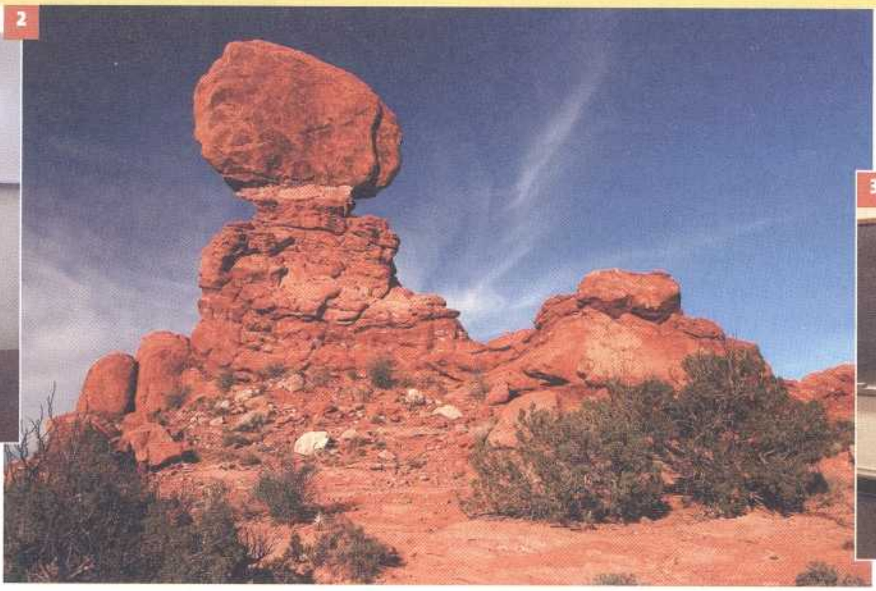
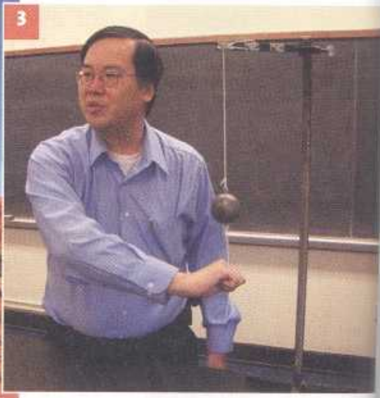
2 Newton's First Law of Motion—Inertia





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

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

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

Isaac Newton (1642–1727)

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

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

Aristotle on Motion

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

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

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

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

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

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

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

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

CHECK POINT

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

Check Your Answer

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

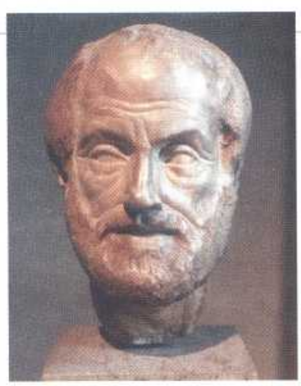
Copernicus and the Moving Earth

Nicolaus Copernicus (1473–1543)

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

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

Aristotle (384–322 BC)



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

Galileo and the Leaning Tower

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

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

FIGURE 2.1
Galileo's famous demonstration.

Galileo's Inclined Planes

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

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Galileo Galilei (1564–1642)

Galileo was born in Pisa, Italy, in the same year Shakespeare was born and Michelangelo died. He studied medicine at the University of Pisa and then changed to mathematics. He developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies. Galileo's experiments with falling bodies discredited Aristotle's assertion that the speed of a falling object was proportional to its weight, as discussed above. But quite importantly, Galileo's findings also threatened the authority of the Church, who held that the teachings of Aristotle were part of Church doctrine. Galileo went on to report his telescopic observations, which got him further in trouble with the Church. He told of his sightings of moons that orbited the planet Jupiter. The Church, however, taught that everything in the heavens revolved around Earth. Galileo also reported dark spots on the Sun, but according to Church doctrine, God created the Sun as a perfect source of light, without blemish. Under pressure, Galileo recanted his discoveries and avoided the fate of Giordano Bruno, who held firm to his belief in the Copernican model of the solar system and was burned at the stake in 1600. Nevertheless, Galileo was sentenced to perpetual house arrest. Earlier, he had damaged his eyes while investigating the Sun in his telescopic studies, which led to blindness at the age of 74. He died 4 years later. Every age has intellectual rebels, some of whom push the frontiers of knowledge further. Among them is certainly Galileo.

