60,000 N upward. It is only this 60,000 N that actually accelerates the rocket. To find the acceleration, Newton's law of motion says to divide the net force by the mass: 60,000 N/15,000 kg = 4 m/s^2.

CONCEPT CHECK 6 Suppose the rocket develops a thrust of only 165,000 N. The acceleration is then (a) 4 m/s^2; (b) 3 m/s^2; (c) 2 m/s^2; (d) 1 m/s^2; (e) 0 m/s^2.

CONCEPT CHECK 7 An astronaut on Earth has a mass of 70 kg and a weight of 700 N. On the moon, the astronaut's mass and weight will be (a) 11 kg and 700 N; (b) 70 kg and 110 N; (c) 11 kg and 110 N; (d) 70 kg and 700 N.

CONCEPT CHECK 8 Would it be easier to lift this book on Earth or on the moon? (a) On the moon, because the book's weight would be smaller. (b) On the moon, because the book's mass would be smaller. (c) On Earth, because the book's weight would be smaller. (d) On Earth, because the book's mass would be smaller. (e) Same in both places.

4.5 THE LAW OF FORCE PAIRS: YOU CAN'T DO JUST ONE THING

How do we know that forces always come in pairs? Try these: Slap a tabletop with your hand. Grasp the edge of a table and pull hard on it. Now push hard on it. Find two balls of any kind; place one at rest on a smooth surface and roll the other one toward it so that they collide.

——Pause. I hope you're actually doing some of this stuff that I suggest. It keeps your brain awake.

When you slap a table, it slaps back, as you can feel when it stings your hand. This slap by the table is a force, because it accelerates your hand (by stopping your hand). When you pull on a table, the table pulls you toward it. And when you push on the table, the table pushes you away. These are forces exerted by the table on you. When the balls collide, the ball you rolled (call it the first ball) exerts a force on the second ball, as you can see from the fact that the second ball accelerates into motion. But the second ball exerts a force on the first ball, too, as you can see from the fact that the first ball's velocity changes. These experiments indicate that whenever one object exerts a force on a second object, the second exerts a force on the first: Forces always come in pairs, called **force pairs.**

Do things still work out this way even if the two objects are not touching? You could investigate this with a pair of magnets. Place the magnets on a smooth surface and hold them at rest with their poles near each other but not touching. When you release them, they both accelerate (if they don't then find a smoother surface). So each exerts a force on the other.

Physicists like to think of every force as an *interaction between two objects,* rather than as something one object does to another. If you think of slapping a table as an *interaction* between your hand and the table, it's natural to conclude that each exerts a force on the other.

Touch your friend's face. Your hand is touched by your friend's face. You cannot touch without being touched.[5]

Slap lightly on a tabletop. Now slap hard. The table slapped back harder the second time, right? This gives us quantitative information about force pairs: When one member of a force pair grows bigger, so does the other. In fact, quantitative experiments show that the two members of any force pair have the same strength. If one of them is, say, 3.71 newtons, the other one will be 3.71 newtons too. The directions of the two forces in a force pair are not the same, however. In fact, our examples show that they are in opposite directions. For instance, when you pull a table toward you, the table pulls you toward it (**Figure 4.13**).

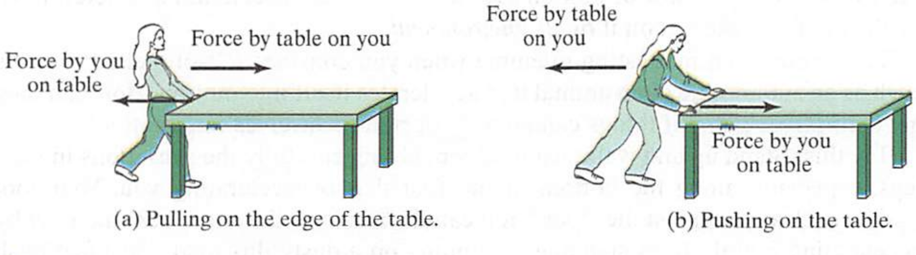
Newton recognized this idea as a key physical principle. I'll summarize it as follows:

The Law of Force Pairs[6]

Every force is an interaction between two objects. Thus, forces must come in pairs: Whenever one body exerts a force on a second body, the second exerts a force on the first. Furthermore, the two forces are equal in strength but opposite in direction.

