3 NEWTON'S FIRST LAW OF MOTION—INERTIA

Objectives

- Describe Aristotle's concept of motion. (3.1)
- Describe Copernicus' idea about Earth's motion. (3.2)
- Describe Galileo's idea about when a force is needed to keep an object moving. (3.3)
- State Newton's first law of motion. (3.4)
- Describe the relationship between mass and inertia. (3.5)
- Explain how the law of inertia applies to objects in motion. (3.6)

discover!

MATERIALS file card, penny

EXPECTED OUTCOME The coin will stay on the finger.

ANALYZE AND CONCLUDE

1. The penny stayed on the finger. Using the quarter made it easier to snap the card away.
2. No, as there would be more friction between the card and the coin.
3. The coin's inertia kept it from accelerating with the card.

TEACHING TIP Resistance to change in motion, or inertia, is directly related to an object's mass. More massive coins have greater inertia and are more difficult to accelerate. The card's smooth surface and its rapid removal are additional factors critical to the success of this demonstration.

3 NEWTON'S FIRST LAW OF MOTION—INERTIA

THE BIG IDEA Forces cause changes in motion.

If you see a ball at rest in the middle of a flat field you know it's in equilibrium. No net force acts on it. But if you suddenly saw it begin to move across the ground, you'd look for forces that don't balance to zero. If there's no wind and nobody kicking it, you might look to see if someone was pulling the ball with a rope or pushing it with a stick. You would reason that something was causing it to move. We don't believe that changes in motion occur without cause.

discover!

Can You Snap a Card Out From Under a Coin?

1. Balance half of a 3″ × 5″ file card on the tip of an index finger.
2. Place a penny on the card just above your fingertip.
3. Give the card a quick horizontal snap with the fingernail of your other index finger.
4. Repeat Steps 1 through 3 using a quarter.

Analyze and Conclude

1. **Observing** What happened to the penny when the card was quickly removed? Did changing the coin affect results?
2. **Predicting** Do you think this would work with a card made of sandpaper?
3. **Making Generalizations** Why were you able to snap the card without moving the coin?

3.1 Aristotle on Motion

The idea that a force causes motion goes back to the fourth century B.C., when the Greeks were developing some of the ideas of science. **Aristotle, the foremost Greek scientist, studied motion and divided it into two types: *natural motion* and *violent motion.***

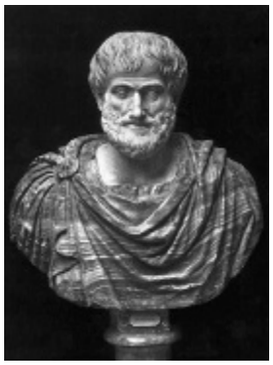
Natural motion on Earth was thought to be either straight up or straight down, such as a boulder falling toward the ground or a puff of smoke rising in the air. Objects would seek their natural resting places: boulders on the ground and smoke high in the air like the clouds. It was "natural" for heavy things to fall and for very light things to rise. Aristotle proclaimed circular motion was natural for the heavens, for he saw both circular motion and the heavens as being without beginning or end. Thus, the planets and stars moved in perfect circles around Earth. Since these motions were considered natural, they were not thought to be caused by forces.

Violent motion, on the other hand, was imposed motion. It was the result of forces that pushed or pulled. A cart moved because it was pulled by a horse; a tug-of-war was won by pulling on a rope; a ship was pushed by the force of the wind. The important thing about defining violent motion was that it had an external cause. Violent motion was imparted to objects. Objects in their natural resting places could not move by themselves; they had to be pushed or pulled.

FIGURE 3.1 ▲
Boulders do not move without cause.

Link to HISTORY

Aristotle (384–322 B.C.)
Aristotle was the most famous philosopher, scientist, and educator of ancient Greece. He was the son of a physician who personally served the king of Macedonia. At age 17, Aristotle 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, Aristotle formed his own school. His aim was to arrange existing knowledge in a system, just as Euclid had done earlier with geometry. Aristotle made careful observations, collected specimens, and gathered together and classified almost all existing knowledge of the physical world. His systematic approach became the method from which European 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 came to a stop in most of Europe during the Dark Ages, and many of the works of Aristotle were forgotten and lost. Some of his texts, however, were reintroduced to Europe during the 1000s and 1100s and were translated into Latin. The Church, the dominant political and cultural force in Western Europe, at first prohibited the works of Aristotle. But soon thereafter the Church accepted them and incorporated them into Christian doctrine.



A historical perspective is used to introduce the concept of inertia in this chapter. If you're a science-history buff you should consider amplifying the small amount of history in this text.

PAUL

3.1 Aristotle on Motion

Although students can usually memorize "In the absence of a force an object in motion tends to stay in motion," many fallaciously believe motion requires the presence of a force. This belief is rooted in experience, where in most cases a force must be applied to overcome friction. It is a sophisticated step to remove friction in one's mind and see the physics of nature beneath.

PAUL

CONCEPT CHECK Aristotle, the foremost Greek scientist, studied motion and divided it into two types: *natural motion* and *violent motion*.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Conceptual Physics Alive! DVDs**
  Newton's First Law

3.2 Copernicus and the Moving Earth

CONCEPT CHECK Copernicus reasoned that the simplest way to interpret astronomical observations was to assume that Earth and the other planets move around the sun.

3.3 Galileo on Motion

Key Terms
friction, inertia

▶ **Teaching Tip** Point to an object in the room and state that if it started moving, one would reasonably look for a cause for its motion. A force, a push or a pull of some kind, must be responsible. Only living things can move by themselves! A cannonball remains at rest in the cannon until a force is applied, and the force of expanding gases drives the ball out of the barrel when the cannon is fired. But what keeps the ball moving when the expanding gases no longer act on it? Inertia.

It was commonly thought for nearly 2000 years that if an object was moving "against its nature," then a force of some kind was responsible. Such motion was possible only because of an outside force. If there were no force there would be no motion (except in the vertical direction). So the proper state of objects was one of rest, unless they were being pushed or pulled, or were moving toward their natural resting place. Most thinkers before the 1500s considered it obvious that Earth must be in its natural resting place and assumed that a force large enough to move it was unthinkable. To them it was clear that Earth did not move.

CONCEPT CHECK **According to Aristotle, what were the two types of motion?**

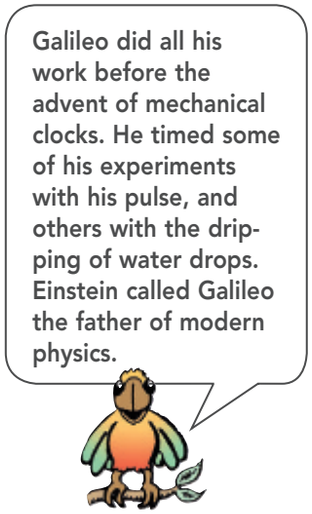
FIGURE 3.2 ▼
Nicolaus Copernicus proposed that Earth moved around the sun.

3.2 Copernicus and the Moving Earth

It was in this intellectual climate that the astronomer Nicolaus Copernicus (1473–1543), shown in Figure 3.2, formulated his theory of the moving Earth. ✓ **Copernicus reasoned that the simplest way to interpret astronomical observations was to assume that Earth and the other planets move around the sun.** This idea was extremely controversial at the time. People preferred to believe that Earth was at the center of the universe.

