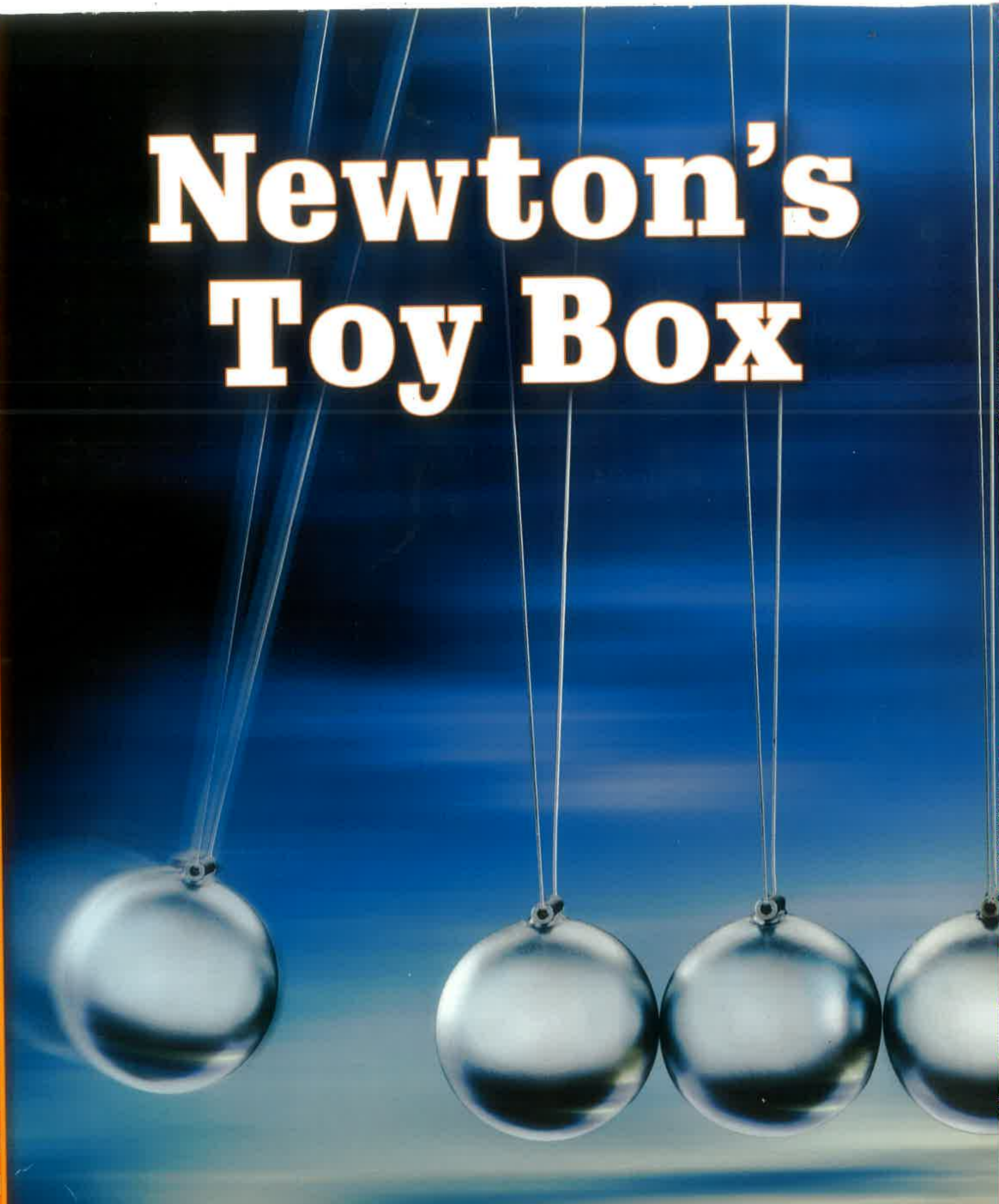
Newton's Toy Box



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Newton's Toy Box

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Think About . . .

Motion and Speed

Figure 1
We can tell this horse is moving because we see it pass by objects that are not moving—fence posts. The fence posts are our reference points.

READ TO UNDERSTAND

- How are position and motion related?
- How can we describe the motion of an object?
- What is speed, and how is speed related to velocity?

VOCABULARY

motion
position
reference point
distance
displacement
speed
average speed
velocity

Changing Position

Motion is the process of changing from one **position,** or place, to another. How do we know when something is moving? We often compare its position to the position of nearby objects that are stationary, or not moving. These other objects are called **reference points.** An object is moving if its position changes compared to a reference point. When you ride a bus, you can tell that you are moving because you pass stationary objects, such as buildings or trees. These objects are your reference points. When you are standing still, you can see that a bird flying overhead is moving because it gets farther and farther away from you. In this example, you are the reference point.

Changes in an object's motion and position can be measured in various ways. **Distance** is the measure of how far it is from one point to another. In the United States, distance is often measured in inches, feet, or miles. In science, we use centimeters, meters, and kilometers, the basic units of distance or length in the International System of Units (SI). An insect might crawl a distance of 30 centimeters (about 12 inches) along a branch. A student might walk a distance of 6 meters (about 20 feet) in the school lunch line. A runner might run a distance of 10 kilometers (about 6 miles) in a race.

Sometimes we need to know more than simply the distance an object traveled. **Displacement** describes both how far an object moved from its original position and in what direction it moved. For example, a runner following a path through a park might travel 3 kilometers north, turn right, and travel 4 kilometers east. The total distance the runner traveled is 7 kilometers. But her final position is actually only 5 kilometers northeast of her starting point. So the runner's displacement is 5 kilometers northeast.

Speed and Velocity

Sometimes we describe an object's motion in terms of its **speed,** or how fast it changes position. Speed compares the distance an object travels with the time it takes to travel that distance. So speed is a rate, a comparison of two quantities that have different units of measure. Speed is described in units of distance divided by units of time, such as meters per second (m/s) or kilometers per hour (km/h). For example, cheetahs can run at speeds of more than 30 m/s.

To calculate speed, we divide the distance an object travels by the time it takes to travel that distance. For example, a horse may travel 180 meters in 60 seconds. The horse's speed is calculated below:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$= \frac{180\text{ m}}{60\text{ s}}$$

$$= 3\text{ m/s}$$

So we know the horse moves at a speed of 3 meters per second (m/s).

Objects do not always move at one steady speed, however. Imagine a family traveling in a car from one place to another (Figure 2). The first part of the trip is on a highway. The car travels 95 kilometers (about 59 miles) in 1 hour. During the next 3 hours, the family first gets stuck in a traffic jam, then makes a rest stop, and finally finishes the drive. The car travels 115 km (about 71 miles) in these 3 hours. How can we describe the car's speed during the whole trip? Since we know the total distance and the total time, we can calculate the car's **average speed.**

$$\text{average speed} = \frac{\text{total distance}}{\text{total time}}$$

$$\text{total distance} = 95\text{ km} + 115\text{ km} = 210\text{ km}$$

$$\text{total time} = 1\text{ h} + 3\text{ h} = 4\text{ h}$$

$$\text{average speed} = \frac{210\text{ km}}{4\text{ h}} = 52.5\text{ km/h}$$

▲ **Figure 2** This distance-time graph shows changes in the motion of a car as a family took a trip. When was the car stopped?

Speed describes how fast an object is moving, but it does not describe the object's direction. **Velocity** describes both an object's speed *and* its direction. Suppose a bicyclist is traveling north at a speed of 15 km/h. At that moment, the bicyclist's velocity is 15 km/h north. Any change in the bicyclist's speed *or* direction changes his velocity.

Forces and Motion

▲ **Figure 3** The force of a kicker's foot causes a soccer ball to start moving, change speed, or change direction.

READ TO UNDERSTAND

- How are force and motion related?
- How do friction and gravity affect objects?
- What is momentum, and how can it be conserved?

VOCABULARY

force
gravity
newton
net force
balanced forces
unbalanced forces
acceleration
friction
air resistance
mass
weight
terminal velocity
momentum
law of conservation of momentum

What Are Forces?

A **force** is a push or pull. Forces can cause objects to move, change speed, or change direction. Some forces act between objects that are touching one another. For example, a soccer player's foot touches a ball as he kicks it along the ground. A student's hand touches a book as she lifts it out of a backpack. Other forces can act on objects over long distances. For example, **gravity** is a force that pulls all objects toward one another. Gravity between the Sun and the planets keeps the planets in their orbits. Magnetism is another force that can act at a distance. A magnet can attract a magnetic object without touching it.