The fact that the two forces always have exactly the same strength is surprising. This says, for example, that a bug hits a car with the same force that the car hits the bug! Surprising—but true. However, these equal forces cause vastly different *responses* in the bug and the car: The bug feels an enormous acceleration, while the car experiences a barely measurable acceleration. The reason for this difference is Newton's law of motion, and the vastly different masses of the bug and the car.

Figure 4.14 illustrates an interesting point. Since Earth exerts a gravitational force on an apple, the law of force pairs says that the apple must exert a gravitational force on Earth! Furthermore, the strengths of these two forces must be equal: If Earth exerts a 2 N force on the apple, then the apple must exert a 2 N force on Earth. This might seem surprising. Why haven't you noticed this force, by apples and other objects, on Earth? Why doesn't Earth accelerate toward the apple?



(a) Pulling on the edge of the table. (b) Pushing on the table.

Figure 4.13
When you pull or push on a table, it pulls or pushes on you in the opposite direction.

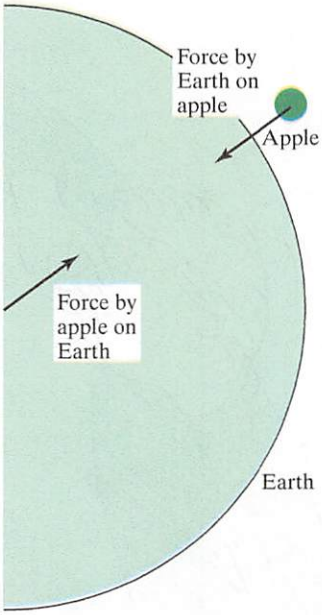


Figure 4.14
Earth and a falling apple: Which one exerts the larger force? (Answer: They are the same).

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[5] Thanks to my friend Paul Hewitt, author of *Conceptual Physics*, 10th ed. (New York: Addison Wesley 2006), for this nice way of putting it.

[6] Often called, boringly, Newton's third law.

The answer is that an apple causes only a slight acceleration of Earth because Earth's mass is so large. You can't use an apple to noticeably accelerate a planet. Large astronomical objects, however, can noticeably accelerate a planet. For example, scientists can detect Earth's acceleration in response to the motions of the moon.

CONCEPT CHECK 9 Your hands push a heavy box across the floor. The other member of the force pair is (a) friction pushing backward on the box; (b) gravity pulling downward on the box; (c) the box pushing backward against your hands; (d) the box pushing downward against the floor.

As you can see from Concept Check 9, the two forces in a force pair always act on different objects; your hands exert a force on the *box,* while the box pushes back against *your hands.* Similarly, if a rope pulls forward on a water skier, the skier pulls backward on the rope. So both the skier and the rope feel forces. The first force keeps the skier moving forward, while the second force keeps the rope taut.

CONCEPT CHECK 10 A big truck and a small car collide head on. Regarding the forces: (a) the truck exerts a larger force on the car than the car does on the truck; (b) the car exerts a larger force on the truck than the truck does on the car; (c) the truck and car exert equally large forces on each other.

CONCEPT CHECK 11 Regarding the accelerations in the preceding question: (a) The truck's acceleration is largest; (b) The car's acceleration is largest; (c) The truck and the car have equally large accelerations.