Copernicus worked on his ideas in secret to escape persecution. In the last days of his life and at the urging of close friends, he sent his ideas to the printer. The first copy of his work, *De Revolutionibus,* reached him on the day of his death, May 24, 1543.

CONCEPT CHECK **What did Copernicus state about Earth's motion?**



3.3 Galileo on Motion

Galileo, the foremost scientist of late-Renaissance Italy, was outspoken in his support of Copernicus. As a result, he suffered a trial and house arrest. One of Galileo's great contributions to physics was demolishing the notion that a force is necessary to keep an object moving.

A force is any push or pull. **Friction** is the name given to the force that acts between materials that touch as they move past each other. Friction is caused by the irregularities in the surfaces of objects that are touching. Even very smooth surfaces have microscopic irregularities that obstruct motion. If friction were absent, a moving object would need no force whatever to remain in motion.

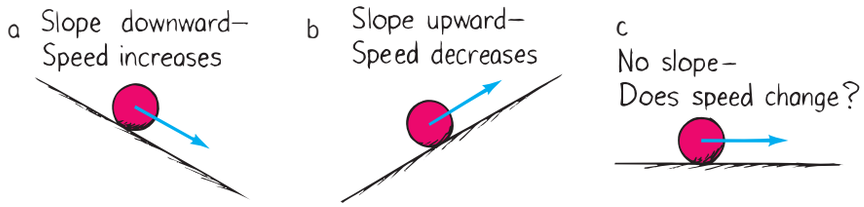


FIGURE 3.3
Galileo rolled balls along surfaces tilted at different angles. **a.** When the ball rolls downward, it moves with Earth's gravity, and its speed increases. **b.** When the ball rolls upward, it moves against gravity and loses speed. **c.** When the ball rolls on a level plane, it does not move with or against gravity.

Galileo argued that only when friction is present—as it usually is—is a force needed to keep an object moving. He tested his idea by rolling balls along plane surfaces tilted at different angles. He noted that a ball rolling down an inclined plane speeds up, as shown in Figure 3.3a. The ball is rolling partly in the direction of the pull of Earth's gravity. He also noted that a ball rolling up an inclined plane—in a direction opposed by gravity—slows down, as shown in Figure 3.3b. What about a ball rolling on a level surface, as shown in Figure 3.3c? That ball does not roll with or against gravity. Galileo found that a ball rolling on a smooth horizontal plane has almost constant velocity. He stated that if friction were entirely absent, a ball moving horizontally would move forever. No push or pull would be required to keep it moving once it is set in motion.

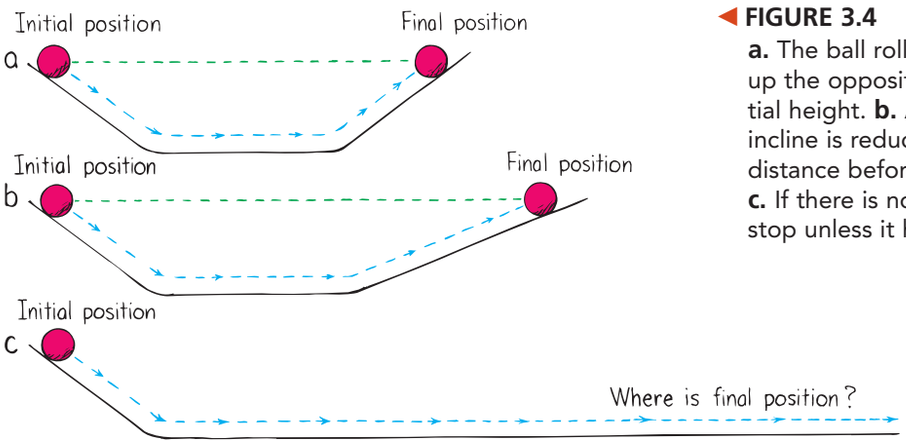


FIGURE 3.4
a. The ball rolling down the incline rolls up the opposite incline and reaches its initial height. **b.** As the angle of the upward incline is reduced, the ball rolls a greater distance before reaching its initial height. **c.** If there is no friction, the ball will never stop unless it hits something.

Galileo's conclusion was supported by another line of reasoning. He described two inclined planes facing each other, as in Figure 3.4. A ball released to roll down one plane would roll up the other to reach nearly the same height. The smoother the planes were, the more nearly equal would be the initial and final heights. He noted that the ball tended to attain the same height, even when the second plane was longer and inclined at a smaller angle than the first plane. Always, the ball went farther and tended to reach the same height.

Teaching Tip Explain that a frictional force acts on each of two objects which are in contact when one object moves or when there is an attempt to move it relative to the other. These forces are parallel to the surfaces in contact and they act in directions so as to oppose any motion.

Teaching Tip Explain that in the everyday sense, inertia refers to inactivity or perhaps a habit. In physics, it's another word for laziness, or the resistance to change as far as the state of motion of an object is concerned. Roll your ball along a lecture table to show its tendency to keep rolling. Inertia was introduced by Galileo for his inclined plane experiments.

Teaching Tip Contrast Aristotle's and Galileo's ways of looking at motion—Aristotle's classification of natural and violent motion, and Galileo's idea of inertia—that objects once set in motion *do* continue moving without added effort. This is easy to understand when air resistance and other factors are not part of the situation, as happens in outer space. It's easier to visualize the unchanging motion of a ball thrown in outer space than at Earth's surface (it may curve in outer space also, due to gravity, but there is no air resistance to affect its motion).

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

PAUL

▶ **Teaching Tip** Point out that Galileo asked *how* things move, not *why* they move.

CONCEPT CHECK Galileo argued that only when friction is present—as it usually is—is a force needed to keep an object moving.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

think!

A ball is rolled across a counter top and rolls slowly to a stop. How would Aristotle interpret this behavior? How would Galileo interpret it? How would you interpret it?
Answer: 3.3

What if the angle of incline of the second plane were reduced to zero so that the plane was perfectly horizontal? How far would the ball roll? He realized that only friction would keep it from rolling forever. It was not the nature of the ball to come to rest as Aristotle had claimed. In the absence of friction, the moving ball would naturally keep moving. Galileo stated that this tendency of a moving body to keep moving is natural and that every material object resists change to its state of motion. The property of a body to resist changes to its state of motion is called **inertia.**

Galileo was concerned with *how* things move rather than *why* they move. He showed that experiment, not logic, is the best test of knowledge. Galileo's findings about motion and his concept of inertia discredited Aristotle's theory of motion. The way was open for Isaac Newton (1642–1727) to synthesize a new vision of the universe.

CONCEPT CHECK **According to Galileo, when is a force needed to keep an object moving?**

Link to HISTORY

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 his studies to mathematics. He developed an early interest in motion and was soon at odds with others around him, who held to Aristotelian ideas on falling bodies. He left Pisa to teach at the University of Padua and became an advocate of the new theory of the solar system advanced by Copernicus. Galileo was one of the first to build a telescope, and was the first to direct it to the nighttime sky. He discovered mountains on the moon and the moons of Jupiter. He published his findings in Italian instead of in Latin, the standard scholarly language of his time, and because of the recent invention of the printing press, his ideas reached many people.