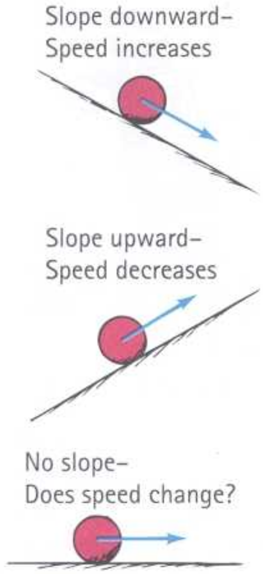

FIGURE 2.2
Motion of balls on various planes.

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

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

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

fyi

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

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

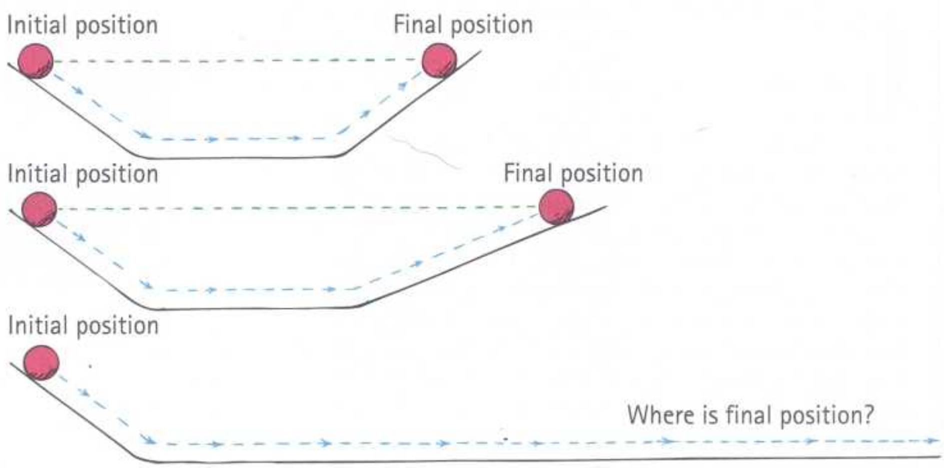

FIGURE 2.3
A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

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

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

CHECK POINT

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

Check Your Answer

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

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

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

Newton's First Law of Motion

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

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

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Inertia of a Cylinder
Inertia of an Anvil

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

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

FIGURE 2.4
Inertia in action.

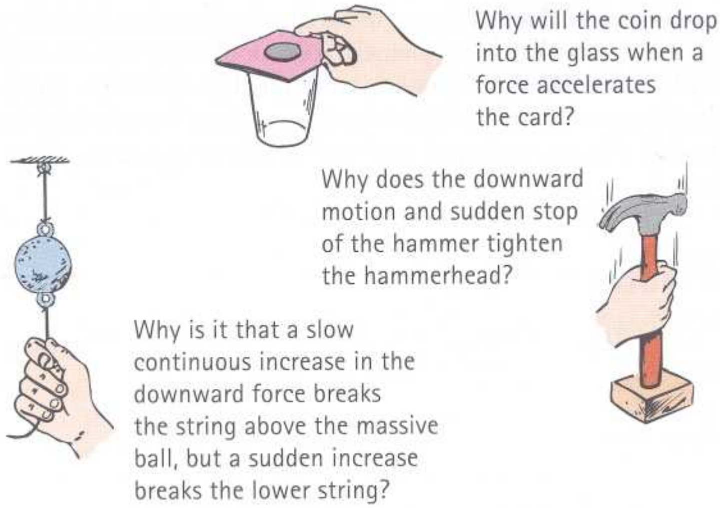

FIGURE 2.5
Examples of inertia.