4.6 NEWTON MEETS THE AUTOMOBILE

You can't get anywhere by pulling on your nose. Try it (**Figure 4.15**)! You might pull your nose out of joint, but you won't go anywhere because your nose pulls back on your hand, and both pulls are on your body, so they result in zero net force on your body—they "cancel out." The same argument shows that you can't get anywhere by pushing or pulling anywhere on your own body. If you want to accelerate, something outside of you—something in your *environment*—must exert a force on you. That's why Newton's law of motion says that an object's acceleration is determined by the net force exerted on it *by its environment.*

Figure 4.15
You can't get anyplace by pulling on your nose.

This presents an interesting dilemma when you consider self-propelled[7] objects such as an automobile or an animal that accelerates itself into motion. How can they get themselves going if things cannot push or pull themselves into motion?

Try this: Stand up and walk just one step, noting carefully the sensations in your legs, especially along the bottom of the foot that is accelerating you. Your foot pushes backward against the floor.[8] You can demonstrate this more convincingly by accelerating rapidly from standing to running on a dusty dirt road. Your feet push dust backward, showing that they exert a backward force on the road.

The law of force pairs tells us that when your foot pushes backward on the ground, the ground pushes forward on your foot. Voila! We've discovered the force

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[7] "Self-propelled" means that the energy (Chapter 6) to propel the object comes from within the object itself. But, as we'll soon see, the force to propel it comes from the outside.

[8] ... if you are barefoot. Otherwise, your foot pushes backward against your shoe, which in turn pushes backward against the floor.

that accelerates you forward! It's the *ground* pushing forward on your foot. This force arises from friction between the two surfaces (the surface of the ground and the bottom of your foot), as you can demonstrate by accelerating quickly from rest to a fast run on a nearly frictionless surface such as a smooth sheet of ice (be careful!).

Automobiles are useful applications of Newtonian principles. What's more important, automobile technology has drastically reshaped the social fabric of the modern world. Like all powerful technologies, cars have important social pros and cons. They provide unparalleled freedom of movement, have transformed our cities, use most of our petroleum, create much of our pollution, and are the leading cause of death of Americans under 35. They will come in for lots of discussion in this book.

Before reading further, try listing or drawing the forces exerted on a car by its environment while traveling along a straight, level road.

———(A pause, for listing or drawing.)

As shown in **Figure 4.16**, one force is the gravitational force, or weight of the car, exerted downward by Earth on the car. A second force is the normal force, exerted upward by the road on the car. These two forces act vertically. Since a car on a level road has no acceleration in the vertical direction, the net vertical force must be zero. So these two vertical forces must be of equal strength.

The three horizontal forces relate more directly to the car's motion. Two backward **resistive forces** act on the car: The atmosphere exerts the force of air resistance already discussed in Section 4.1, and the contact between tires and road creates another backward force known as **rolling resistance.** Rolling resistance is caused by flattening of the tire where the rubber meets the road. It turns out that the force that the road exerts on the deformed tire acts to slow the tire's rotation, so the road exerts a retarding (backward) force on the car. This is most pronounced in more flexible, air-filled tires. Hard tires rolling on a smooth, hard surface, such as steel wheels on steel tracks, reduce rolling resistance to a minimum—one reason trains are far more energy efficient than cars. Rolling resistance also explains why under-inflated tires reduce your gas mileage. High-mileage cars such as the Toyota Prius use special low-rolling-resistance tires for this same reason.

The four forces discussed so far act even on a car that is coasting with its engine shut off. If these are the only forces on the car, then the net force must be backward, so the acceleration is backward and the car must slow down. But when a car is driving instead of coasting, there is an additional force on it. It's a misconception to think that this force is exerted by the engine, because things cannot accelerate themselves and the engine is part of the car. Instead, the engine causes the drive wheels to turn; the drive wheels exert a frictional force backward against the road; and (because of the law of force pairs) the *road* in turn exerts a frictional force forward against the drive wheels.

If the car moves at an unchanging velocity, there is no acceleration. Newton's law of motion tells us that the net force must then be zero, which means that the five forces shown in Figure 4.16 must balance. In this case, the forward force on the drive wheels must equal the sum of the two resistive forces. In order for the car to speed up, the forward frictional force on the drive wheels must be larger than the sum of the two resistive forces; in order for the car to slow down, this forward force must be smaller than the sum of the resistive forces.