He soon encountered disagreements with the Roman Catholic Church and was warned not to teach and not to adhere to Copernican views. He restrained himself publicly for nearly 15 years. Thinking he had found a way to present the Copernican views without contradicting Church doctrine, Galileo published his observations and conclusions. However, he was brought to trial and was found guilty, and he was forced to renounce his discoveries. By then an old man broken in health and spirit, he was sentenced to house arrest for the remainder of his life. Nevertheless, he completed his studies on motion and his writings were smuggled from Italy and published in Holland. Galileo had damaged his eyes years earlier by looking at the sun through a telescope, which led to blindness at the age of 74. He died 4 years later.

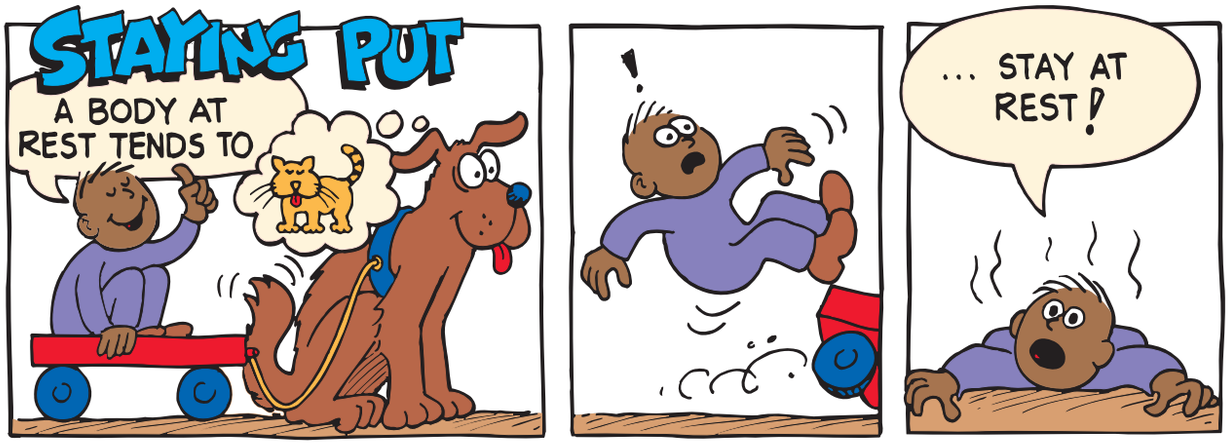
3.4 Newton's Law of Inertia

On Christmas day in the year Galileo died, Isaac Newton was born. By age 24, he had developed his famous laws of motion. They replaced the Aristotelian ideas that dominated the thinking of the best minds for most of the previous 2000 years. This chapter covers the first of Newton's three laws of motion. Newton's two other laws of motion are covered in following chapters.

Newton's first law, usually called the **law of inertia,** is a restatement of Galileo's idea that a force is not needed to keep an object moving. ✓ **Newton's first law states that every object continues in a state of rest, or of uniform speed in a straight line, unless acted on by a nonzero net force.**

think!

A force of gravity between the sun and its planets holds the planets in orbit around the sun. If that force of gravity suddenly disappeared, in what kind of path would the planets move?
Answer: 3.4.1



Objects at Rest Simply put, things tend to keep on doing what they're already doing. Dishes on a tabletop, for example, are in a state of rest. They tend to remain at rest, as is evidenced if you snap a tablecloth from beneath them, as shown in Figure 3.5. Try this at first with some unbreakable dishes. If you do it properly, you'll find the brief and small forces of friction are not significant enough to appreciably move the dishes (close inspection will show that brief friction between the dishes and the fast-moving tablecloth starts the dishes moving, but immediately after the tablecloth is removed friction between the dishes and table stops them). Objects in a state of rest tend to remain at rest. Only a force will change that state.

FIGURE 3.5 ▲
Objects at rest tend to remain at rest.

3.4 Newton's Law of Inertia

Key Terms
Newton's first law, law of inertia

Common Misconceptions
Even if no force acts on a moving object, it will eventually stop.

FACT Only a force can cause a change in the motion of a moving object.

Demonstrations

Bend a wire coat hanger into an "m" shape. Stick one glob of clay (or any massive material) to each end as shown. Balance the hanger on your head, with one glob in front of your face. State that you wish to view the other glob and ask how you can do so without touching the apparatus. Then simply turn around and there it is! Inertia in action!

Balance a 3 × 5 card on your finger. Flick it away with your other hand.

Place a wooden block on a piece of cloth and ask what will happen to the block if you pull suddenly on the cloth (the old table cloth and dishes trick).

Perform the classic table cloth demonstration complete with dishes. (Use a cheap set of dishes and a tablecloth without a hem.) Pull slightly downward when you whip the table cloth from beneath the dishes to ensure that the cloth moves horizontally. (Even the slightest upward component produces disaster.)

Though your students may know what to expect, it is well worth your while to do the tablecloth demo. Seeing it done live, and by you, will be a delight!

PAUL

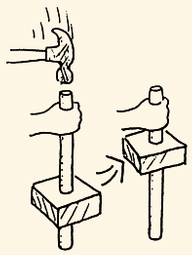
▶ **Teaching Tip** Emphasize the motion part of Newton's first law—that moving things continue at constant velocity in the absence of a force.

Demonstration

Show how you tighten the head of a hammer not by banging the head against a solid surface, but by banging the handle, as shown in the sketch.

Why? Because the massive head remains in motion, nestling it tighter on the handle.

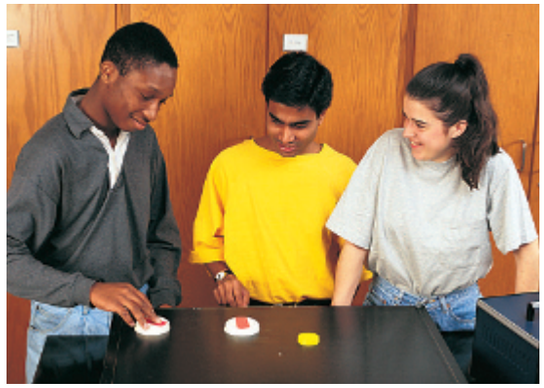
Follow the hammer demo with a broom handle or wooden dowel that fits rather snugly in a hole through a wooden block. When held as shown below, they stay together due to friction. Strike the top of the dowel with a hammer and voilà, the block climbs the handle! The block tends to stay put while the handle suddenly moves downward. More inertia in action.



think!

Is it correct to say that the *reason* an object resists change and persists in its state of motion is that it has inertia?
Answer: 3.4.2

FIGURE 3.6 ▶
Blasts of air from many tiny holes provide a nearly friction-free surface on the air table.