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

CHECK POINT

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

Check Your Answers

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

Net Force

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Definition of a Newton

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

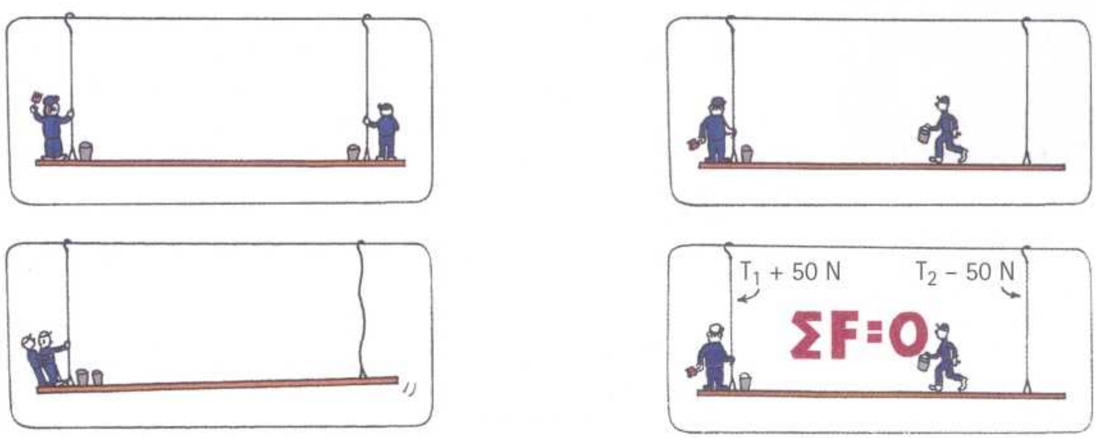
Figure 2.6 shows how forces combine to produce a net force. A pair of 5-newton forces in the same direction produce a net force of 10 newtons (the newton, N, is the scientific unit of force). If the 5-newton forces are in opposite directions, the net force is zero. If 10 newtons of force is exerted to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

Personal Essay

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

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

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



tightly stretched guitar string, the rope with greater tension twangs at a higher pitch. The finding that Burl's rope had a higher pitch seemed reasonable because his rope supported more of the load.

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

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

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

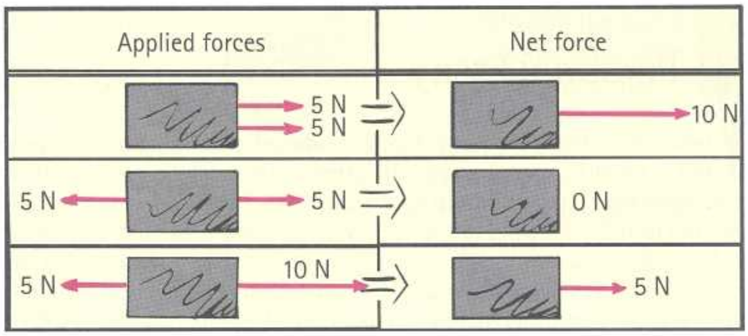


FIGURE 2.6
Net force (a force of 5 N is about 1.1 lb).

The Equilibrium Rule

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

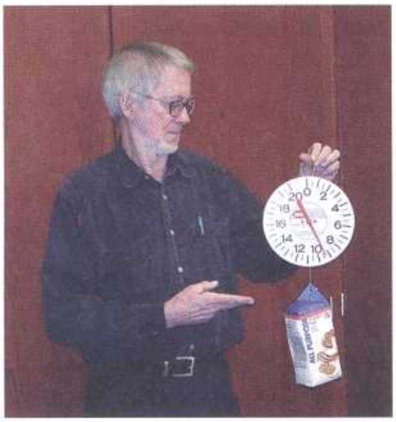


FIGURE 2.7
Burl Grey, who first introduced the author to tension forces, suspends a 2-lb bag of flour from a spring scale, showing its weight and the tension in the string of about 9 N.

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

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

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

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

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

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

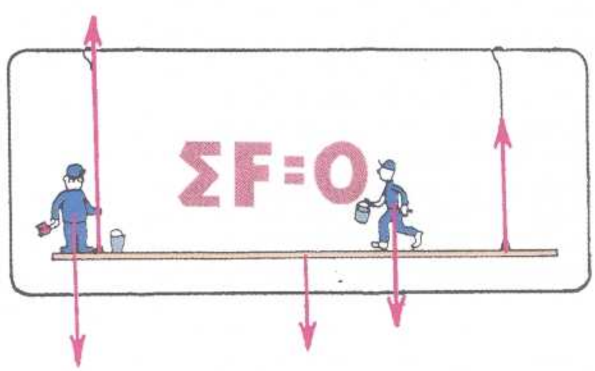
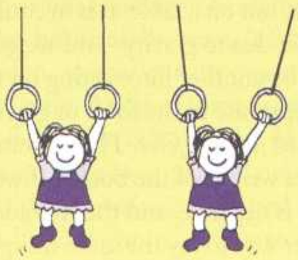


FIGURE 2.8
The sum of the upward vectors equals the sum of the downward vectors. $\Sigma \mathbf{F} = 0$ and the scaffold is in equilibrium.