Most other self-propelled objects are similar to this: A swimmer pushes backward on the surrounding water, and the water pushes forward on the swimmer. A motorboat's propeller pushes backward on the water, and the water pushes forward on the propeller. An airplane's propeller pushes backward on the surrounding air,

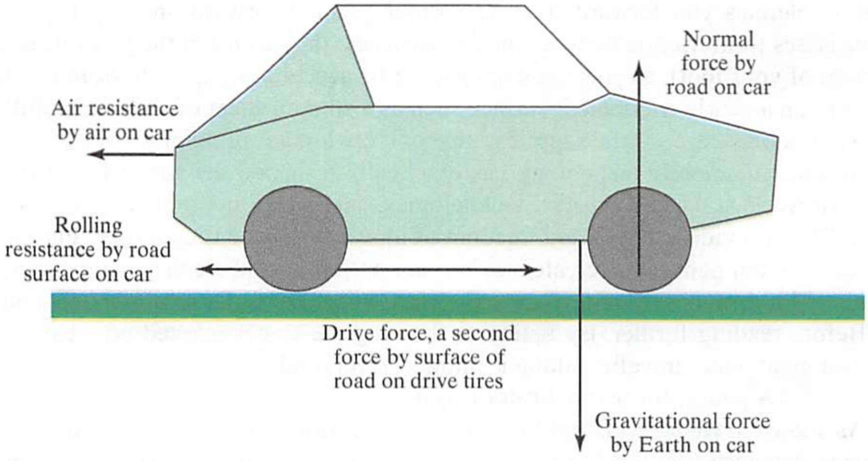

Figure 4.16
The five forces on an automobile.

and the air pushes forward on the propeller. A jet airplane pushes air backward, too. As a jet engine moves through air, the air flowing into its front end heats by combustion with jet fuel, and the heated gas expands and rushes out of the back end at high velocity.

One nice thing about space travel is that there are no resistive forces in space, so you don't need a forward force by the environment on the spaceship to keep going. Your spaceship keeps going because of the law of inertia. But if you want to accelerate your spaceship—by changing its direction for instance—you have a problem. It's difficult to get the surroundings to exert a force on your spaceship because there's nothing around to push against!

You would have a similar problem if you were stranded in the middle of a smoothly frozen pond. If the ice were absolutely smooth, you could not walk off it because, with no friction, you could not push backward on the ice. How could you get off? You could fan the air, pushing air backward in the way that a swimmer pushes water backward. That would work. But suppose that, as in space, there were no air. What then? Well, suppose you had something with you that you could throw away—your physics book, or a shoe. While throwing your shoe, you would push on the shoe, so it would push in the other direction on you, so your body would accelerate away from the shoe. When you let go of the shoe, you would have acquired a velocity. So you would slide along the pond.

This is the principle of **rocket propulsion.** Rockets take along their own material just to have something to push against. Shoes would work, but they aren't terribly practical (**Figure 4.17**). The rocket fuel for the U.S. space shuttle's main rocket engines is hydrogen and oxygen, stored as low-temperature liquids. When combined, their combustion produces steam, which accelerates rapidly out the back end of the engine. Thanks to the law of force pairs, this backward push by the shuttle on the steam means that the escaping steam must push the shuttle forward.

There are about 1000 large "near Earth asteroids" in our solar system—rocks more than 1 kilometer in diameter that orbit the sun and can cross Earth's orbit and can therefore hit us, possibly dealing civilization a death blow. People are thinking about methods to nudge such rocks off course in case one of them is discovered heading for Earth. One suggested method: Send a space probe to attach itself to the asteroid, scoop up rock, and hurl it away. Thus is just like hurling shoes: The asteroid would react by moving in the opposite direction, deflecting it from its collision course. The law of force pairs comes to the rescue!