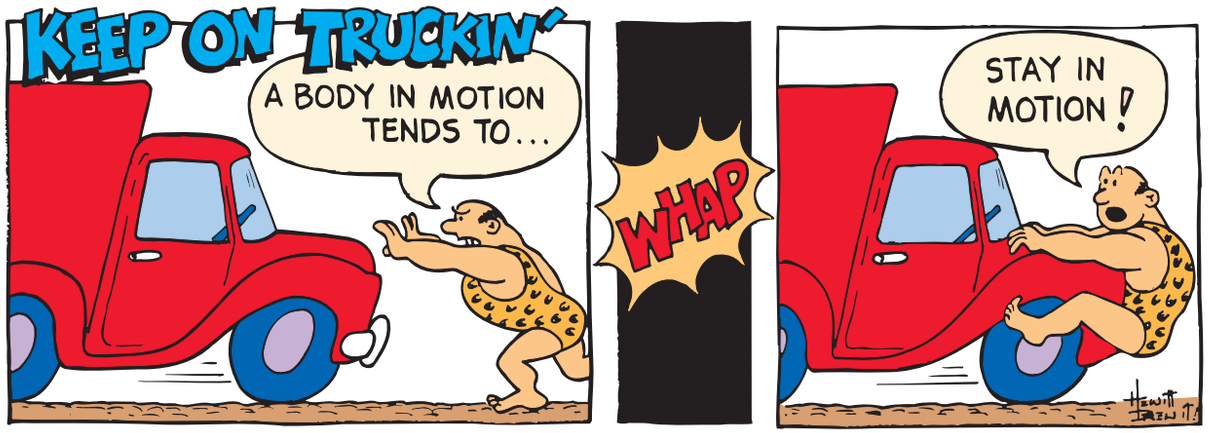


Notice that Newton's law of inertia and the equilibrium rule of Chapter 2 say the same thing: When $\Sigma F = 0$, objects don't change their states of motion.

Objects in Motion Now consider an object in motion. If you slide a hockey puck along the surface of a city street, the puck quite soon comes to rest. If you slide it along ice, it slides for a longer distance. This is because the friction force is very small. If you slide it along an air table where friction is practically absent, such as the one shown in Figure 3.6, it slides with no apparent loss in speed. We see that in the absence of forces, a moving object tends to move in a straight line indefinitely. Toss an object from a space station located in the vacuum of outer space, and the object will move forever. It will move by virtue of its own inertia.

We see that the law of inertia provides a completely different way of viewing motion. Whereas the ancients thought continual forces were needed to maintain motion, we now know that objects continue to move by themselves. Forces are needed to overcome any friction that may be present and to set objects in motion initially. Once the object is moving in a force-free environment, it will move in a straight line indefinitely. In Chapter 6 we'll see that forces are needed to accelerate objects, but not to maintain motion if there is no friction.

CONCEPT CHECK What is Newton's first law of motion?



Link to HISTORY

Isaac Newton (1642–1727)

On Christmas day in the year 1642, the year that Galileo died, Isaac Newton was born prematurely and barely survived. Newton's birthplace was his mother's farmhouse in Woolsthorpe, England. His father died several months before his birth, and Isaac grew up under the care of his mother and grandmother. As a child he showed no particular signs of brightness, and at the age of 14 he was taken out of school to work on his mother's farm. As a farmer he was a failure, preferring to read books he borrowed from a neighboring pharmacist. An uncle sensed the scholarly potential in young Isaac and prompted him to study at the University of Cambridge, which he did for 5 years, graduating without particular distinction.

A plague swept through England, and Newton retreated to his mother's farm—this time to continue his studies. At the farm, when he was 23 and 24 years old, he laid the foundations for the science of physics. 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. He invented the calculus, a very important mathematical tool in science. He extended Galileo's work and developed the three fundamental laws of motion. He also formulated a theory of the nature of light and showed, using prisms, that white light is composed of all colors of the rainbow. It was his experiments with prisms that first made him famous.

When the plague subsided, Newton returned to Cambridge and soon established a reputation for himself as a first-rate mathematician. His mathematics teacher resigned in his favor and Newton was appointed the Lucasian professor of mathematics. He held this post for 28 years. In 1672 he was elected to the Royal Society, where he exhibited the world's first reflector telescope. It can still be seen, preserved at the library of the Royal Society in London with the inscription: "The first reflecting telescope, invented by Sir Isaac Newton, and made with his own hands."

It wasn't until Newton was 42 that he began to write one of the greatest scientific books ever written, the *Principia Mathematica Philosophiae Naturalis.* He wrote the work in Latin and completed it in 18 months. It appeared in print in 1687 and wasn't printed in English until 1729, two years after his death. When asked how he was able to make so many discoveries, Newton replied that he solved his problems by continually thinking very long and hard about them—and not by sudden insight.

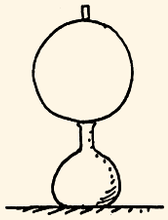
At the age of 46 he was elected a member of Parliament. He attended the sessions in Parliament for two years and never gave a speech. One day he rose and the House fell silent to hear the great man. Newton's "speech" was very brief; he simply requested that a window be closed because of a draft.

Although Newton's hair turned gray at 30, it remained full, long, and wavy all his life. Unlike others in his time, he did not wear a wig. He was a modest man, although very sensitive to criticism. He never married. He remained healthy in body and mind into old age. At 80, he still had all his teeth, his eyesight and hearing were sharp, and his mind was alert. In his lifetime he was regarded by his countrymen as the greatest scientist who ever lived. In 1705 he was knighted by Queen Anne. Newton died at the age of 85 and was buried in Westminster Abbey along with England's kings and heroes.

Newton "opened up" the universe, showing that the same natural laws that act on Earth govern the larger cosmos as well. For humankind this led to increased humility, but also to hope and inspiration because of the evidence of a rational order. Newton ushered in the Age of Reason. His ideas and insights truly changed the world and elevated the human condition.

Demonstration

Place a metal hoop atop a narrow jar. On top of the hoop balance a piece of chalk. Whisk the hoop away and the chalk falls neatly into the narrow opening. Grabbing the hoop on the inside, on the side farthest from your sweep, elongates the hoop horizontally and the part that supports the chalk drops from beneath the chalk. (If you grab the hoop on the near side, the elongation will be vertical and the chalk will pop up into the air!)



Ask **What would be the motion of a ball tossed in empty space, practically away from gravity and other forces?** *Straight-line path at constant speed* **Consider a rock swinging in a circle at the end of a string: what is the path of the rock when the string breaks?** *A straight line, except for the influence of gravity*

CONCEPT CHECK Newton's first law states that every object continues in a state of rest, or of uniform speed in a straight line, unless acted on by a nonzero net force.

Teaching Resources

- **Reading and Study Workbook**
- **Laboratory Manual** *6*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *3-1, 3-2, 3-3*

3.5 Mass—A Measure of Inertia

Key Terms
kilograms, mass, weight, newton

Common Misconceptions
Mass, weight, and volume are the same thing.

FACT Mass is the amount of matter in an object; volume is the amount of space that matter occupies; weight is the force of gravity on an object.

▶ **Teaching Tip** Distinguish between mass and volume. Give an automobile battery and a fluffy king-size pillow as examples. Mass is not volume, as Figure 3.8 illustrates.

▶ **Teaching Tip** Distinguish between mass and weight. Mass is more fundamental, meaning that it concerns only matter and not any external gravity. Weight is the force due to Earth's gravity on an object and depends on both gravity and the mass of the object. In a region where there is negligible gravity, there is negligible weight, but objects there still have mass. In the same part of Earth's gravitational field, twice the mass also has twice the weight. But this does not mean that mass is weight.