The amount of force acting on an object can be measured using a spring scale, as shown in Figure 4. Force is measured in units called **newtons.** The force needed to lift a large apple is approximately 1 newton (N).

▲ **Figure 4** The spring scale shows that the force needed to lift the apple is 1 newton.

How Do Forces Affect Objects?

An object can be acted upon by more than one force at a time. The forces can act together or against each other. The force that results from all the combined forces acting on an object is called the **net force.**

A stationary object has at least two forces acting on it. Hold an apple in your hand. The force of gravity pulls the apple down against your hand. At the same time, your hand pushes up on the apple with an equal force. Without the upward force supplied by your hand, gravity would cause the apple to fall to the floor.

Every force has both size and direction. In the case of the apple in your hand, the forces acting on it are equal in size but opposite in direction. The forces balance, or cancel, each other and the apple stays in the same position. Forces that cancel each other completely are called **balanced forces.** The net force is zero.

Sometimes the forces acting on an object do not cancel each other. These forces are called **unbalanced forces.** The net force is not zero. In the game called tug-of-war, two teams pull on a rope in opposite directions. If one team pulls harder on the rope, the forces are unbalanced. The amount of force in one direction cancels only part of the force in the opposite direction, leaving a net force that is not zero. The rope moves in the direction of the greater force.

A net force that is not zero causes changes in velocity. That means the object changes speed or direction or both. **Acceleration** is the rate at which an object's velocity changes. You may have heard people use the word *accelerate* for "speed up." Acceleration actually refers to speeding up, slowing down, or changing direction. Acceleration is calculated by dividing the change in velocity by the time it takes for the change to occur.

Velocity is measured in meters per second, and time is measured in seconds. So acceleration involves two units of time. This is why the unit of acceleration is meters per second per second, or meters per second squared (m/s²).

Suppose you want to know the acceleration of a ski racer. You know the racer's velocity increased from 0 m/s to 20 m/s in 5 seconds. Substitute the amounts into the formula for acceleration:

$$\textbf{acceleration} = \frac{\textbf{final velocity} - \textbf{initial velocity}}{\textbf{time}}$$

$$= \frac{20\ \text{m/s} - 0\ \text{m/s}}{5\ \text{s}}$$

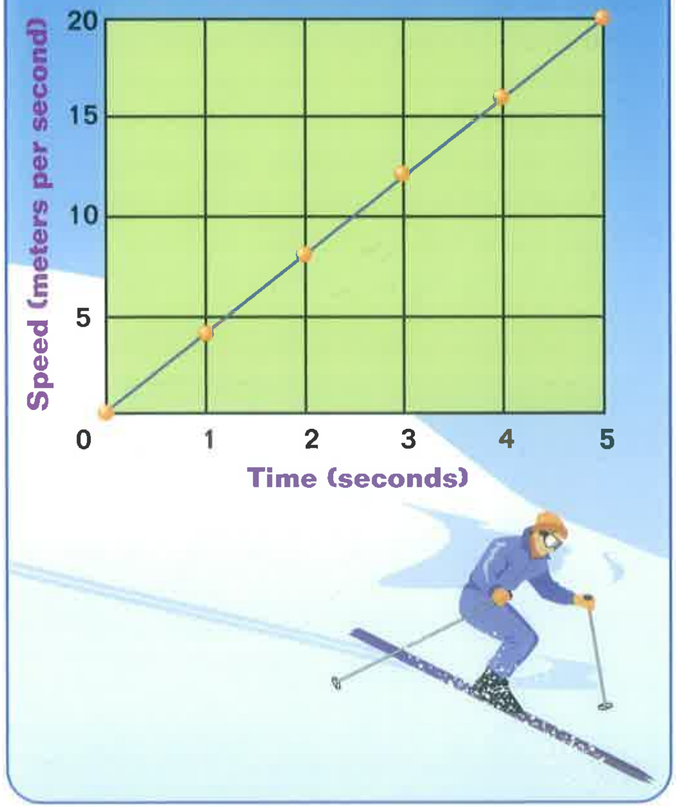
$$= \frac{20\ \text{m/s}}{5\ \text{s}}$$

$$= 4\ \text{m/s}^2$$

So the skier's acceleration was 4 m/s². In other words, the skier's speed increased by 4 meters per second each second during the first 5 seconds of the race. The changes in the skier's speed and distance over time are shown in Figure 5.

Changes in Speed and Distance Over Time

Time (s)	Speed (m/s)	Distance (m)
0	0	0
1	4	2
2	8	8
3	12	18
4	16	32
5	20	50



▲ **Figure 5** Notice how the line on the speed-time graph slopes upward and to the right. This shows that the skier's speed increased at a constant rate. We say the skier's acceleration was positive. Look at the last column of the data table, which shows the total distance traveled. What do you notice about the distance the skier traveled each second?

Now suppose the skier was slowing down at a constant rate. The skier's acceleration would be negative. How would that change the slope of the line on the graph?

What Is Friction?

Friction is a force that occurs when two surfaces rub against each other. Every surface has tiny high and low spots. On a smooth surface, such as glass or polished steel, the high and low spots may be so tiny that you can see them only with a microscope (Figure 6). However, on a rough surface such as sandpaper, you can easily see or feel these uneven places. When two surfaces are touching, the high spots of one surface can get stuck in the low spots of the other. This causes friction. The force of friction always acts opposite to the direction of an object's motion. Friction can slow the motion of an object or keep an object from moving at all.

Without friction, our world would be a very different place. Every surface would be more slippery than the smoothest sheet of ice. Walking would be impossible. You would not even be able to hold a pencil or write on paper. The four main types of friction are static friction, sliding friction, rolling friction, and fluid friction.

▲ **Figure 6** This magnification of a piece of metal shows that even a very smooth surface has tiny high and low areas that cause friction.

Static Friction Static friction occurs between stationary objects. It is the force that keeps a book from sliding off a desktop, even if the desktop is slightly tilted. Static friction also keeps a pencil from slipping through your fingers when you hold it to write. You experience static friction every time you walk. As you push off with each step, static friction between the ground and your shoe keeps your shoe from sliding. Static friction also keeps a box of books in place on a carpet. To begin to slide the box along the floor, you have to first overcome the force of static friction between the box and the carpet.

▲ **Figure 7** Without static friction, a climber's hands and feet could not grip a steep rock.

Sliding Friction Sliding friction occurs when one object slides over another object. If you push hard enough on a box of books, the box may slide across the carpet. Sliding friction is now acting between the box and the carpet. Sliding friction is weaker than static friction. So it takes less force to keep the box sliding than it did to get it moving in the first place. Sliding friction also causes surfaces in contact to heat up. When we rub our hands together, sliding friction produces heat that warms our skin.

▲ **Figure 8** Friction between a racer's tires and the surface of the road may slow the athlete down, but it also allows for control.

Rolling Friction Rolling friction occurs when one surface rolls across another. When a wheel or other round object rolls over another surface, the high spots on one surface are lifted up and over the other surface's high spots. Rolling friction is not as strong as sliding friction. It also produces less heat than sliding friction does.

Putting a box of books on a wheeled cart makes the box easier to move. It is easier because the rolling friction between the carpet and the cart's wheels is weaker than the sliding friction between the box and the carpet. Movers often use wheeled dollies to make it easier to move heavy objects such as refrigerators.

Many machines contain ball bearings, such as those inside the skate wheel in Figure 9, to reduce friction. A ball bearing is a set of round balls placed between two smooth surfaces. The balls roll as the surfaces move past each other. This rolling friction helps keep the machine parts from wearing out.

▼ **Figure 9** To reduce friction, ball bearings are often used inside wheels for inline skates and skateboards.

Fluid Friction Liquids, such as water, and gases, such as air, are both called fluids. When an object moves through a fluid, the object experiences fluid friction. An aquatic animal experiences fluid friction when it moves through the water (Figure 10). The surface of its body rubs against the water particles. An airplane experiences **air resistance,** which is a kind of fluid friction, as it flies through the air.