Figure 4.17
Shoe power.

CONCEPT CHECK 12 A car weighing 10,000 N moves along a straight, level road at a steady 80 km/hr. Air resistance is 300 N, and rolling resistance is 400 N. The net force on this car (a) is 10,000 N; (b) is 9300 N; (c) is 10,700 N; (d) is 700 N; (e) cannot be determined without knowing the strength of the drive force; (f) is zero.

CONCEPT CHECK 13 In the preceding question, the strength and direction of the drive force are (a) 10,000 N forward; (b) 700 N backward; (c) 700 N forward; (d) 400 N forward; (e) zero.

4.7 MOMENTUM

An object's **momentum** is defined as its mass times its velocity. It's conventional to abbreviate it with the symbol "p" (I have no idea why):

$$\text{momentum} = \text{mass} \times \text{velocity}$$
$$p = mv$$

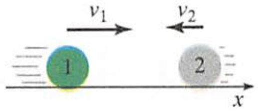

Figure 4.18
Two pool balls, moving along the x-axis in the + and – direction, respectively, about to collide.

Momentum measures an object's "amount of motion"—how much mass is moving how fast. It's useful in connection with any "system" (this word simply means a collection of objects) of two or more objects that interact with each other via "internal" forces—forces exerted by objects in the system on other objects in the system. A good example is two colliding pool balls. When they collide, each ball exerts a brief force on the other during the short time they're in contact. As a result of these forces, both balls accelerate—usually changing both the magnitude (speed) and direction of their velocity. To keep things simple, suppose the balls collide head-on so that all motion occurs along a single direction, call it the x-axis (Figure 4.18).

One reason momentum is important in physics is that it's one of nature's "conserved quantities," in other words a system's total momentum remains unchanged throughout collisions such as is shown in Figure 4.18, despite the changes in both balls' velocities during the collision. Here's why:

How do we know momentum is conserved? During the short impact time, which we'll call Δt, each ball experiences a change in velocity, which we'll call Δv_1 and Δv_2. (The symbol Δ is often used to mean "a change in"). According to the definition of acceleration (Section 3.5), the accelerations of ball 1 and ball 2 during the impact are $\Delta v_1/\Delta t$ and $\Delta v_2/\Delta t$. Using Newton's law of motion and Newton's law of force pairs and making the important assumption that *the only significant forces acting on either ball during the collision are the force by ball 1 on ball 2 and the force by ball 2 on ball 1,* a little algebra[9] shows that the change in the quantity $m_1 v_1$ is equal in magnitude but opposite in direction to the change in the quantity $m_2 v_2$. In symbols,

$$\Delta (m_1 v_1) = -\Delta (m_2 v_2)$$

The minus sign means "in the opposite direction along the x-axis." In other words, the change in the first object's momentum is the negative of the change in the second object's momentum. But this means that the *sum* of the two momenta (plural of *momentum*) doesn't change at all during the collision.

Momentum has a direction, namely the same direction as the velocity. For motion along a single axis, the direction can be indicated by a + or – sign: A positive momentum is along the +x direction, while a negative momentum is along the –x direction.

I showed above that the total momentum $p_1 + p_2$ remains unchanged throughout the collision, where **total momentum** means the sum of the two individual momenta, with the directions (+ or –) included. This important result is known as **conservation of momentum.** Remember that it only applies so long as there are no external forces (forces other than the internal forces by each object on the other) on the system.