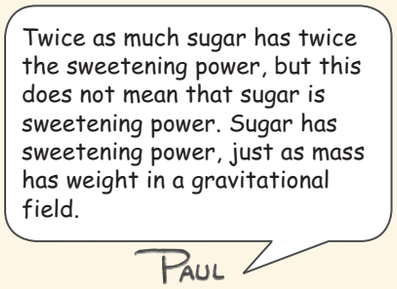


FIGURE 3.7 ▲
You can tell how much matter is in a can when you kick it.

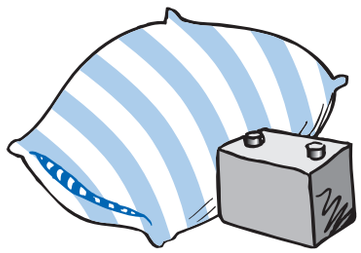
3.5 Mass—A Measure of Inertia

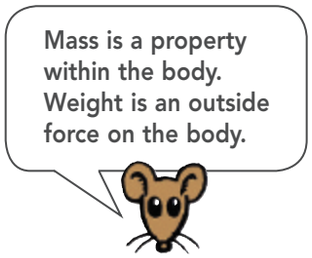
Kick an empty can, as shown in Figure 3.7, and it moves. Kick a can filled with sand and it doesn't move as much. Kick a can filled with steel nails and you'll hurt your foot. The nail-filled can has more inertia than the sand-filled can, which in turn has more inertia than the empty can. The amount of inertia an object has depends on its *mass*—which is roughly the amount of material present in the object. ✓ **The more mass an object has, the greater its inertia and the more force it takes to change its state of motion.** Mass is a measure of the inertia of an object.

Mass Is Not Volume Do not confuse mass and volume. They are entirely different concepts. Volume is a measure of space and is measured in units such as cubic centimeters, cubic meters, and liters. Mass is measured in the fundamental unit of **kilograms.** If an object has a large mass, it may or may not have a large volume. For example, equal-size bags of cotton and nails may have equal volumes, but very unequal masses. How many kilograms of matter an object contains and how much space the object occupies are two different things. (A liter of milk, juice, or soda—anything that is mainly water—has a mass of about one kilogram.)

Which has more mass, a feather pillow or a common automobile battery as shown in Figure 3.8? Clearly an automobile battery is more difficult to set into motion. This is evidence of the battery's greater inertia and hence its greater mass. The pillow may be bigger, that is, it may have a larger volume, but it has less mass. Mass is different from volume.

FIGURE 3.8 ▶
The pillow has a larger size (volume) but a smaller mass than the battery.





Mass Is Not Weight Mass is often confused with *weight*. We say a heavy object contains a lot of matter. We often determine the amount of matter in an object by measuring its gravitational attraction to Earth. However, mass is more fundamental than weight. Mass is a measure of the amount of material in an object and depends only on the number of and kind of atoms that compose it. Weight on the other hand is a measure of the gravitational force acting on the object. Weight depends on an object's location.

Mass Is Inertia The amount of material in a particular stone is the same whether the stone is located on Earth, on the moon, or in outer space. Hence, the stone's mass is the same in all of these locations. This could be demonstrated by shaking the stone back and forth in these three locations. The same force would be required to shake the stone with the same rhythm whether the stone was on Earth, on the moon, or in a force-free region of outer space, as shown in Figure 3.9. The stone's inertia, or mass, is solely a property of the stone and not its location.

But the weight of the stone would be very different on Earth and on the moon, and still different in outer space. On the surface of the moon, the stone would have only one-sixth the weight it has on Earth. This is because the force of gravity on the moon is only one-sixth as strong as it is on Earth. If the stone were in a gravity-free region of space, its weight would be zero. Its mass, on the other hand, would not be zero. Mass is different from weight.

We can define mass and weight as follows:

Mass is the quantity of matter in an object. More specifically, mass is a measure of the inertia, or "laziness," that an object exhibits in response to any effort made to start it, stop it, or otherwise change its state of motion.

Weight is the force of gravity on an object.

While mass and weight are not the same, they are proportional to each other in a given place. Objects with great mass have great weight; objects with little mass have little weight. In the same location, twice the mass weighs twice as much. Mass and weight are proportional to each other, but they are not equal to each other. Remember that mass has to do with the amount of matter in the object, while weight has to do with how strongly that matter is attracted by gravity.

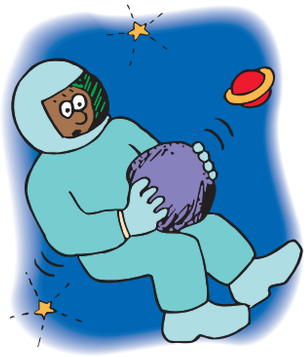


FIGURE 3.9 ▲
It's just as difficult to shake a stone in its weightless state in space as it is in its weighted state on Earth.

think!

Does a 2-kilogram bunch of bananas have twice as much *inertia* as a 1-kilogram loaf of bread? Twice as much *mass?* Twice as much *volume?* Twice as much *weight,* when weighed in the same location?
Answer: 3.5

Demonstrations

Place two objects of about equal mass in the hands of a student. Ask the student to judge which is heavier. If the student responds by shaking the objects back and forth, one in each hand, point out that the student is subconsciously comparing their *inertias*, and is making use of the intuitive notion that mass and weight are directly proportional.

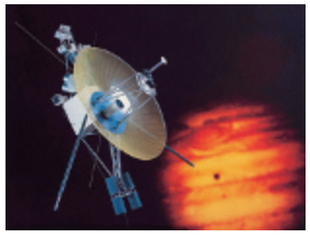
Place a massive block on your hand and strike it with a hammer. You are not hurt, because of the mass of the block.

Or do as I used to do in my lectures—place an anvil on your stomach and invite a skillful person to strike it with a sledgehammer. In any event, be sure to show the relationship of this demonstration to Think and Explain 42 on page 43.

PAUL

Link to SPACE SCIENCE

Inertia in Action



Pioneer and *Voyager* spacecraft launched in the late 1970s have gone beyond the orbits of Saturn, Uranus, and Pluto, and are still cruising beyond the solar system. Initially, force supplied by rockets sent the spacecraft on their journeys. However, once in outer space these engines supplied no more force. Except for the gravitational effect of the stars and planets in the universe, the motion of the spacecraft will continue without change.

CONCEPT CHECK The more mass an object has, the greater its inertia and the more force it takes to change its state of motion.

Teaching Resources

- Reading and Study Workbook
- Concept-Development Practice Book *3-1, 3-2*
- Presentation*EXPRESS*
- Interactive Textbook

3.6 The Moving Earth Again

Demonstration

Stand next to a wall on the west side of your classroom. State that relative to the sun, the wall and the whole room are traveling at about 30 km/s, toward the east. Aristotle's followers would say that you move at 30 km/s also because you are standing on the moving floor. Now jump up. Ask why the wall didn't slam into you. After all, you can say, when you are no longer "attached" to the moving floor, there is no force making you travel along with the moving floor. Let your class discuss this before you point out that this is simply the bird and worm example discussed in this section.