The amount of fluid friction acting on an object depends on the object's size and shape and the kind of fluid it is moving through. Objects with more surface area experience greater fluid friction and move more slowly through air or water. A flat sheet of paper falls slowly through the air. If you crumple the paper into a ball, you reduce its surface area, and the paper will fall much faster.

▲ **Figure 10** Fluid friction acts on a fish as it moves through the water. Fluid friction is sometimes called drag. Competitive swimmers often wear special caps or swimsuits. These items are designed to reduce the drag between a swimmer's body and the water.

▲ **Figure 11** Due to the force of gravity, spring toys can "walk" down stairs, water flows downhill, sand falls in an hourglass, and roller coasters zoom down tracks.

What Is Gravity?

Every object exerts a force on every other object. This force, called gravity, pulls objects toward each other. The strength of the force of gravity depends on the distance between the objects and their masses. **Mass** is the amount of material, or matter, in an object. Mass is expressed in kilograms (kg). The force of gravity is stronger when objects have more mass or are closer together. The force of gravity is hard to detect unless at least one of the objects has a lot of mass.

Gravity holds us on the ground. The force of Earth's gravity acting on an object is the object's **weight.** Weight is expressed in newtons (N), because newtons are units of force. An object's weight depends on its mass and the acceleration due to gravity. For example, gravity causes all objects near Earth's surface to fall with an acceleration of 9.8 meters (about 32 feet) per second squared. So on Earth, the weight of an object with a mass of 60 kg can be calculated as follows:

$$\begin{aligned}\textbf{weight} &= \textbf{mass} \times \textbf{acceleration}\\ &= 60\text{ kg} \times 9.8\text{ m/s}^2\\ &= 588\text{ N}\end{aligned}$$

Gravity causes objects to accelerate. Suppose a skydiver jumps from a plane. Gravity causes her to begin accelerating toward Earth's surface at 9.8 m/s^2. As the skydiver's velocity increases, so does the upward force of air resistance. After about 10 seconds, the forces of gravity and air resistance acting on the skydiver are equal. The skydiver has reached a constant velocity known as **terminal velocity.** The diver will continue at this same velocity until she opens a parachute. The parachute creates more air resistance and slows the diver down for a safe landing.

▲ **Figure 12** When a skydiver reaches terminal velocity, the forces of gravity and air resistance are balanced. The skydiver stops accelerating and moves at a constant velocity.

What Is Momentum?

Suppose a toy car rolls toward you at a velocity of 1 meter per second (m/s). You can stop it easily with your hand. Now suppose a real car is moving at the same velocity. You know that you would not be able to stop it with your hand. It takes more force to stop the real car because it has more momentum. **Momentum** is a property that a moving object has because of its mass and velocity.

We can calculate an object's momentum by multiplying its mass by its velocity. So the momentum of a 5-kg bowling ball rolling down a lane at a velocity of 7 m/s is as follows:

momentum = mass x velocity
= 5 kg × 7 m/s
= 35 kg•m/s

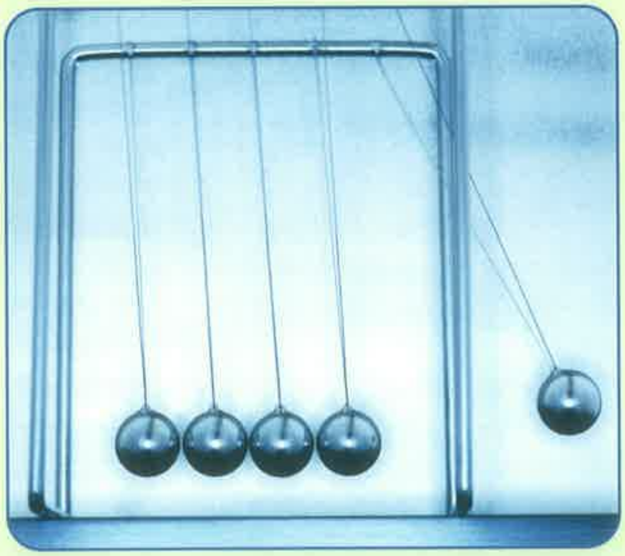
The bowling ball has a momentum of 35 kg•m/s forward. The unit of momentum is the kilogram-meter per second (kg•m/s). Momentum is always described with a direction because velocity has a direction.

Think about a slow-moving object like a bulldozer and a fast-moving object like a baseball thrown by a major league pitcher. Both have a lot of momentum. The bulldozer has a large momentum because of its large mass. The baseball has a large momentum because of its high velocity. The momentum of an object does not change unless its mass changes, its velocity changes, or both change.

Momentum can be transferred from one object to another. Suppose a bowling ball hits some bowling pins and knocks them over. At first, the bowling ball has momentum and the pins do not. When the ball hits the pins, they gain momentum and start moving. At the same instant, the ball slows down and loses momentum. The momentum the pins gain is equal to the momentum the ball loses. The total momentum does not change.

The total amount of momentum in a group of interacting objects does not change unless outside forces act on the objects. This principle is called the ***law of conservation of momentum.***

▲ **Figure 13** The bowling ball's momentum is transferred to the pins. Together, the bowling ball and the pins are a kind of system. The total amount of momentum in the system stays the same.



▲ **Figure 14** "Newton's Cradle" is a toy that demonstrates conservation of momentum. A single sphere on one side is pulled back and released. When it strikes the remaining spheres, it stops. The momentum of the first sphere is transferred to the others. What do you think happens next?

Newton's Laws of Motion

▶ Figure 15
Galileo is shown demonstrating his ramp experiments in this painting by Giuseppe Bezzuoli (1784–1855), of Florence, Italy. Galileo is the tall man just to the left of the center of the painting.

Before the 1600s, most scholars accepted the Greek philosopher Aristotle's theories of motion. Aristotle (384–322 B.C.E.) thought that the speed of a falling object depended on its mass. He believed that an object with a large mass would fall more quickly than an object with a small mass.

Galileo Galilei (1564–1642), a natural philosopher from Italy, did not agree. He hypothesized that all objects fall at the same rate and that they accelerate as they fall. But Galileo could not measure the speed of falling objects because they fell too quickly to record. Today we can use special cameras and timing equipment to do this. But this kind of technology did not exist in Galileo's time. So Galileo came up with a solution. He rolled balls of different masses down a ramp. Using a ramp allowed Galileo to slow down an object's fall so he could measure it. Galileo's experiments showed that all objects do fall at the same rate and that objects accelerate as they fall.

Sir Isaac Newton (1642–1727) built on Galileo's ideas. Newton observed that a force could change an object's motion. For example, the force of gravity makes a falling object accelerate. Newton explained that the motion of objects follows three basic principles, which we now call the three laws of motion.

It can be difficult to contradict the accepted ideas of the time. At first, Galileo's ideas were considered absurd because they challenged what people thought was true. However, Galileo's and Newton's experiments have been repeated many times with the same outcomes. So their hypotheses can be accepted as correct. Scientific knowledge is indeed the result of the contributions of many people over time.

READ TO UNDERSTAND

- What are Newton's three laws of motion? Give an example of each.

VOCABULARY

Newton's first law of motion
inertia
Newton's second law of motion
Newton's third law of motion

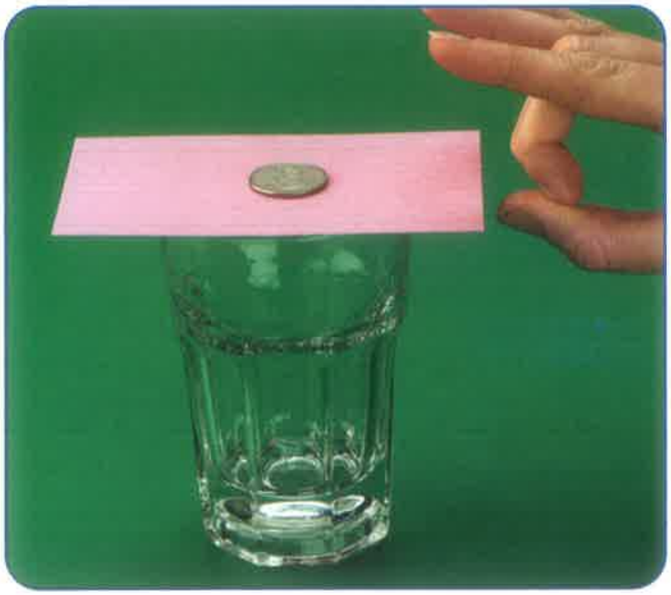
Newton's three laws of motion help us predict how forces will affect objects on Earth and, in fact, anywhere in the universe.