For instance, suppose that ball 2 is initially at rest and ball 1, moving with a velocity of +3 m/s (the + emphasizes that it's in the +x direction), hits it. Then the system's total momentum before collision is

$$m_1 v_1 + m_2 v_2 = m \times (3\ \text{m/s}) + m \times 0 = (3\ \text{m/s})\, m,$$

where "m" means the mass of either ball (pool balls all have the same mass). Conservation of momentum says that the total momentum after collision must also be 3 m:

$$p_1 + p_2 = (3\ \text{m/s})\, m$$

or

$$m v_1 + m v_2 = (3\ \text{m/s})\, m$$

or (with simple algebra)

$$v_1 + v_2 = 3\ \text{m/s}$$

---

[9] Newton's law of motion applied to each ball tells us

$$\Delta v_1/\Delta t = F\,(\text{on ball 1})/m_1 \text{ and } \Delta v_2/\Delta t = F\,(\text{on ball 2})/m_2.$$

Multiply both sides of the first equation by m_1 and both sides of the second equation by m_2 to get

$$m_1\, \Delta v_1/\Delta t = F\,(\text{on ball 1}) \text{ and } m_2\, \Delta v_2/\Delta t = F\,(\text{on ball 2})$$

But Newton's law of force pairs says that the force on 1 by 2 and the force on 2 by 1 are equal and opposite, in other words

$$F\,(\text{on ball 1}) = -F\,(\text{on ball 2}).$$

It follows that

$$m_1\, \Delta v_1 = -m_2\, \Delta v_2.$$

But m_1 is just a fixed number, so m_1 times the change in v_1 is the same as the change in $m_1 v_1$, and the same goes for ball 2. So the previous equation says that $\Delta (m_1 v_1) = -\Delta (m_2 v_2)$.

where v_1 and v_2 now represent the two balls' final velocities. This result could be useful: If you knew one of the two final velocities, you could find the other. For instance, suppose ball 1 stops when it collides with ball 2. Then $v_1 = 0$ and our result says that $v_2 = +3$ m/s. So ball 2 takes off with the same velocity ball 1 had just before the collision.

For another instance, suppose the balls are made of soft clay and that they stick together after collision. Then $v_1 = v_2$ and so $v_1 + v_2 = 3$ m/s tells us that $2v_1 = 3$ m/s. Simple algebra then says that $v_1 = v_2 = +1.5$ m/s.

CONCEPT CHECK 14 If ball 2 takes off with a velocity of 2 m/s, ball 1's final velocity is (a) 0 m/s; (b) 0.5 m/s; (c) 1 m/s; (d) –1 m/s (in the –x direction); (e) 1.25 m/s.

For yet another oddball (so to speak) instance, suppose both balls are covered with a small amount of gunpowder, in such a way that a small explosion occurs when they collide. And suppose that the explosion sends ball 2 zooming off with a velocity of +10 m/s. Notice that momentum must be conserved even in this situation, because all the significant forces on the balls during the collision/explosion (including the explosive force) are by 1 on 2 and by 2 on 1. If you worked through Concept Check 14, I'll bet you'll be able to work through this problem and conclude that $v_1 = -7$ m/s. Both balls are now moving faster than ball 1 was moving before collision. In the language of Chapter 6, the system gained kinetic energy (energy of motion), and this kinetic energy came from the chemical energy of the gunpowder.

For a violent but instructive example involving objects of different mass, suppose that a 30,000 kg "18 wheeler" truck moving at 20 m/s (72 km/hr) collides head-on into a small 1000 kg car moving in the opposite direction at 20 m/s. Suppose that the car and truck become enmeshed in each other, so that they stick together. How fast is the combined wreckage moving just after the collision (before the frictional force by the road has had time to begin to slow the wreckage)? It's easiest if you let the x-axis be in the direction of the truck's initial motion, so that the car's velocity is negative.

———A pause, for figuring.

The result is that the truck is hardly slowed by the collision; it slows from its initial +20 m/s to +18.7 m/s (the speed of the wreckage). But the car changes its velocity from –20 m/s to +18.7 m/s. This is a huge velocity change of +38.7 m/s in a small fraction of a second, and implies an enormous acceleration and hence (see Newton's law of motion) enormous forces by the windshield, seats, etc., on the car's occupants. Ouch. Notice that the forces on the car driver's body would be much smaller if the driver's velocity change of 38.7 m/s occurred in a much longer time, such as one second instead of a small fraction of a second. This is why air bags and vehicle front-ends designed to crumple slowly upon collision are a good idea. The truck driver, on the other hand, suffers a much more mild velocity change of only 1.3 m/s.