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

CHECK POINT

Consider the gymnast hanging from the rings.



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

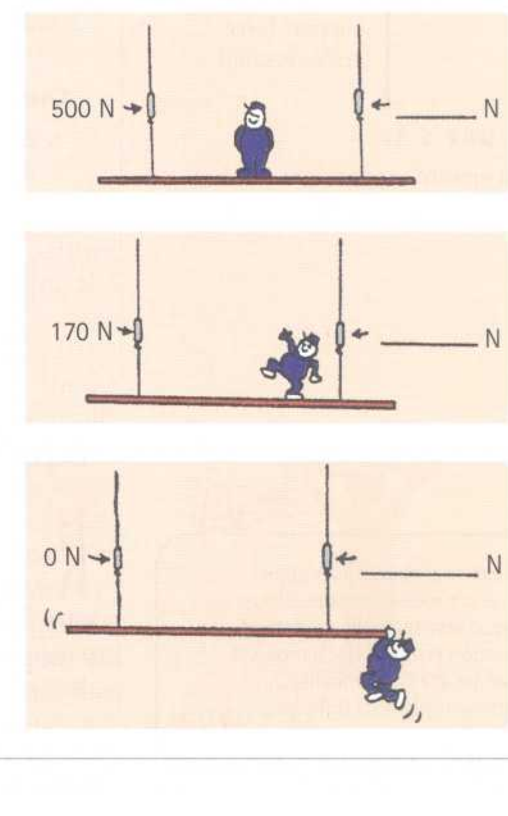
Check Your Answers

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

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

Practicing Physics

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



Practicing Physics Answers

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

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

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

Support Force

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

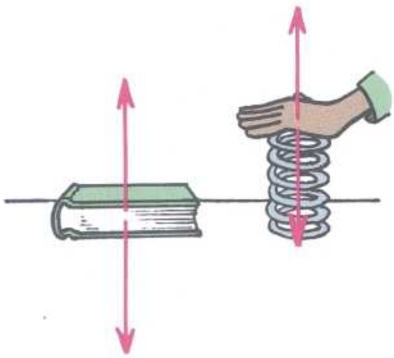


FIGURE 2.9
(Left) The table pushes up on the book with as much force as the downward force of gravity on the book. (Right) The spring pushes up on your hand with as much force as you exert to push down on the spring.

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

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

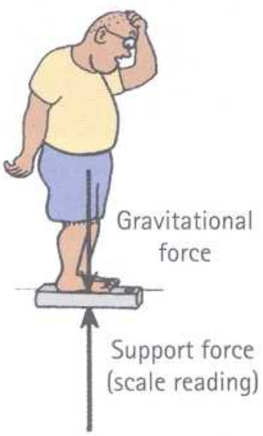


FIGURE 2.10
The upward support is as much as the downward gravitational force.

CHECK POINT

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

Check Your Answers

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

Equilibrium of Moving Things

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

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

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

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

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

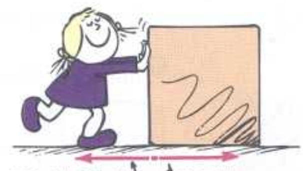


FIGURE 2.11

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

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

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

CHECK POINT

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

Check Your Answer

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

The Moving Earth

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

FIGURE 2.12

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

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

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

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

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

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

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

SUMMARY OF TERMS

Inertia The property of things to resist changes in motion.

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

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

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

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

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

REVIEW QUESTIONS

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

Aristotle on Motion

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

Copernicus and the Moving Earth

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

Galileo and the Leaning Tower

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

Galileo's Inclined Planes

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

Newton's First Law of Motion

9. Cite Newton's first law of motion.

Net Force

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

The Equilibrium Rule

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

Support Force

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

Equilibrium of Moving Things

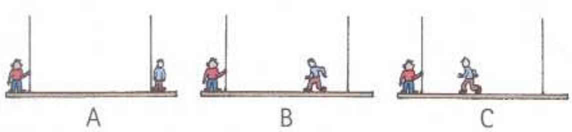
19. A bowling ball at rest is in equilibrium. Is the ball in equilibrium when it moves at constant speed in a straight-line path?
20. What is the test for whether or not a moving object is in equilibrium?
21. If you push on a crate with a force of 100 N and it slides at constant velocity, how much is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