Newton's First Law

An object at rest will remain at rest and an object in motion will continue to move at the same speed in a straight line unless a net force acts on it.

Have you ever lurched forward in your seat when the car or bus you were riding in suddenly slowed down? If so, you have experienced **Newton's first law of motion.** It states that a moving object will continue to move with the same velocity in a straight line until a large enough force acts on it and changes its motion. The law also states that an object at rest remains at rest unless a large enough force acts on it and makes it move.

It is easy to see how objects that are at rest because of balanced forces will stay at rest until another force is added. A ball at rest on a soccer field will not move until it is kicked. A chair will stay in place until it is pushed. However, it is difficult to find examples of objects in motion that continue to move at the same speed in a straight line forever. This is because the forces of gravity and friction act on these moving objects, changing their direction or speed.



▲ **Figure 16** When the cardboard is flicked out from under the coin, inertia will cause the coin to stay in one place until gravity causes it to drop into the glass.

Newton's first law of motion is sometimes called the law of inertia. **Inertia** is the tendency of a still or moving object to resist changes in its motion. The amount of inertia an object has depends on its mass. The greater the mass of an object, the greater the force needed to overcome inertia and cause a change in the object's motion. This is why it may take five people to push a car while just one person can push a bicycle.

Crash test dummies are often used to study what might happen in a real car crash (Figure 17). Suppose a fast-moving test car crashes head-on into a barrier. The car crumples, slows down, then stops. This all happens in less than a second. Because of inertia, any test dummies that are not wearing seat belts continue to move forward at the same speed the car was traveling. The test dummies may hit the windshield in front of them. On the other hand, test dummies that are wearing seat belts are attached to the seats in the car. They slow down as the car slows down.

▲ **Figure 17** Inertia causes a test dummy to keep moving forward when the car stops suddenly. The seat belt and air bag keep the test dummy "driver" from hitting the steering wheel or windshield.

Newton's Second Law

An object acted on by a net force will accelerate in the direction of the force. The object's acceleration equals the net force on the object divided by the object's mass:

acceleration = force / mass

Another way of stating this relationship is that the net force on an object is equal to the product of its mass and its acceleration:

force = mass × acceleration

Newton's second law of motion shows how force, mass, and acceleration are related. An object's acceleration will change if either the force on the object or the object's mass changes. This law is often shown in two ways:

$$\textbf{acceleration} = \frac{\textbf{force}}{\textbf{mass}}$$

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

Recall that force is measured in units called newtons. One newton (N) is equal to the force needed to accelerate 1 kilogram (kg) of mass at 1 meter per second squared (m/s²).

If an object's mass stays the same, you can increase the object's acceleration by applying more force. Think about what happens when you throw a baseball. You apply a force to the ball when you throw it. The harder you throw, the more the ball accelerates. According to Newton's second law, if you double the force on the baseball, the acceleration doubles as well.

If the same force is applied to two different objects, the one with a smaller mass will accelerate more than the one with a larger mass. Suppose you are pushing a grocery cart that has a total mass of 30 kg, as shown in Figure 18. If the net force on the cart is 60 N, the cart will accelerate at 2 m/s^2. Now suppose the same 60-N force is exerted on a cart that has a mass of 60 kg, twice the mass of the first cart. The second cart will accelerate at only 1 m/s^2, half the acceleration of the first cart.

Newton's second law also applies when a force acts in the opposite direction of an object's motion. In this case, the force decreases the acceleration. Imagine that an empty grocery cart is rolling down a hill. A fairly small force is needed to stop the cart. But if the cart is piled high with groceries, a larger force is needed to stop the cart because it has more mass.

▲ **Figure 18** One grocery cart has twice the mass of the other. The same net force (60 N) acts on both carts. The cart with twice the mass has half the acceleration of the other cart.

Newton's Third Law

For every action force exerted on an object, the object will exert an equal and opposite reaction force.

When you are swimming and you pull your arms through the water in one direction, your body moves in the opposite direction. **Newton's third law of motion** states that for every action, there is an equal and opposite reaction. This law explains how swimming works. You push the water backward when you move your arms through it. The water pushes your body forward (Figure 19).

Newton's third law describes action and reaction forces. When one object exerts a force on a second object, the second one exerts a force on the first that is equal in strength and opposite in direction. A diver jumping from a platform exerts a downward force on the platform. The platform exerts an equal, upward force on the diver. This force pushes the diver up into the air.

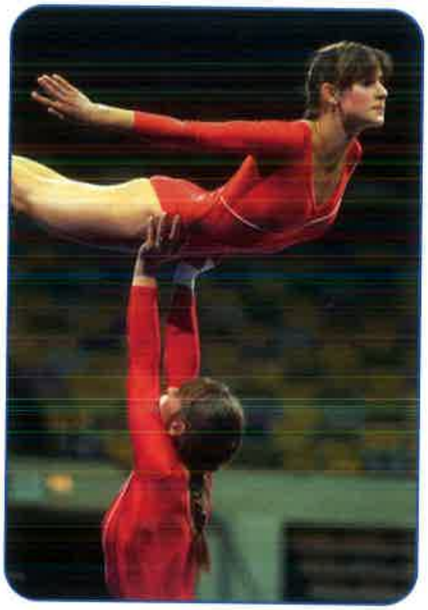
A skateboarder uses action and reaction forces to push himself forward. The action force is the skateboarder's foot pushing against the ground. The reaction force is the ground pushing back. The reaction force makes the skateboarder move forward along the ground.

You may wonder why action and reaction forces do not always cancel each other out. The reason is that the action and reaction forces act on different objects. The skateboarder pushes against Earth, an object with a huge mass. Earth pushes back on the skateboarder, an object with a small mass. The amount of push or force is the same in each case. But the acceleration of the objects is different. The force is strong enough to accelerate the skateboarder, but not strong enough to accelerate Earth.

▲ **Figure 19** The swimmer pushes against a large mass of water. The water pushes back with an equal force, but on the swimmer's much smaller mass. The net force accelerates the swimmer enough to overcome fluid friction and move her forward.

▲ **Figure 20** The hammer exerts a force on the nail and the nail exerts an equal and opposite force on the hammer. However, the nail accelerates more than the hammer does because the nail has a smaller mass.

Work, Energy, and Power



▲ **Figure 21** Power tells how quickly work is done. The power needed for the gymnast to lift her 450-newton partner a distance of 2 meters in 3 seconds is

$$\frac{450 \text{ N} \times 2 \text{ m}}{3 \text{ s}} = 300 \text{ watts}$$

READ TO UNDERSTAND

- How are work, energy, and power related?
- What is the difference between kinetic energy and potential energy?

VOCABULARY

work
joule
energy
kinetic energy
potential energy
power

In science, the word *work* has a special meaning. **Work** is done only when a force is exerted over a distance. For example, you do work when you lift a book from the floor. But you do not do work when you just hold the book above the floor. The amount of work done depends on two things: the amount of force exerted and the distance over which the force is applied. When a force acts over a distance in the direction of an object's motion, the work done can be calculated using this formula:

$$\textbf{work} = \textbf{force} \times \textbf{distance}$$

The unit for work is the **joule** (J). One joule is equal to a newton-meter, which is the amount of work done when a force of 1 newton acts over a distance of 1 meter. This is about the same amount of work it takes to pick up an apple from the ground and raise it 1 meter high.

Energy is the ability to do work or cause change. Work is the transfer of energy through motion. When a batter hits a softball, the bat changes the motion of the ball, so the bat does work on the ball. The bat transfers energy to the ball. The amount of work done is the amount of energy that is transferred. Energy, like work, is measured in joules. **Kinetic energy** is the energy an object has because it is moving. A pitched ball and a swinging bat have kinetic energy. But energy does not have to involve motion. **Potential energy** is stored energy. Stored energy gives an object the potential to do work. A rock on the edge of a cliff has potential energy because of its position. Suppose something knocks the rock loose. Gravity will cause it to fall down the cliff. As the rock falls, its potential energy changes to kinetic energy.