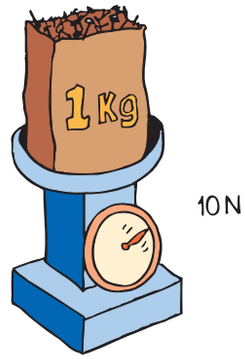


FIGURE 3.10 ▲
One kilogram of nails weighs 10 newtons, which is equal to 2.2 pounds.

One Kilogram Weighs 10 Newtons In the United States it is common to describe the amount of matter in an object by its gravitational pull to Earth, that is, by its weight. In the United States, the traditional unit of weight is the pound. In most parts of the world, however, the measure of matter is commonly expressed in units of mass. The SI[3.5.1] unit of mass is the kilogram; its symbol is kg. At Earth's surface, a 1-kg bag of nails has a weight of 2.2 pounds.

The SI unit of *force* is the **newton** (named after guess who?). One newton is equal to slightly less than a quarter pound, about the weight of a quarter-pound burger *after* it is cooked. The SI symbol for the newton is N and is written with a capital letter because it is named after a person. A 1-kg bag of nails weighs 10 N in SI units as shown in Figure 3.10. Away from Earth's surface, where the force of gravity is less, the bag of nails weighs less.

If you know the mass of something in kilograms and want its weight in newtons at Earth's surface, multiply the number of kilograms by 10. Or, if you know the weight in newtons, divide by 10 and you'll have the mass in kilograms. Once again, weight and mass are proportional to each other.[3.5.2]

CONCEPT CHECK **What is the relationship between mass and inertia?**

3.6 The Moving Earth Again

Copernicus announced the idea of a moving Earth in the sixteenth century. This controversial idea stimulated much argument and debate. One of the arguments against a moving Earth was as follows. Consider a bird sitting at rest in the top of a tall tree, as shown in Figure 3.11. On the ground below is a fat, juicy worm. The bird sees the worm, drops down vertically, and catches it. It was argued that this would not be possible if Earth moved as Copernicus suggested. If Copernicus were correct, Earth would have to travel at a speed of 107,000 km/h to circle the sun in one year. Convert this speed to kilometers per second and you'll get 30 km/s. Even if the bird could descend from its branch in one second, the worm would have been swept away by the moving Earth for a distance of 30 kilometers. For the bird to catch the worm under this circumstance would be an impossible task. The fact that birds *do* catch worms from high tree branches seemed to be clear evidence that Earth must be at rest.

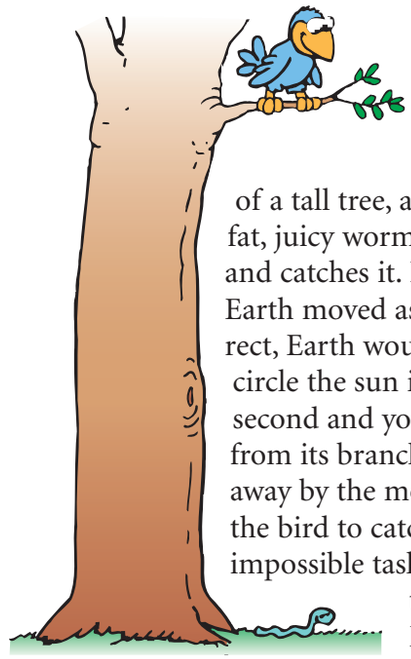


FIGURE 3.11 ▶
Earth does not need to be at rest for the bird to catch the worm.

Objects Move With Earth Can you refute this argument? You can if you invoke the idea of inertia. You see, not only is Earth moving at 30 km/s, 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 are moving at 30 km/s. **The law of inertia states that objects in motion remain in motion if no unbalanced forces act on them.** So objects on Earth move with Earth as Earth moves around the sun. When the bird drops from the branch, its initial sideways motion of 30 km/s remains unchanged. It catches the worm and is quite unaffected by the motion of its total environment.

Stand next to a wall. Jump up so that your feet no longer touch the floor. Does the 30-km/s wall slam into you? Why not? Because you are also traveling at 30 km/s, before, during, and after your jump. The 30 km/s is the speed of Earth relative to the sun, not the speed of the wall relative to you.

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Objects Move With Vehicles Four hundred years ago, people had difficulty with ideas like these, not only because they failed to acknowledge the concept of inertia, but also because they were not accustomed to moving in high-speed vehicles. Slow, bumpy rides in horse-drawn carriages do not lend themselves to experiments that reveal inertia. Today, as shown in Figure 3.12, we flip a coin in a high-speed car, bus, or plane and 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.

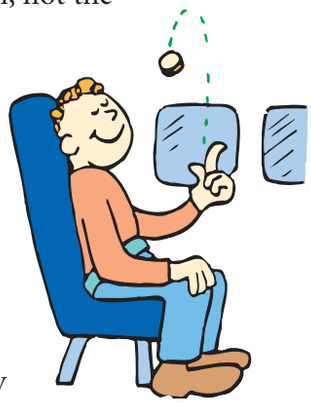

FIGURE 3.12
Flip a coin in a high-speed airplane, and it behaves as if the plane were at rest. The coin keeps up with you—inertia in action!

Our notions of motion today are very different from those of our distant ancestors. Aristotle did not recognize the idea of inertia, because he did not see that all moving things follow the same rules. He imagined different rules for motion in the heavens and motion on Earth. He saw 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 required *no* force to keep moving if friction was not present. We can only wonder how differently science might have progressed if Aristotle had recognized the unity of all kinds of motion and friction's effect on motion.

CONCEPT CHECK How does the law of inertia apply to objects in motion?

Inertia safety—the more than 3-million-kg steel ball hanging at the 87th floor of the tallest skyscraper in Taipei helps stabilize the 101-story building against vibrations caused by earthquakes or strong winds.

Teaching Tidbit Newton lived half his life in the 1600s and the other half in the 1700s.

Ask **At the circus when the horseback rider standing in his saddle approaches a hoop, does he jump forward, backward, or straight up from the saddle? What physics law is being demonstrated here?** *The rider jumps straight up, and returns to the saddle, in accord with Newton's first law.*

CONCEPT CHECK The law of inertia states that objects in motion remain in motion if no unbalanced forces act on them.

Teaching Resources
- Reading and Study Workbook
- Laboratory Manual *7*
- Presentation*EXPRESS*
- Interactive Textbook

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Lab *2*
- Conceptual Physics Alive! DVDs *Newton's First Law*

3 REVIEW

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Concept Summary

- Aristotle, the foremost Greek scientist, studied motion and divided it into two types: *natural motion* and *violent motion*.
- Copernicus reasoned that the simplest way to interpret astronomical observations was to assume that Earth and the other planets move around the sun.
- Galileo argued that only when friction is present—as it usually is—is a force needed to keep an object moving.
- Newton's first law states that every object continues in a state of rest, or of uniform speed in a straight line, unless acted on by a nonzero net force.
- The more mass an object has, the greater its inertia and the more force it takes to change its state of motion.
- The law of inertia states that objects in motion remain in motion if no unbalanced forces act on them.