The Moving Earth

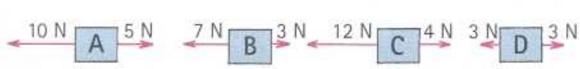
22. What concept was missing in people's minds in the 16th century when they couldn't believe Earth was moving?
23. A bird sitting in a tree is traveling at 30 km/s relative to the faraway Sun. When the bird drops to the ground below, does it still go 30 km/s, or does this speed become zero?
24. Stand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

RANKING

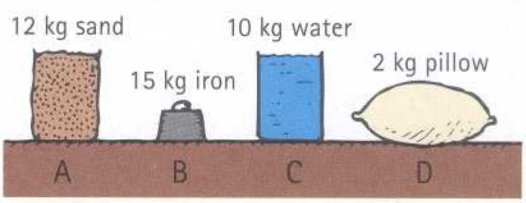
1. The weights of Burl, Paul, and the scaffold produce tensions in the supporting ropes. Rank the tension in the *left* rope, from most to least, in the three situations, A, B, and C.



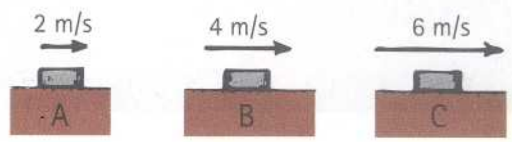
2. Rank the net force on the block from least to most in the four situations, A, B, C, and D.



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



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

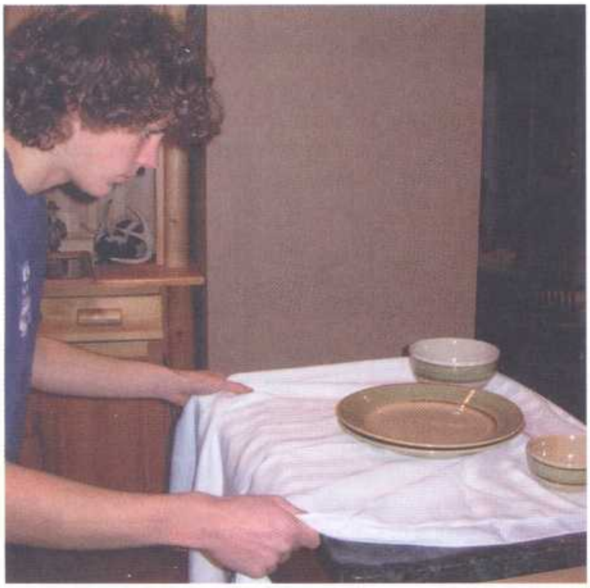


   a. Rank them, from greatest to least, by the force needed to keep them moving.
   b. Rank them, from greatest to least, by the force needed to stop them in the same time interval.

EXERCISES

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

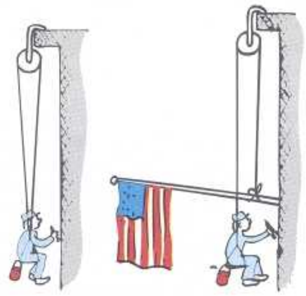
1. A ball rolling along a floor doesn't continue rolling indefinitely. Is it because it is seeking a place of rest or because some force is acting upon it? If the latter, identify the force.
2. Copernicus postulated that Earth moves around the Sun (rather than the other way around), but he was troubled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



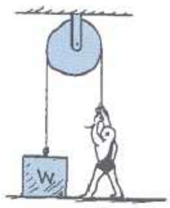
11. Consider a ball at rest in the middle of a toy wagon. When the wagon is pulled forward, the ball rolls against the back of the wagon. Interpret this observation in terms of Newton's first law.
12. In tearing a paper towel or plastic bag from a roll, why is a sharp jerk more effective than a slow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