Power is the amount of work done in a period of time (Figure 21). You use more power if you lift a weight quickly than you do if you lift it slowly. Power can be calculated using this formula:

$$\textbf{power} = \frac{\textbf{work}}{\textbf{time}}$$

Work is measured in joules, and time is measured in seconds. The unit of power is the joule per second, also called a watt (W). One watt equals 1 joule per second. So 1 watt is the power needed to raise a 1-newton apple 1 meter high in 1 second.

Machines and Work

A **machine** is a device that makes work easier. Tools and machines are used to apply forces to make things move. Machines can be simple, like a crowbar, or complex, like a bulldozer. A **simple machine** is a device that has few or no moving parts and makes work easier. A combination of two or more simple machines is known as a **compound machine.**

Simple machines can make work easier in three ways. First, a machine can increase, or multiply, the force a person puts into a task. A bottle opener multiplies the force a person applies to lift a cap. Second, a machine can change the direction in which the force is exerted. When a person pulls down on the rope that moves through a pulley at the top of a flagpole, the flag moves up. Third, a machine can increase the distance or speed at which the force acts. A hockey stick is a simple machine that increases the speed and distance over which a force acts.

Mechanical Advantage

To find out the advantage of using any machine, we can compare the forces going into and coming out of it. The amount of force we put into a machine is called the **input force.** The amount of force that comes out of a machine is the **output force.** The **mechanical advantage** (MA) of a machine is found by comparing the output force with the input force. The mechanical advantage can be calculated by dividing the output force by the input force:

$$\textbf{mechanical advantage} = \frac{\textbf{output force}}{\textbf{input force}}$$

Machines that multiply your force cause the output force to be greater than the input force. These machines have a mechanical advantage that is *greater than 1*. Machines that change only the direction of your force have equal input and output forces. Their mechanical advantage is *equal to 1*. Finally, machines that increase the distance or speed at which a force acts have an output force that is less than the input force. Their mechanical advantage is *less than 1*.

▲ **Figure 22** The pulley at the top of a flagpole is a machine that changes the direction of the input force.

READ TO UNDERSTAND

- What are the six types of simple machines?
- What are some everyday examples of simple machines?
- How is a compound machine different from a simple machine?

VOCABULARY

machine
simple machine
compound machine
input force
output force
mechanical advantage
work input
work output
efficiency
inclined plane
wedge
screw
lever
fulcrum
wheel and axle
pulley
gear

Efficiency

Two kinds of work are involved when a machine is used. One is the work done *on* the machine, and the other is the work done *by* the machine. The work done on the machine is called the **work input,** and the work done by the machine is called the **work output.**

Energy, like momentum, is always conserved. So you can never get more work out of a machine than you put into it. In a machine, the work output is always less than the work input because friction causes some energy to be changed into heat energy.

A machine's **efficiency** is a measure of how much of the work input is changed to useful work output. Efficiency is described as a percentage. A high-efficiency machine changes a large proportion of work input to useful work output. A machine's efficiency can be calculated using this formula:

$$\textbf{efficiency} = \frac{\textbf{work output}}{\textbf{work input}} \times 100\%$$

A bicycle is a very efficient machine. Many bikes can produce about 9.5 joules of work output for every 10 joules of work input. The efficiency can be calculated like this:

$$\frac{9.5\text{ J}}{10\text{ J}} \times 100\% = 95\%$$

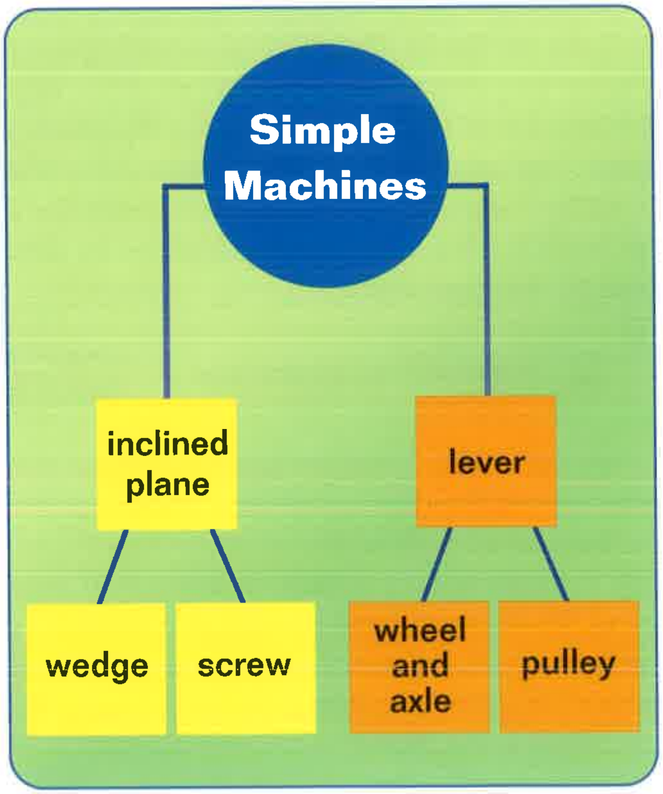
Only 0.5 joule out of every 10 joules is changed to heat by friction.

▲ **Figure 23** Almost all of the work we put into turning the pedals of a bicycle is changed into useful work output, moving the bike forward.

Simple Machines

Simple machines are the basic components of which all other machines are made. Most simple machines work by helping people move objects using less force. However, a trade-off is involved. In order to use less force, that force must be applied over a longer distance. If you use a screwdriver to pry the lid off a paint can, you are using a simple machine. The force you apply to the handle of the screwdriver is the input force, and the force the screwdriver applies to lift the lid is the output force. Although you move the screwdriver's handle a long distance, you gain a greater force where the screwdriver meets the lid.

There are two main "families" of simple machines (Figure 24). The first group includes the inclined plane and its relatives, the wedge and the screw. The second group includes the lever and its relatives, the wheel and axle and the pulley.

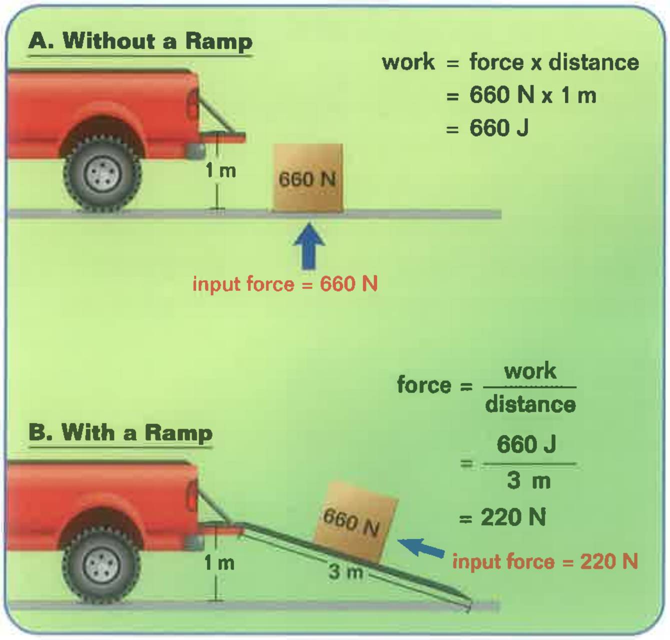


▲ **Figure 24** All simple machines can be grouped into two main families: those related to the inclined plane and those related to the lever.

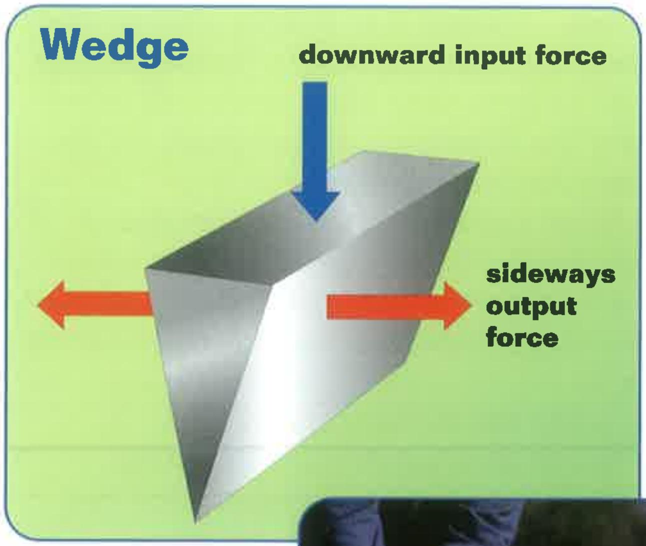
Inclined Plane An **inclined plane** is a slope, a surface that has one end raised higher than the other end. Inclined planes do not move. People use inclined planes to gradually raise or lower objects. Ramps used for wheelchairs or to load trucks are inclined planes.