Key Terms

friction *(p. 30)*
inertia *(p. 32)*
Newton's first law *(p. 33)*
law of inertia *(p. 33)*
kilograms *(p. 36)*
mass *(p. 37)*
weight *(p. 37)*
newton *(p. 38)*

think! Answers

3.3 Aristotle would probably say that the ball stops because it seeks its natural state of rest. Galileo would probably say that the friction between the ball and the table overcomes the ball's natural tendency to continue rolling—overcomes the ball's inertia—and brings it to a stop. Only you can answer the last question!

3.4.1 Each planet would move in straight lines at constant speed.

3.4.2 In a strict sense, no. We don't know the reason *why* objects persist in their motion when nothing acts on them, but we know that they do, and we call this property *inertia*. We understand many things, and we have labels for these things. There are also many things we do not understand, and we have labels for these things too. Education consists not so much in acquiring new labels, but in learning what is understood, what is not, and why.

3.5 Two kilograms of *anything* has twice the inertia and twice the mass of one kilogram of anything else. In the same location, where mass and weight are proportional, two kilograms of anything will weigh twice as much as one kilogram of anything. Except for volume, the answer to all the questions is yes. Bananas are much more dense than bread, so two kilograms of bananas must occupy less volume than one kilogram of bread.

40

3 ASSESS

Check Concepts

Section 3.1

1. What were the two classifications of motion, according to Aristotle?
2. According to Aristotle, what kinds of motion required no forces?

Section 3.2

3. What simple way of interpreting astronomical observations did Copernicus advocate?

Section 3.3

4. What were the consequences to Galileo for supporting the ideas of Copernicus?
5. Who relied on experiment, Aristotle or Galileo?
6. How did Galileo discredit Aristotle's assertion that a force is needed to keep objects moving?
7. Galileo let a ball roll down one incline and then up another. Compared with its initial height, how high did the ball roll up the second incline?
8. What name is given to the property of an object to resist changes in motion?

Section 3.4

9. Who was the first to consider the role of inertia, Galileo or Newton?
10. What is the tendency of an object at rest when no forces act on it?
11. What is the tendency of a moving object when no forces act on it?

Section 3.5

12. What relationship does mass have with inertia?
13. What does it mean to say mass and weight are proportional to each other?
14. When does an object with twice the mass of another weigh twice as much?
15. What do you feel when you shake something to and fro? What do you feel when you hold it against the pull of gravity?
16. What is the standard (or SI) unit of measurement for mass?
17. What is the standard (or SI) unit of measurement for weight?
18. What is the weight of a 1-kg brick?

Section 3.6

19. How fast are you moving relative to Earth when you are standing still? How fast are you moving relative to the sun?
20. If you're in a smooth-riding bus that is going at 40 km/h and you flip a coin vertically, how fast does the coin move horizontally while in midair?

3 ASSESS

Check Concepts

1. Natural motion and violent motion
2. Natural motion on Earth and circular motions in the heavens required no force.
3. That Earth and other planets move around the sun
4. A trial and house arrest
5. Galileo
6. Galileo discredited Aristotle's notions with his experiments on inclined planes.
7. It rolled almost to the same height.
8. Inertia
9. Galileo. Newton incorporated it in a fundamental law that underlies all motion.
10. To remain at rest
11. To move in a straight line at constant speed indefinitely
12. Mass is a measure of inertia; more mass, more inertia and more force to change state of motion.
13. If one increases or decreases, the other changes in same way (mathematically, by same factor).
14. When the objects are at the same location
15. Mass (or inertia); weight
16. The kilogram
17. The newton
18. 10 newtons
19. Zero speed relative to Earth; 30 km/s relative to the sun
20. Coin's horizontal speed is same as bus speed, 40 km/h (relative to Earth, faster relative to the Sun).

Think and Rank

21. **a.** B, A, C, D
b. B, A, C, D
c. B, A, C, D

22. **a.** A = B = C (no force)
b. C, B, A

Plug and Chug

23. $W = mg = 50\text{ kg} \times 10\text{ N/kg} = 500\text{ N}$

24. $W = mg = 2000\text{ kg} \times 10\text{ N/kg} = 20{,}000\text{ N}$

25. $W = mg = 2.5\text{ kg} \times 10\text{ N/kg} = 25\text{ N}$;
$(2.5\text{ kg})(2.2\text{ lb}/1\text{ kg}) = 5.5\text{ lb}$

26. From $W = mg$, $m = W/g = 1\text{ N}/(10\text{ N/kg}) = 0.1\text{ kg}$; 0.22 lb

27. $m = W/g = (300\text{ N})/(10\text{ N/kg}) = 30\text{ kg}$

Think and Explain

28. Aristotle: Ball slows to reach its natural state of rest.
Galileo: Ball encounters friction, an unbalanced force that slows it.

29. Rolling down, going with gravity; going up, against; horizontally, gravity at right angle to the motion, neither slowing nor speeding

30. Your physics is better if you agree with Sophia.

31. Nothing keeps the probe moving. With no propelling force it continues moving in a straight line—moving of its own *inertia*.

32. The one easier to shake is the lighter one with less mass.

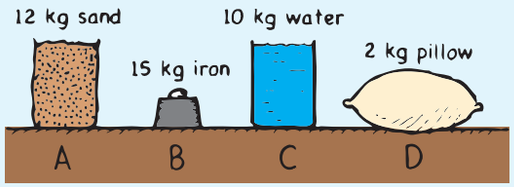
33. They keep the body and head moving together when the car is suddenly accelerated forward.

3 ASSESS *(continued)*

Think and Rank

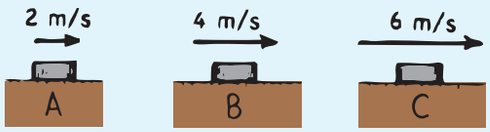
Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

21. Different materials 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 weight.
c. From greatest to least, rank them by the support (normal) force the table exerts on them.

22. The three pucks are sliding across ice at the noted speeds. Air resistance and ice friction are negligible.



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

Plug and Chug

23. If a woman has a mass of 50 kg, calculate her weight in newtons.

24. Calculate in newtons the weight of a 2000-kg elephant.

25. Calculate in newtons the weight of a 2.5-kg melon. What is its weight in pounds?

26. An apple weighs about 1 N. What is its mass in kilograms? What is its weight in pounds?

27. Susie Small finds she weighs 300 N. Calculate her mass.

Think and Explain

28. A bowling ball rolling along a lane gradually slows as it rolls. How would Aristotle interpret this observation? How would Galileo interpret it?

29. When a ball rolls down an inclined plane, it gains speed because of gravity. When rolling up it loses speed because of gravity. Why doesn't gravity play a role when it rolls on a horizontal surface?

30. Jacob gives his skateboard a push and it rolls across the classroom floor. Emily says that after it leaves Jacob's hand, his *force* remains with it, keeping it going. Sophia disagrees and says that Jacob's push gives the skateboard *speed*, not force, and that when his hand is no longer in contact the force is no more. Who do you agree with? Discuss this with your classmates.

31. A space probe can be carried by a rocket into outer space. Your friend asks what kind of force keeps the probe moving after it is released from the rocket and on its own. What is your answer?

32. In an orbiting spacecraft, you are handed two identical closed boxes, one filled with sand and the other filled with feathers. How can you tell which is which without opening the boxes?