This example gives you a feel for the momentum concept. Momentum involves both mass and velocity, so more massive objects possess more of it, and faster objects possess more of it. Despite the equal speeds of the car and the truck, the truck has far more momentum because of its larger mass. Momentum is a measure of the tendency of an object to keep moving despite forces (such as collisions) that act to change the velocity: The truck slows only slightly, while the car changes its velocity radically.

Conservation of momentum applies to an amazing variety of situations. Here are a few.

First, suppose the pool ball collision is a glancing collision, so that the two balls shoot off into different directions (**Figure 4.19**). The collision is then "two-dimensional," not along a single line but still on the surface of the pool table. Conservation of momentum is still valid; in fact, it applies to each of the two directions on the table (since in this book we're staying away from something ominously called "vectors," I won't go into exactly what this means).

Now suppose there are more than two balls; for instance, suppose the collision is between a cue ball and a rack of 15 pool balls. It's amazing (at least I've always found it amazing) but true that momentum is conserved: The total momentum of all 16 pool balls just after collision equals the momentum of the cue ball just before collision. The 16 balls might be scattering all over the place, but if you add up all 16 momenta[10] you'll find that the result is equal, in both magnitude and direction, to the magnitude and direction of the initial momentum mv of the cue ball! But notice that momentum is conserved only from just before to just after the collision, before any "external forces" such as friction from the table top or bounces from pool table walls have had time to change any of the 16 velocities.

The balls could all have different sizes and masses, and momentum would still be conserved. In fact, I allowed for two different masses in arriving (above) at the principle of conservation of momentum for two pool balls.

The objects needn't physically collide (bang against each other) at all. The "collision" could be between two magnets sliding on a frictionless surface, never touching but simply influencing each others' motion magnetically, or an encounter between two stars that exert gravitational forces on each other and remain millions of miles apart. The two stars' interaction ("collision" isn't the appropriate word here) could take years, but so long as external forces (by other stars, for instance) don't interfere, the total momentum of the two stars remains the same throughout the entire interaction.

We'll find in later chapters that Newton's laws are far from absolute. They break down for fast-moving (comparable to the speed of light) objects, for small objects such as individual molecules, and in situations involving strong gravitational forces or distances stretching across many galaxies. Since Newton's laws break down, it's natural to question the principle of conservation of momentum in these situations. But surprisingly, physicists have checked a wide variety of such situations and found that momentum is always conserved. In fact, a very broad argument based simply on the notion that the laws of physics are the same everywhere in the universe leads to the conclusion that momentum must be conserved in any system that has no external forces exerted on it, regardless of whether Newton's laws are valid.

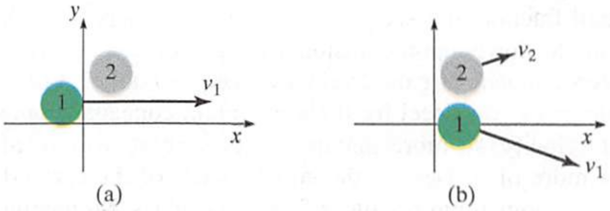

Figure 4.19
A cue ball glancing off another ball, viewed from above. The second ball is initially at rest. Arrows show the initial velocity of the cue ball and final velocities of both balls. Arrows point in the direction of the velocity; longer arrows represent greater speeds. (a) Just before collision. (b) Just after collision.

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[10] Since the collision occurs in two dimensions, the 16 momenta must be added using something called "vector addition," which means roughly that you should add up 16 arrows whose lengths and directions represent the magnitudes and directions of the 16 balls' momenta.

Conservation of momentum seems to be one of the universe's most fundamental principles.