Suppose a worker needs to lift a heavy box into a pickup truck that is 1 meter high. The box weighs 660 N. The worker could lift the box up into the truck bed, or he could use a ramp. The amount of work done on the box is the same either way. The worker must raise the 660-N box a distance of 1 meter, which equals 660 joules of work.

Recall that work equals force times distance. Another way of saying this is that force equals work divided by distance. So if the worker lifts the box straight up, he applies 660 N of force to do 660 joules of work (Figure 25-A). If the worker uses a ramp that is 3 meters long, the same 660 joules of work is divided by 3 meters. So the input force required is only 220 N (Figure 25-B). With a longer ramp, the worker would need even less force to move the box.



▲ **Figure 25** A worker can trade force for distance by using a ramp instead of lifting an object straight up. Using a ramp, the worker must move the object a greater distance, but can do so by applying a smaller input force.



▶ **Figure 26**
An ax is a wedge that can be used to chop logs for firewood. A downward input force is transferred to a sideways output force that splits a piece of wood in half.

Wedge A **wedge** is a simple machine that has one or two sloping sides that meet at a sharp edge or point (Figure 26). A doorstop is a wedge with one sloping side, and the head of an ax is a wedge with two sloping sides. A wedge is a moving form of inclined plane. People use wedges to cut, split, or pierce things. Other examples of wedges are scissors blades, chisels, boat hulls, needles, and nails.

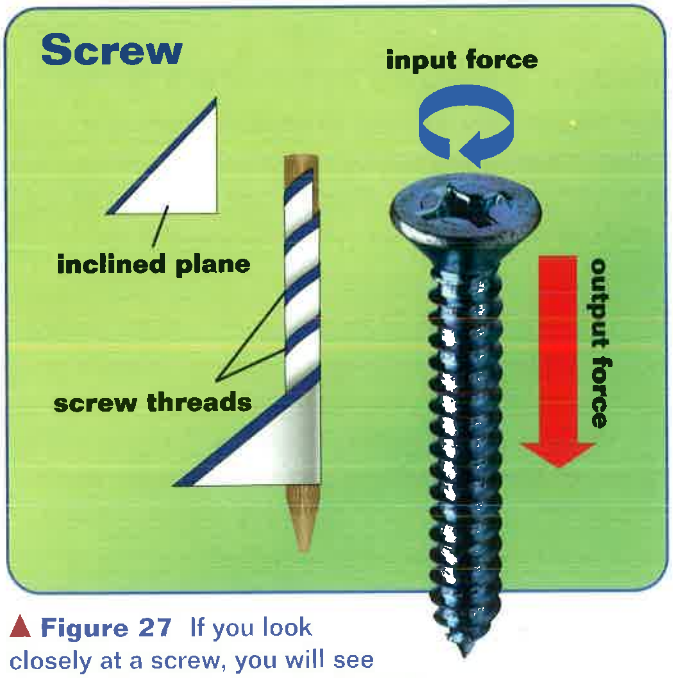
Wedges increase and change the direction of force. For example, a downward input force can be changed into a sideways splitting force. Our front teeth are wedges. When we take a bite out of an apple, we push our front teeth down into the apple. Our teeth change the downward input force into a sideways output force that splits the apple.

Screw A **screw** is an inclined plane wrapped around a cylinder (Figure 27). The slanted edge of the inclined plane forms the threads of the screw. The closer together the threads are, the longer the inclined plane.

When you turn a screw, the direction of your force is changed. The screwdriver rotates to make the screw move downward. In addition, your force is multiplied. The closer together the threads are, the less force you need to apply and the greater the mechanical advantage.

Screws often are used to fasten things together, including lids that screw onto jars. Drill bits are screws that are used to make holes. Propellers and fan blades are screws. Their tilted blades are like threads. These machines turn circular motion into forward motion.

Archimedes (287–212 B.C.E.) was a Greek scientist and mathematician. He invented the Archimedes screw, a machine used for raising water or other materials to a higher level. The machine is a hollow cylinder that has a screw inside. A handle at the top is used to turn the screw. By placing the lower end in water and turning the screw, you can raise water to the top, where it flows out an opening.



▲ **Figure 27** If you look closely at a screw, you will see that the threads form a tiny "ramp" that runs from the tip nearly to the top.

Lever A **lever** is a simple machine that is made up of a rigid bar that turns about a fixed point. The fixed point is called the **fulcrum.** When a screwdriver is used to open a paint can, the lever is the screwdriver and the fulcrum is the edge of the can where the screwdriver rests. Levers are grouped into three classes based on the locations of the input force, the output force, and the fulcrum.

A **first-class lever** has its fulcrum between the input force and the output force (Figures 28 and 30). The input force and output force act in opposite directions. A hammer used to remove nails is a first-class lever. A person applies a downward force to the handle at one end of the lever. The head of the hammer is the fulcrum. The output force of the claw pulls the nail upward.

The mechanical advantage of a first-class lever can be greater than 1, equal to 1, or less than 1. The mechanical advantage is greater when the fulcrum is closer to the output force.

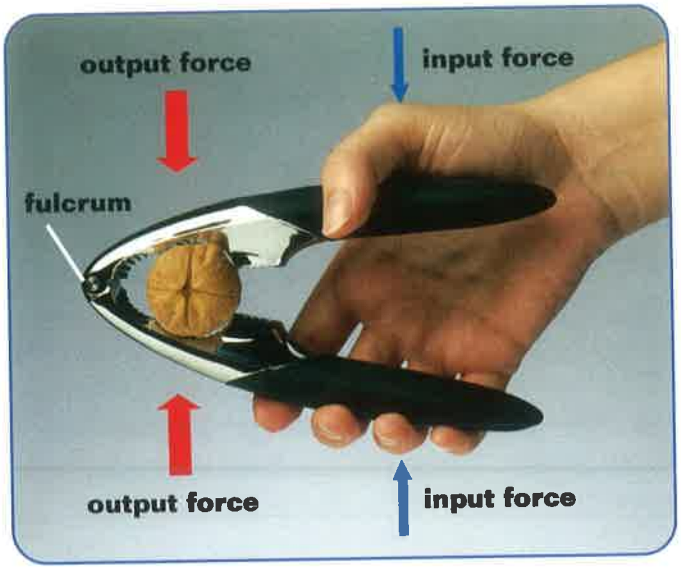
In the case of the hammer claw, the nail is much closer to the fulcrum than is the carpenter's hand on the handle. So the input force must act over a greater distance than the output force does. As a result, the input force is magnified.

A rowboat oar is an example of a first-class lever with a mechanical advantage less than 1. The input force from the rower's hand is closer to the fulcrum than the output force of the paddle. This type of lever multiplies the distance over which the force is applied.

◀ **Figure 28** When a hammer is used to pry out a nail, the hammer is a first-class lever.

A **second-class lever** has its output force located between the input force and the fulcrum (Figures 29 and 30). Both the input force and the output force move in the same direction. A wheelbarrow is a second-class lever. The wheel is the fulcrum. The upward input force is applied to the handles by a person's hands and the output force is applied to the load in the wheelbarrow.

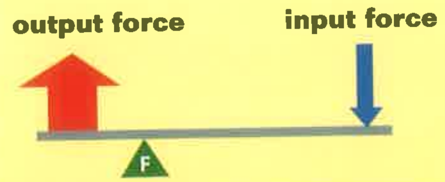
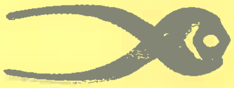
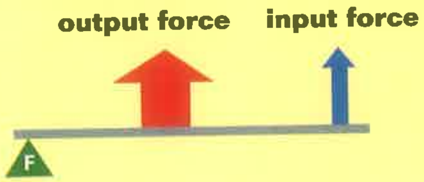
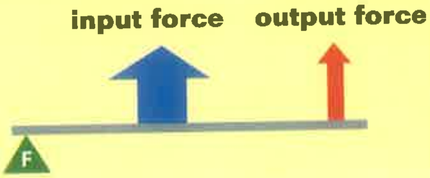
The mechanical advantage of a second-class lever is always greater than 1. To reduce the input force the most, the wheel is located under the bed of the wheelbarrow. This makes the distance from the load to the fulcrum almost zero. It also magnifies the input force the most and increases the mechanical advantage.



▲ **Figure 29** Each side of a nutcracker is a second-class lever.

▼ **Figure 30** Notice the locations of the input force, output force, and fulcrum in each class of lever.

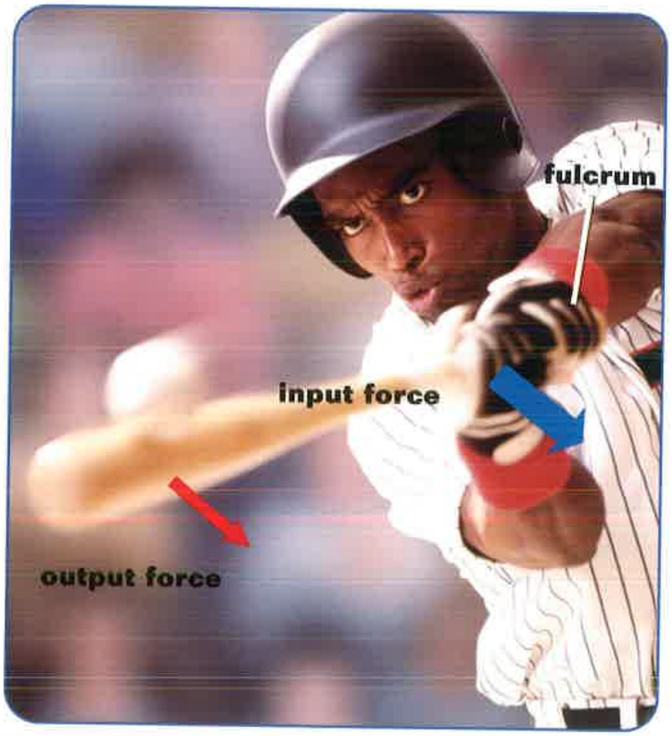
Three Classes of Levers

Lever	Examples	Action
First-Class Lever 	seesaws, pliers, scissors, crowbars, boat oars 	Multiplies force if the input force is farther away from the fulcrum than the output force. Multiplies distance if the input force is closer to the fulcrum than the output force. Also changes the direction of the force. MA: >1, =1, or <1
Second-Class Lever 	wheelbarrows, nutcrackers, bottle openers 	Always multiplies force. Does not change the direction of the force. MA: >1
Third-Class Lever 	shovels, brooms, fishing rods, baseball bats, tweezers, golf clubs, rakes, human forearms 	Always multiplies distance and reduces force. Does not change the direction of the force. MA: <1

A **third-class lever** has its input force located between the fulcrum and the output force (Figures 30 and 31). Third-class levers are common in the human body. Your forearm is a third-class lever. Your elbow joint is the fulcrum and your biceps muscle applies the force between your elbow and your hand to bend your arm.

Tweezers are an example of a double third-class lever. The fulcrum is located where the two arms of the tweezers are attached. The input force is applied in the middle of the tweezers to squeeze the tips together.

The mechanical advantage of a third-class lever is always less than 1. Third-class levers require greater input force, but they increase the distance over which the output force acts. Both the input and output forces act in the same amount of time. So although the output force is smaller, it acts at a greater speed. A baseball bat lets a batter use a large input force on the handle to move the tip of the bat at a high speed.



▲ **Figure 31** A baseball bat is a third-class lever.

▲ **Figure 32** The larger the handle is in relation to the axle, the easier it is to turn on the faucet.

Wheel and Axle A **wheel and axle** is a simple machine consisting of a large wheel fixed to a smaller shaft, or axle. Both rotate together around the same point. A wheel and axle machine is actually a kind of lever that rotates in a circle around a center fulcrum (the axle). Think of a ship's steering wheel or a round faucet handle (Figure 32). Each "spoke" of the wheel is a second-class lever connected to the center axle.

A wheel and axle trades distance for force. As the wheel and axle turn together, a point on the wheel moves farther than a point on the axle. In return, the output force exerted by the axle is greater than the input force applied to the wheel.

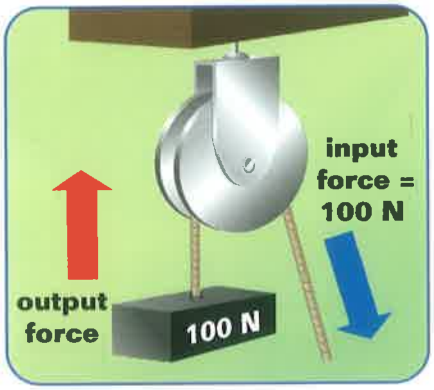
The mechanical advantage of a wheel and axle can be determined by dividing the radius of the wheel (the distance from its center to its edge) by the radius of the axle. If the radius of a wheel is 6 centimeters and the radius of the axle is 2 centimeters, the mechanical advantage is 3. The bigger the wheel is in relation to the axle, the greater the mechanical advantage.

Pulley A **pulley** is a simple machine made of a rope that fits into a grooved wheel. Like the wheel and axle, a pulley is a kind of circular lever. Pulleys produce an output force that is different from the input force in size, direction, or both.

Pulleys are used to raise and lower flags and to open curtains or window blinds. They are also used to lift heavy objects such as pianos or car engines and to unload cargo from ships.

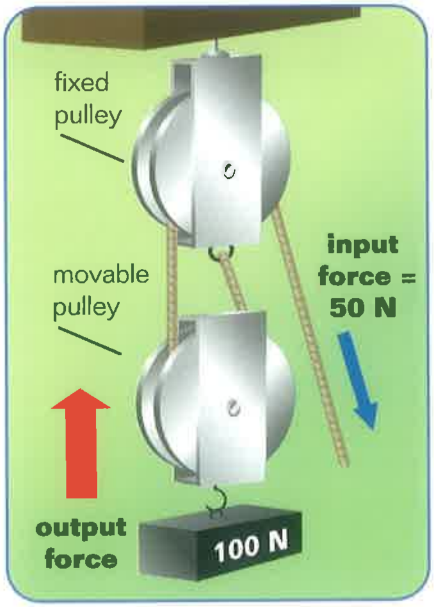
A single fixed pulley changes only the direction of the input force (Figure 33). A compound pulley is a combination of fixed and movable pulleys (Figure 34). A compound pulley magnifies the input force, so the mechanical advantage is greater than 1.

Fixed Pulley



◀ **Figure 33** A single fixed pulley does not magnify the input force. This kind of pulley changes only the direction of the force. So it has a mechanical advantage of 1.

Compound Pulley



◀ **Figure 34** A compound pulley can magnify the input force. An input force of 50 N can lift a 100-N weight with the compound pulley shown. So the mechanical advantage is 2.

Compound Machines

Compound machines such as the pencil sharpener in Figure 35 are made up of two or more simple machines working together. The handle of a pencil sharpener is a wheel and axle. The axle is connected to wheels with teeth called **gears.** When the handle is turned, the axle moves and transfers the force to the gears. The gears then move two spiral wedges with sharp edges, which turn around a pencil and cut the wood away. Two screws hold the sharpener together.

Scissors and axes are actually compound machines. The sharp edges of scissors blades are wedges. Each blade and handle is a first-class lever, and the pin that holds the two levers together is the fulcrum. The head of an ax is a wedge, and the handle is a third-class lever. Bicycles, roller coasters, and Ferris wheels are just a few other compound machines.

▲ **Figure 35** A pencil sharpener is an example of a compound machine that we see every day. It contains several simple machines that work together.

Sir Isaac Newton (1642–1727)

Isaac Newton was born in 1642 about 160 kilometers (100 miles) north of London, England, in the village of Woolsthorpe. His father died before he was born, and young Newton had a difficult childhood. But he was good at building things. He built sundials, water clocks, a crank-powered carriage, and even a model windmill powered by a mouse.

In 1661 Newton entered Trinity College. He paid for school by working as a servant for wealthy students. Newton studied mathematics, astronomy, and optics (lenses and mirrors) and earned his bachelor of arts degree in 1665.

Newton wanted to continue his schooling, but an outbreak of bubonic plague forced Trinity College to close temporarily. He returned to the family farm and spent the next two years studying on his own. During this time, he began to think about gravity. According to legend, Newton was sitting in an orchard when he saw an apple fall from a tree. He wondered, "What force pulled the apple to the ground? Is it the same force that keeps the Moon in orbit around Earth?" Questions like these led Newton to state what would become the **law of universal gravitation.** This law states that a force of attraction exists between any two objects that have mass.

Newton returned to Trinity College when the school reopened in 1667. He earned a master's degree and became a professor of mathematics there. His research in optics led him to invent the reflecting telescope.

In 1687 Newton published his most famous book, *Mathematical Principles of Natural Philosophy*. This book is believed by many people to be the greatest scientific work ever written. In it, Newton described three principles of motion that govern the movement of all objects on Earth and in space. He also presented his theory of universal gravitation in the book.

In 1705 Newton was knighted by England's Queen Anne, and he received the title "Sir." Newton's contributions to science are enormous. Perhaps his greatest achievement was to apply mathematics to the study of the natural world. He was the first to develop many basic principles that remain the foundation of physical science today.

▲ **Figure 36** Sir Isaac Newton was an English mathematician, astronomer, and natural philosopher. He once said, "If I have seen further, it is by standing upon the shoulders of giants." What do you think he meant by this statement?

Did You Know?

About Satellite Motion

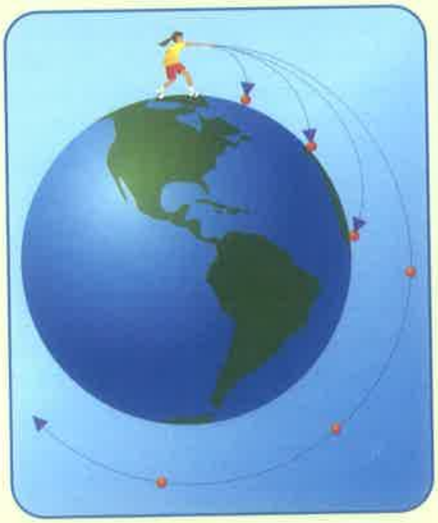
The Moon, spacecraft, and other objects in orbit around Earth are called **satellites.** Some people think that satellites can float in space because there is no gravity there, but that is not true. Gravity affects all objects, even those in space. In fact, gravity causes orbiting objects to constantly fall toward Earth in a condition called **free fall.**

So how do satellites stay "up"? When a satellite is launched, rockets move the satellite up and away from Earth's surface. Once the satellite reaches a certain height, its rockets briefly fire again to get the satellite moving horizontally at a very high speed. According to Newton's first law, the satellite would continue moving in a straight line out into space if not for the force of gravity. The downward force of gravity combines with the horizontal force from the rocket blasts. The combination results in a net force that keeps the satellite moving in orbit around Earth.

To understand satellite motion, imagine throwing a ball through the air. The initial horizontal force from your hand combines with the downward force of gravity. The net force causes the ball to arc and return to the ground. The more force you apply to the ball, the faster the ball moves and the farther the ball travels before it hits the ground. Now suppose you could throw the ball from a tall mountain *very* fast and *very* far (Figure 37). The curved path of the ball would match the curve of Earth's surface! This is what happens with a satellite. Like a fast-moving ball, a satellite is falling in an arc toward Earth. But satellites are moving so quickly that the curve of Earth's surface always stays a distance away from them. A satellite's high speed allows it to stay in orbit, rather than come crashing down to Earth.

So why do astronauts experience "weightlessness" if gravity affects objects in space? The spacecraft and the astronauts inside it are all in free fall. They all accelerate downward at the same rate due to gravity. Because the astronauts move at the same velocity as the reference points around them, they seem to float (Figure 38).

▶ **Figure 37**
The faster an object is thrown, the farther it travels before gravity causes it to hit the ground. In order to put an object into orbit around Earth, you would have to throw the object about 30,000 kilometers (about 19,000 miles) per hour.



◀ **Figure 38**
Astronauts are in free fall. They seem to be floating because they are falling at the same rate as their surroundings.

Glossary

A page number in boldface type indicates the page on which the word is defined in the text.

acceleration rate at which an object's velocity changes (**5**, 8, 12, 13)

air resistance fluid friction acting on an object moving through air; also called drag (**7**, 8)

average speed total distance traveled divided by the time it takes to travel that distance (**3**)

balanced forces forces that cancel each other because they are equal in strength and opposite in direction (**4**, 11)

compound machine combination of two or more simple machines that work together (**15**, 21)

displacement how far an object moved from its original position and in what direction the object moved (**3**)

distance how far it is from one point to another (**2**–5, 8, 14–20, 23)

efficiency in a machine, percentage of the work input that is changed to useful work output (**16**)

energy ability to do work or cause change (**14**, 16)

first-class lever lever with its fulcrum located between the input force and the output force (**18**, 19, 21)

force push or pull that acts on an object, causing it to move, change speed or direction, or stop moving (**4**–6, 8–23)

free fall when gravity alone is acting on an object (**23**)

friction force that opposes motion, or resistance caused when two surfaces touch or rub together (**6**, 7, 11, 13, 16)

fulcrum fixed point around which a lever rotates (**18**–21)

gear wheel with "teeth" around its edge (**21**)

gravity force that exists between any two objects that have mass, attracting or pulling them together (**4**, 8, 10, 11,14, 22, 23)

inclined plane simple machine that is a slope, a surface with one end raised higher than the other end; also called a ramp (16, **17**, 18)

inertia tendency of a still or moving object to resist a change in its motion (**11**)

input force force put into a machine (**15**–21)

joule unit of work or energy (**14**, 16, 17)

kinetic energy energy an object has due to its motion (**14**)

law of conservation of momentum the total momentum of a group of interacting objects does not change unless an outside force acts on the objects (**9**)

law of universal gravitation force of attraction that exists between any two objects with mass (**22**)

lever simple machine made up of a rigid bar that turns about a fixed point, or fulcrum (16, **18**–21)

machine device that changes a force to make work easier (7, **15**–18, 20, 21)

mass amount of matter in an object (**8**–13, 22)

mechanical advantage ratio of the input force to the output force for a given machine (**15**, 18–21)

momentum property of matter due to its mass and velocity (**9**, 16)

motion change in position or place (**2**–4, 6, 10–14, 18, 22, 23)

net force force that results from the combination of all the forces that act on an object (**4**, 5, 11–13, 23)

newton unit of force, equal to the force that causes a 1-kilogram mass to accelerate at a rate of 1 m/s^2 (**4**, 8, 12, 14)

Newton's first law of motion an object at rest will remain at rest and an object in motion will continue to move at the same speed in a straight line unless a net force acts on it (**11**)

Newton's second law of motion an object acted on by a net force will accelerate in the direction of the force. The object's acceleration equals the net force on the object divided by the object's mass. (**12**)

Newton's third law of motion for every action force exerted on an object, the object will exert an equal and opposite reaction force (**13**)

output force force produced by a machine (**15**–21)

position object's place or location (**2**–4, 14)

potential energy energy that is stored, available as a result of an object's position or condition (**14**)

power rate at which work is done; measured in watts (**14**)

pulley simple machine made up of a wheel with a groove in the rim for a rope or cable (15, 16, **21**)

reference point stationary object used to determine the motion of another nearby object (**2**, 23)

satellite object that travels around, or orbits, another object (**23**)

screw simple machine that is an inclined plane wrapped around a cylinder (16, **18**, 21)

second-class lever lever with the output force located between the input force and fulcrum (**19**, 20)

simple machine tool with few or no moving parts that changes the direction or size of a force in order to do work (**15**–18, 20, 21)

speed rate at which the position of an object changes (2, **3**–5, 10, 11, 15, 20, 23)

terminal velocity constant velocity reached by a falling object when the force of air resistance equals the force of gravity (**8**)

third-class lever lever with the input force located between the fulcrum and the output force (19, **20**, 21)

unbalanced forces forces that do not cancel each other out and result in a net force on an object (**5**)

velocity rate at which an object moves in a certain direction (**3**, 5, 8, 9, 11, 23)

wedge simple machine with one or two sloping sides that meet at a sharp edge or point (16, **17**, 21)

weight measure of the force of gravity acting on an object (**8**, 14, 21)

wheel and axle simple machine made up of a wheel fixed to a smaller shaft; both rotate together (16, **20**, 21)

work result of a force moving an object over a distance (**14**–17)

work input work done on a machine (**16**)

work output work done by a machine (**16**)