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

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



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

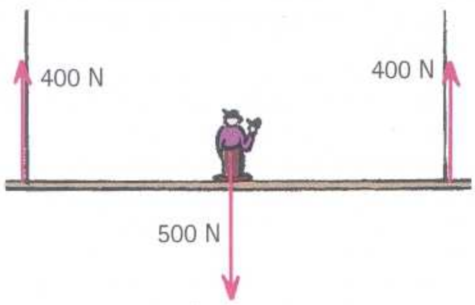


30. If the strong man in the previous exercise exerts a downward force of 800 N on the rope, how much upward force is exerted on the block?
31. A force of gravity pulls downward on a book on a table. What force prevents the book from accelerating downward?
32. How many significant forces act on a book at rest on a table? Identify the forces.
33. Consider the normal force on a book at rest on a tabletop. If the table is tilted so that the surface forms an inclined plane, will the magnitude of the normal force change? If so, how?
34. When you push downward on a book at rest on a table, you feel an upward force. Does this force depend on friction? Defend your answer.
35. Place a heavy book on a table and the table pushes up on the book. Why doesn't this upward push cause the book to rise from the table?
36. As you stand on a floor, does the floor exert an upward force against your feet? How much force does it exert? Why are you not moved upward by this force?
37. An empty jug of weight W rests on a table. What is the support force exerted on the jug by the table? What is the support force when water of weight w is poured into the jug?
38. If you pull horizontally on a crate with a force of 200 N, it slides across the floor in dynamic equilibrium. How much friction is acting on the crate?
39. In order to slide a heavy cabinet across the floor at constant speed, you exert a horizontal force of 600 N. Is the force of friction between the cabinet and the floor greater than, less than, or equal to 600 N? Defend your answer.
40. Consider a crate at rest on a factory floor. As a pair of workmen begin lifting it, does the support force on the crate provided by the floor increase, decrease, or remain unchanged? What happens to the support force on the workmen's feet?
41. Two people each pull with 300 N on a rope in a tug of war. What is the net force on the rope? How much force is exerted on each person by the rope?
42. Two forces act on a parachutist falling in air: weight and air drag. If the fall is steady, with no gain or loss of speed, then the parachutist is in dynamic equilibrium. How do the magnitudes of weight and air drag compare?
43. A child learns in school that Earth is traveling faster than 100,000 kilometers per hour around the Sun and, in a frightened tone, asks why we aren't swept off. What is your explanation?
44. Before the time of Galileo and Newton, some learned scholars thought that a stone dropped from the top of a tall mast of a moving ship would fall vertically and hit the deck behind the mast by a distance equal to how far the ship had moved forward while the stone was falling. In light of your understanding of Newton's first law, what do you think about this?
45. Because Earth rotates once every 24 hours, the west wall in your room moves in a direction toward you at a linear speed that is probably more than 1000 kilometers per hour (the exact speed depends on your latitude). When you stand facing the wall, you are carried along at the same speed, so you don't notice it. But when you jump upward, with your feet no longer in contact with the floor, why doesn't the high-speed wall slam into you?
46. If you toss a coin straight upward while riding in a train, where does the coin land when the motion of the train is uniform along a straight-line track? When the train slows while the coin is in the air? When the train is turning?
47. The smokestack of a stationary toy train consists of a vertical spring gun that shoots a steel ball a meter or so straight into the air—so straight that the ball always falls back into the smokestack. Suppose the train moves at constant speed along the straight track. Do you think the ball will still return to the smokestack if shot from the moving train? What if the train gains speed along the straight track? What if it moves at a constant speed on a circular track? Why do your answers differ?
48. Consider an airplane that flies due east on a trip, then returns flying due west. Flying in one direction, the plane flies with Earth's rotation, and in the opposite direction, against Earth's rotation. But, in the absence of winds, the times of flight are equal either way. Why is this so?

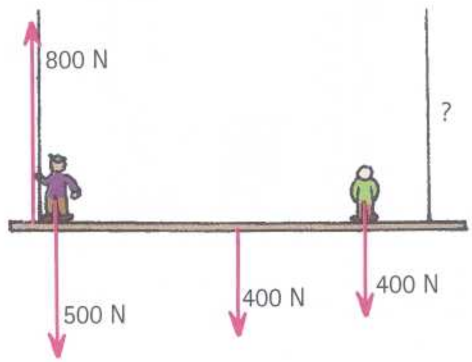
PROBLEMS

1. Lucy Lightfoot stands with one foot on one bathroom scale and her other foot on a second bathroom scale. Each scale reads 350 N. What is Lucy's weight?
2. Henry Heavyweight weighs 1200 N and stands on a pair of bathroom scales so that one scale reads twice as much as the other. What are the scale readings?

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



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



CHAPTER 2 ONLINE RESOURCES

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