To summarize:

The Law of Conservation of Momentum

The total momentum of any system remains unchanged, regardless of interactions among the system's parts, so long as no part of the system is acted upon by forces external to that system.

Contemporary physicists have learned that many of nature's deepest principles are conservation laws in which some quantity such as momentum remains unchanged over time. We'll encounter two other conservation laws: conservation of energy in Chapter 6, and conservation of electric charge in Chapter 8.

Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

Review Questions

FORCE

1. How can we tell whether a body is exerting a force on another body?
2. Can an object have force? Can an object exert a force? Can an object be a force? Can an object feel a force?
3. List at least six specific examples of forces. Try to list examples that are significantly different.
4. What is a resistive force? Give two examples.
5. Give two examples of forces that act at a distance.

NEWTON'S LAW OF MOTION

6. What does Newton say that forces cause? What does Aristotle say?
7. What do we mean when we say that one object has "more inertia" than another object?
8. When you move an object from Earth to the moon, does its inertia change? Does its weight change? Does its mass change? Does its amount of matter change? Does its acceleration differ while falling freely? Does it respond differently to a net force of 1 N?
9. Forces of 8 N and 3 N act on an object. How strong is the net force if the two forces have opposite directions? The same directions?
10. Is an object's acceleration always in the same direction as its velocity (its direction of motion)? If not, give an example in which it is not. Is an object's acceleration always in the same direction as the net force on the object? If not, give an example in which it is not.
11. As you increase the net force on an object, what happens to its acceleration? What if you double the net force? As you increase the mass of an object (for example, by gluing additional matter to it), what happens to its acceleration? What if you double the mass?

WEIGHT

12. What is weight? Is it the same as mass? If not, what is the difference?
13. Describe a simple way to determine, in a lab, whether two objects have equal masses. Would this method work in distant space? What would work in distant space?
14. Find the gravitational force on a 1 N apple. Would it still weigh 1 N if we took it to the moon?
15. Draw a force diagram showing the forces on an apple at rest on a table. Find the net force on the apple.
16. Draw a force diagram showing the forces on a rocket during liftoff. Which force is largest? What is the direction of the net force?
17. Where is it easiest to lift your automobile: on Earth or on the moon? Where is the automobile's mass larger?

LAW OF FORCE PAIRS

18. Describe several experiments demonstrating that forces come in pairs.
19. Do you exert a gravitational force on Earth? How do you know? What direction is this force?
20. Describe the other member of the force pair for each of the following forces: the normal force on a book lying on a table, the weight of an apple, the force by a bat against a baseball, the force by a baseball hitting a catcher's mitt.

THE AUTOMOBILE

21. Describe four examples of forces that propel "self-propelled" objects.
22. Draw a force diagram showing the forces on a car driving along a straight, level road. How would this force diagram be altered if the car were coasting? What if the car were braking?
23. What is the main difference between propeller-driven airplanes and jet airplanes?
24. How does the forward force on a car compare with the resistive forces when the car maintains a constant speed? When the car is speeding up? Slowing down?
25. When a car moves at constant speed along a straight road, is the forward force (the force that moves the car forward) zero? Is the net force zero? Is the acceleration zero? Is the speed zero?
26. What is the main difference between the force that propels a rocket and the force that propels airplanes and automobiles?

MOMENTUM

27. Conservation of momentum follows logically from two other laws of physics. Which two?
28. Which of the following quantities do you need to know in order to calculate the magnitude of the momentum of an object, and how do you do the calculation: weight, mass, acceleration, velocity, location, length?
29. True or false: Every system's total momentum is always conserved. (Recall that a "system" is any collection of physical objects). Explain your answer.
30. A hunter fires a rifle bullet northward and then spins and fires a second bullet (from the same rifle) southward. Do the two bullets have the same momentum? Explain.
31. Which has greater momentum, a truck at rest or a slow-rolling pool ball?
32. What is the magnitude of the momentum of a 7 kg bowling ball rolling at 3 m/s?