33. Many automobile passengers suffer neck injuries when struck by cars from behind. How does Newton's law of inertia apply here? How do headrests help to guard against this type of injury?

34. Tim practices a demonstration before doing it for Sunday dinner. What concept is he illustrating, and why is he careful not to pull the tablecloth slightly upward?

35. Suppose you place a ball in the middle of a wagon that is at rest and then abruptly pull the wagon forward. Describe the motion of the ball relative to the ground and the wagon.

36. To pull a wagon across a lawn with constant velocity, you have to exert a steady force. Does this fact contradict Newton's first law, which tells us that motion with constant velocity indicates no force?

37. When a junked car is crushed into a compact cube, does its mass change? Its volume? Its weight?

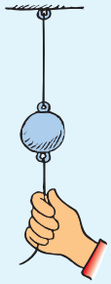
38. If an elephant were chasing you, its enormous mass would be very threatening. But if you zigzagged, the elephant's mass would be to your advantage. Why?

39. When you compress a sponge, which quantity changes: mass, inertia, volume, or weight?

40. Which has more mass, a 2-kg fluffy pillow or a 3-kg small piece of iron? More volume? Why are your answers different?

41. Is it more accurate to say that a dieting person loses mass or loses weight?

42. A massive ball is suspended on a string and slowly pulled by another string attached to it from below, as shown.
    a. Is the string tension greater in the upper or the lower string? Which string is more likely to break? Which property, mass or weight, is more important here?
    b. If the string is instead snapped downward, which string is more likely to break? Is mass or weight more important this time?



34. He's demonstrating the law of inertia. Pulling upward would lift and topple the dishes. Bad show!

35. Except for some change in motion due to friction, there will be no motion of the ball relative to the ground; but relative to the wagon, the ball will move toward the back.

36. No. The key is *net* force. Your steady force overcomes friction. Then net force is zero. An applied force overcomes friction to produce a zero net force.

37. No; yes; no; it has the same amount of matter before and after being crushed.

38. Because of its large mass, the elephant would have difficulty in zigzagging—in changing its motion.

39. Only volume; the mass and therefore the inertia are the same because the same amount of matter is present. The weight is the same because there is no difference in gravitational force upon it.

40. The iron has more mass, but less volume. Answers different because they address completely different concepts.

41. Primarily mass; can lose weight by being at top of a mountain or in space, where gravity is less

42. **a.** Upper string because it supports the weight of the ball in addition to your pull. The lower string supports only your pull. The upper string is more likely to break. Weight is important here.
b. Bottom string; the mass of the ball (its inertia) is more important than its weight in this case.

43. The handle stops when it hits the bench, but the relatively massive head tends to keep moving. The head moves toward the handle and tightens.

44. The helicopter has the same horizontal speed as Earth's surface. When it ascends, it keeps this horizontal speed and moves with Earth below.

45. a; c

46. **a.** Normal force vector drawn straight up with same length as weight vector
b. Support (or normal) force

47. **a.** Two vectors of same length: string tension vector straight up, weight vector straight down
b. Yes.
c. Being at rest means the net force is zero.

48. **a.** Two vectors: longer string tension vector straight up, shorter weight vector straight down
b. The tension in the string is larger than the gravitational force because the net force is upward.

49. **a.** Weight vector straight down
b. No, for there is no support force to counteract its weight.

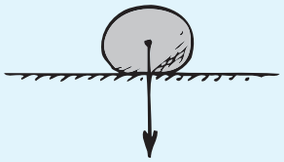
3 ASSESS *(continued)*

43. The head of a hammer is loose and you wish to tighten it by banging it against the top of a workbench. Why is it better to hold the hammer with the handle down, as shown below, rather than with the head down? Explain in terms of inertia.

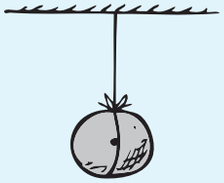
44. As Earth rotates about its axis, it takes three hours for the United States to pass beneath a point above Earth that is stationary relative to the sun. What is wrong with the following scheme? To travel from Washington, D.C. to San Francisco using very little fuel, simply ascend in a helicopter high over Washington, D.C., and wait three hours until San Francisco passes below.

45. In which position is the compression the least in the arms of the weightlifters shown? The most?

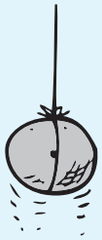
46. A stone is shown at rest on the ground.
a. The vector shows the weight of the stone. Complete the vector diagram showing another vector that results in zero net force on the stone.
b. What is the conventional name of the vector you have drawn?



47. Here a stone is suspended at rest by a string.
a. Draw force vectors for all the forces that act on the stone.
b. Should your vectors have a zero resultant?
c. Why, or why not?



48. Here a stone is being accelerated vertically upward.
a. Draw force vectors to some suitable scale showing relative forces acting on the stone.
b. Which is the longer vector, and why?



49. Suppose the string in the figure in Question 48 breaks and the stone slows in its upward motion.
   a. Draw a force vector diagram of the stone when it reaches the top of its path.
   b. Is the net force on the stone zero at the top?

50. Here is a stone sliding down a friction-free incline.
   a. Identify the forces that act on it and draw appropriate force vectors.
   b. By the parallelogram rule, construct the resultant force on the stone (carefully showing it has a direction parallel to the incline—the same direction as the stone's acceleration).

Think and Solve

51. Calculate your own mass in kilograms and your weight in newtons.

52. A medium-size American automobile has a weight of about 3000 pounds. What is its mass in kilograms?

53. What is the weight in newtons of an automobile with a mass of 1800 kg?

54. If a woman weighed 500 N on Earth, what would she weigh on Jupiter, where the acceleration of gravity is 26 m/s^2?

55. Gravitational force on the moon is only 1/6 that on Earth. What is the weight of a 10-kg object on the moon and on Earth? What is its mass on the moon and on Earth?

Activity

56. Grandparents are interested in the educational progress of their grandchildren. Many have little science background. It's possible that relatives far back in your family tree believed that Earth was stationary in the center of the universe. Write a letter to Grandma or Grandpa. Tell what you've learned about a moving Earth and how a person who might be unsure of it could be convinced.

More Problem-Solving Practice
Appendix F

50. a. Weight vector straight down; normal force vector perpendicular to surface
b. Resultant force parallel to surface

Think and Solve

51. Divide your weight in lb by 2.2 and you'll have your mass in kg. Multiply this by 10 and your weight is in N.

52. 3000 lb × (1 kg/2.2 lb) = 1364 kg

53. $W = mg$ = 1800 kg × 10 N/kg = 18,000 N

54. (500 N)/(10 N/kg) = 50 kg; $W_{Jupiter} = mg_{Jupiter}$ = 50 kg × 26 N/kg = 1300 N

55. Weight of 10-kg object on Earth is 100 N; on moon 1/6 of this, or 17 N. Mass is 10 kg in any location.

Activity

56. Letters will vary. This is a sample of a good one: When people believed the Earth was stationary, they thought that movement would sweep things off Earth. They didn't grasp the concept of inertia. When you jump upward you land in the same place whether the Earth is stationary or moving. That's because during your jump, you maintain whatever horizontal motion you had before, during, and at the end of your jump. We experience this in moving vehicles today. In a moving bus, a dropped pencil will land at your feet.

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests