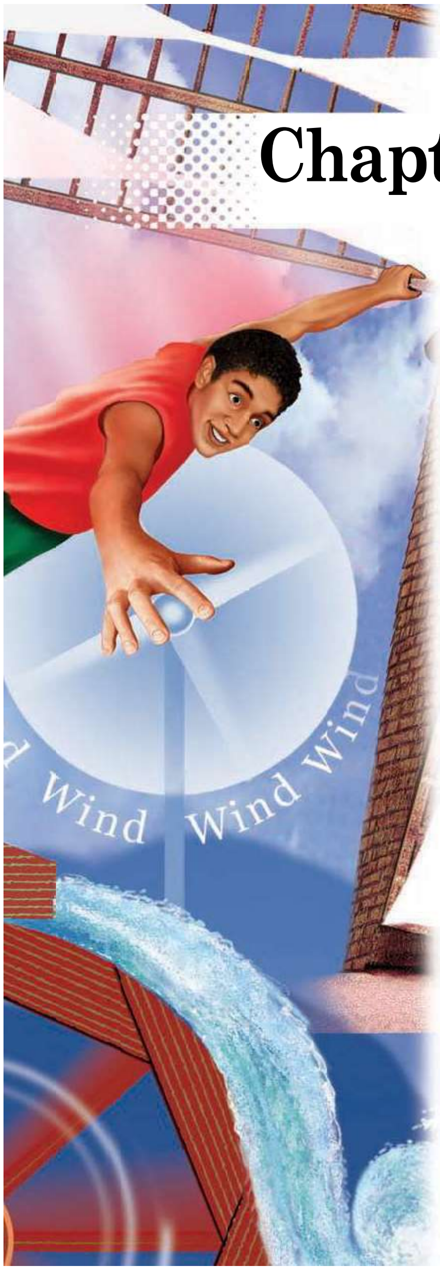

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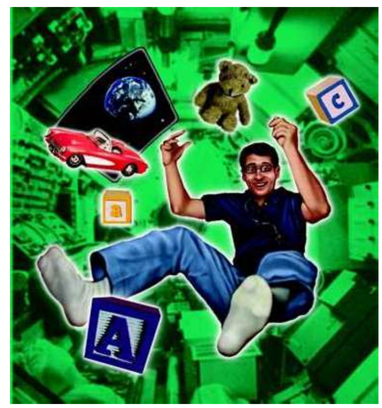
Chapter 2

Laws of Motion

In January 1993, the 53rd space shuttle mission crew, in addition to their usual science experiments, brought some toys on board! During the flight, crew members took the toys out and played with them to see how they would work in what NASA calls “microgravity.” Many people think astronauts float because there is no gravity in space. Not true! If there were no gravity, the space shuttle would not stay in orbit around Earth. So why do astronauts float?

This chapter will help you explain many aspects of motion as it occurs here on Earth, and even how things like simple toys would act in microgravity. You will be able to use Newton's laws of motion to explain why it's possible to throw a basketball through a hoop. What if that hoop and basketball were on the space shuttle? Would the crew members be able to shoot baskets in a microgravity environment?

Sir Isaac Newton, who lived from 1642-1727, attempted to answer similar questions and soon you will know the answers too!



Key Questions

- ✓ Why do thrown objects fall to Earth instead of flying through the air forever?
- ✓ Is it possible for a feather and a hammer to hit the ground at the same time when dropped?
- ✓ What does a graph of motion look like?

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2.1 Newton's First Law

Sir Isaac Newton (1642-1727), an English physicist and mathematician, was one of the most brilliant scientists in history. Before age 30, he had made several important discoveries in physics and had invented a new kind of mathematics called calculus. Newton's three laws of motion are probably the most widely used natural laws in all of science. The laws explain the relationships between the forces acting on an object, the object's mass, and its motion. This section discusses Newton's first law of motion.

Vocabulary

force, Newton's first law, inertia, newton, net force

Objectives

- ✓ Recognize that force is needed to change an object's motion.
- ✓ Explain Newton's first law.
- ✓ Describe how inertia and mass are related.

Changing an object's motion

Suppose you are playing miniature golf and it is your turn. What action must you take to make the golf ball move toward the hole? Would you yell at the ball to make it move? Of course not! You would have to hit the ball with the golf club to get it rolling. The club applies a force to the ball. This force is what changes the ball from being at rest to being in motion (Figure 2.1).

What is force?

A **force** is a *push* or *pull*, or *any action that has the ability to change motion.* The golf ball will stay at rest until you apply force to set it in motion. Once the ball is moving, it will continue to move in a straight line at a constant speed, unless another force changes its motion. You need force to start things moving and also to make any change to their motion once they are moving. Forces can be used to increase or decrease the speed of an object, or to change the direction in which an object is moving.

How are forces created?

Forces are created in many different ways. For example, your muscles create force when you swing the golf club. Earth's gravity creates forces that pull on everything around you. On a windy day, the movement of air can create forces. Each of these actions can create force because they all can change an object's motion.

Force is required to change motion

Forces create changes in motion, and *there can be no change in motion without the presence of a force.* Anytime there is a change in motion a force must exist, even if you cannot immediately recognize the force. For example, when a rolling ball hits a wall and bounces, its motion changes rapidly. That change in motion is caused by the wall exerting a force that changes the direction of the ball's motion.

Figure 2.1: *Force is the action that has the ability to change motion. Without force, the motion of an object cannot be started or changed.*

Forces, mass, and inertia

Stopping a moving object

Let's keep playing golf. Once the golf ball is moving, how can you stop it? The only way to stop the ball is to apply a force in a direction opposite its motion. In general, objects want to keep doing what they are already doing. This idea is known as Newton's first law of motion.

Newton's first law

Newton's first law states that objects tend to continue the motion they already have unless they are acted on by forces. In the absence of forces an object at rest will stay at rest. An object that is moving will keep moving at the same speed and in the same direction. In other words, objects resist changes in their motion.

An object at rest will stay at rest and an object in motion will continue in motion with the same speed and direction UNLESS acted on by a force.

Inertia

Some objects resist changes in motion better than others. **Inertia** is the property of an object that resists changes in its motion. To understand inertia, imagine trying to move a bowling ball and a golf ball. Which requires more force? Of course, the bowling ball needs more force to get it moving at the same speed as the golf ball (assuming the forces act for the same length of time). The bowling ball also requires more force to stop. A bowling ball has more inertia than a golf ball. The greater an object's inertia, the greater the force needed to change its motion. Because inertia is an important idea, Newton's first law is sometimes called the law of inertia.

Mass

Inertia comes from mass. Objects with more mass have more inertia and are more resistant to changes in their motion. Mass is measured in kilograms (kg). A golf ball has a mass of 0.05 kilograms, and the average bowling ball has a mass of 5 kilograms (Figure 2.2). A bowling ball is 100 times as massive, so it has 100 times the inertia. For small amounts of mass, the kilogram is too large a unit to be convenient. One gram (g) is one-thousandth of a kilogram. A dollar bill has a mass of about a gram, so 1,000 dollar bills have a mass of approximately 1 kilogram.

Figure 2.2: *Mass can be measured in grams or kilograms. One kilogram equals 1000 grams.*

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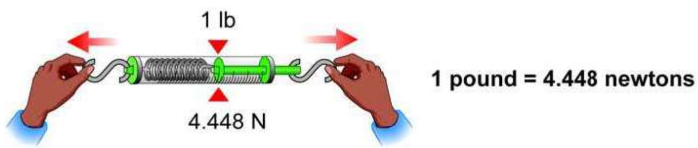
Units of force

Pounds If you are mailing a package at the post office, how does the clerk know how much to charge you? The package is placed on a scale and you are charged based on the package's weight. For example, the scale shows that the package weighs 5 pounds. The pound is a unit of *force* commonly used in the United States. When you measure weight in pounds on a scale, you are measuring the *force of gravity* acting on the object (Figure 2.3).

The origin of the pound The pound measurement of force is based on the Roman unit *libra*, which means "balance" and is the source for pound's abbreviation, "lb." The word "pound" comes from the Latin word *pondus*, which means "weight." The definition of a pound has varied over time and from country to country.

The newton Although the pound is commonly used to express force, scientists prefer to use the newton. The **newton (N)** is the metric unit of force. A force of one newton is the exact amount of force needed to cause a mass of one kilogram to speed up by one meter per second each second (Figure 2.3). We call the unit of force the newton because force in the metric system is defined by Newton's laws. The newton is a useful way to measure force because it connects force directly to its effect on mass and speed.

Converting newtons and pounds The newton is a smaller unit of force than the pound. One pound of force equals 4.448 newtons. How much would a 100-pound person weigh in newtons? Remember that 1 pound = 4.448 newtons. Therefore, a 100-pound person weighs 444.8 newtons.



The force unit of newtons When physics problems are presented in this book, forces will almost always be expressed in newtons. In the next section, on Newton's second law, you will see that the newton is closely related to the metric units for mass and distance.

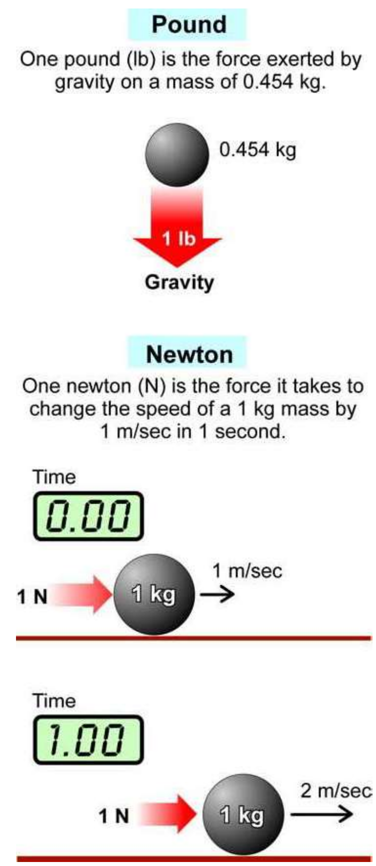


Figure 2.3: *The definition of the pound and the newton.*

The net force

Multiple forces When you hit a golf ball, the force from the club is not the only force that acts. Gravity also exerts a force on the ball. Which force causes the change in the ball's motion: gravity or the force from the golf club? Does gravity stop while the golf club exerts its force?

Forces act together You are right if you are thinking "all forces together." The motion of objects changes in response to the *total force* acting on the object, including gravity and any other force that is present. In fact, it is rare that only one force acts at a time since gravity is always present.

Net force Adding up forces can be different from simply adding numbers because the *directions* of the forces matter. For this reason the term **net force** is used to describe the total of all forces acting on an object. When used this way, the word "net" means *total* but also implies that the direction of the forces has been taken into account when calculating the total.

Forces in the same direction When two forces are in the same direction, the net force is the sum of the two. For example, think about two people pushing a box. If each person pushes with a force of 300 newtons in the same direction, the net force on the box is 600 N (Figure 2.4 top). The box speeds up in the direction of the net force.

Forces in opposite directions What about gravity acting on the box? Gravity exerts a force downward on the box. However, the floor holds the box up. In physics, the term "holds up" means "applies a force." In order to "hold up" the box, the floor exerts a force upward on the box. The net force on the box in the "up-down" direction is *zero* because the force from the floor is opposed to the force of gravity. When equal forces are in the opposite direction they cancel (Figure 2.4 bottom). The motion of the box in the up-down (vertical) direction does not change because the net force in this direction is zero.

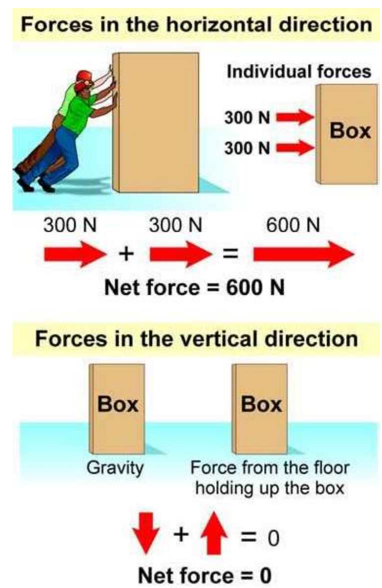


Figure 2.4: *The net force acting on a box being pushed.*

2.1 Section Review

1. State Newton's first law in your own words.
2. How is mass related to inertia?
3. What is the net force and how is it determined?

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2.2 Acceleration and Newton's Second Law

Vocabulary

acceleration, deceleration, Newton's second law

Objectives

- ✓ Define and calculate acceleration.
- ✓ Explain the relationship between force, mass, and acceleration.
- ✓ Determine mass, acceleration, or force given two of the quantities.

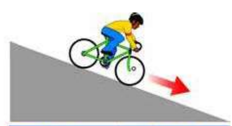
Newton's first law says that a force is needed to change an object's motion. But what kind of change happens? The answer is *acceleration*. Acceleration is how motion changes. The amount of acceleration depends on both force and the mass according to Newton's second law. This section is about Newton's second law, which relates force, mass, and acceleration. The second law is probably the most well-used relationship in all of physics.

Acceleration

Definition of acceleration

What happens if you coast on a bicycle down a long hill without pedaling? At the top of the hill, you move slowly. As you go down the hill, your speed gets faster and faster—you accelerate. **Acceleration** is the rate at which your speed increases. If speed increases by 1 kilometer per hour (km/h) each second, the acceleration is 1 km/h per second.

Time	Speed
0 (start)	0 (start)
1 second	1 km/h
2 seconds	2 km/h
3 seconds	3 km/h
4 seconds	4 km/h
5 seconds	5 km/h



Time	Speed
0 (start)	0 (start)
1 second	2 km/h
2 seconds	4 km/h
3 seconds	6 km/h
4 seconds	8 km/h
5 seconds	10 km/h

Steeper hills

Your acceleration depends on the steepness of the hill. If the hill is a gradual incline, you have a small acceleration, such as 1 km/h per second. If the hill is steeper, your acceleration will be greater, perhaps 2 km/h per second. On the gradual hill, your speedometer increases by 1 km/h every second. On the steeper hill, it increases by 2 km/h every second.

Car acceleration

Advertisements for sports cars often discuss acceleration. A typical ad might boast that a car can go "from zero to 60 in 10 seconds." This means the car's speed begins at zero and reaches 60 miles per hour (96 km/h) after accelerating for 10 seconds. The car's acceleration is therefore 6 miles per hour per second (Figure 2.5).

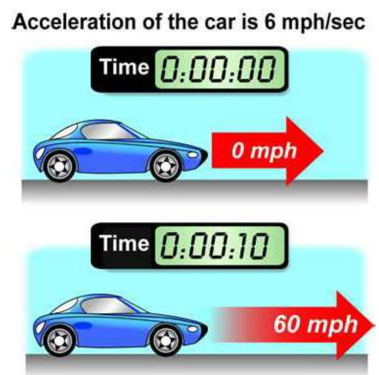


Figure 2.5: *It takes 10 seconds for a car to go from zero to 60 mph if it has an acceleration of 6 mph per second. In metric units the car goes from zero to 96 km/h in 10 seconds. The acceleration is 9.6 km/h per second.*

Units of acceleration

Speed units and time units Acceleration is the rate of change of an object's speed. To calculate acceleration, you divide the change in speed by the amount of time it takes for the change to happen. In the example of the sports car, acceleration was given in kilometers per hour per second. This unit can be abbreviated as km/h/sec. Notice that two time units are included in the unit for acceleration. One unit of time is part of the speed unit, and the other is the time over which the speed changed.

Metric units If the change in speed is in meters per second and the time is in seconds, then the unit for acceleration is m/sec/sec or *meters per second per second.* An acceleration of 10 m/sec/sec means that the speed increases by 10 m/sec *every second.* If the acceleration lasts for three seconds, then the speed increases by a total of 30 m/sec (3 seconds × 10 m/sec/sec). This is approximately the acceleration of an object allowed to fall free after being dropped.

What do units of seconds *squared* mean? An acceleration in m/sec/sec is often written m/sec^2 (meters per second squared). If you apply the rules for simplifying fractions on the units of acceleration (m/sec/sec), the denominator ends up having units of seconds times seconds, or sec^2. Saying *seconds squared* is just a math-shorthand way of talking. It is better to think about acceleration in units of speed change per second (that is, meters per second *per second*).

$$\text{Acceleration} = \frac{\text{Change in speed}}{\text{Change in time}}$$

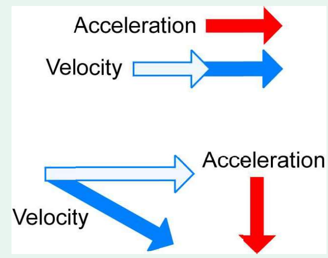
How we get units of m/sec^2

Plug in values — *Clear the compound fraction* — *Final units*

$$50\,\frac{\frac{\text{m}}{\text{sec}}}{\text{sec}} = 50\,\frac{\text{m}}{\text{sec}} \times \frac{1}{\text{sec}} = 50\,\frac{\text{m}}{\text{sec x sec}} = 50\,\frac{\text{m}}{\text{sec}^2}$$

Acceleration in m/sec^2 Nearly all physics problems will use acceleration in m/sec^2 because these units agree with the units of force (newtons). If you measure speed in centimeters per second, you may have to convert to meters/second before calculating acceleration. This is especially true if you do any calculations using force in newtons.

Acceleration and direction



The velocity of an object includes both its speed and the direction it is moving. A car with a velocity of 20 m/sec north has a speed of 20 m/sec and is moving north.

An object accelerates if its *velocity* changes. This can occur if its *speed* changes or if its *direction* changes (or both). Therefore, a car driving at a constant speed of 40 mph around a bend is actually accelerating. The only way a moving object can have an acceleration of zero is to be moving at constant speed in a straight line.

This chapter covers acceleration that involves only changes in speed. In chapter 6, you will learn about the acceleration of moving objects that change direction as well.

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Calculating acceleration

The equation for acceleration

To calculate acceleration, you divide the change in speed by the time over which the speed changed. To find the change in speed, subtract the starting (or initial) speed from the final speed. For example, if a bicycle's speed increases from 2 m/sec to 6 m/sec, its change in speed is 4 m/sec. Because two speeds are involved, subscripts are used to show the difference. The initial speed is v_1, and the final speed is v_2.

ACCELERATION

$$a = \frac{v_2 - v_1}{t}$$

Acceleration (m/sec²) = *Change in speed* (m/sec) / *Time* (sec)

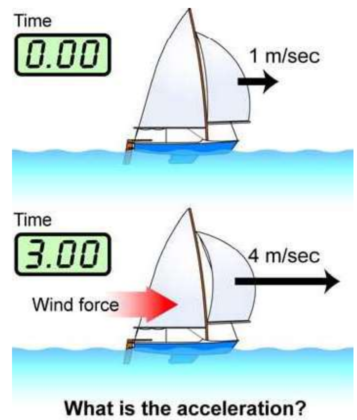


Figure 2.6: *An acceleration example with a sailboat.*

Positive and negative acceleration

If an object *speeds up*, it has a *positive acceleration*. If it *slows down*, it has a *negative acceleration*. In physics, the word acceleration is used to refer to any change in speed, positive or negative. However, people sometimes use the word **deceleration** to describe the motion that is slowing down.

Calculating acceleration (Figure 2.6)

A sailboat moves at 1 m/sec. A strong wind increases its speed to 4 m/sec in 3 seconds (Figure 2.6). Calculate the acceleration.

1. Looking for: You are asked for the acceleration in meters per second.

2. Given: You are given the initial speed in m/sec (v_1), final speed in m/sec (v_2), and the time in seconds.

3. Relationships: Use the formula for acceleration: $a = \frac{v_2 - v_1}{t}$

4. Solution:

$$a = \frac{4 \text{ m/sec} - 1 \text{ m/sec}}{3 \text{ sec}} = \frac{3 \text{ m/sec}}{3 \text{ sec}} = 1 \text{ m/sec}^2$$

Your turn...

a. Calculate the acceleration of an airplane that starts at rest and reaches a speed of 45 m/sec in 9 seconds. **Answer:** 5 m/sec^2

b. Calculate the acceleration of a car that slows from 50 m/sec to 30 m/sec in 10 seconds. **Answer:** -2 m/sec^2

Force, mass, and acceleration

Newton's second law **Newton's second law** relates the net force on an object, the mass of the object, and acceleration. It states that the stronger the net force on an object, the greater its acceleration. If twice the net force is applied, the acceleration will be twice as great. The law also says that the greater the mass, the smaller the acceleration for a given net force (Figure 2.7). An object with twice the mass will have half the acceleration if the same force is applied.

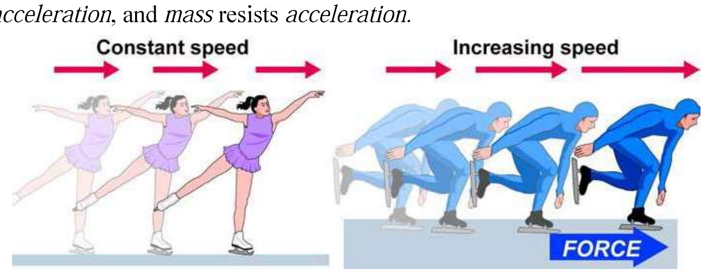
Direct and inverse proportions In mathematical terms, the acceleration of an object is directly proportional to the net applied force and inversely proportional to the mass. These two relationships are combined in Newton's second law (below).

NEWTON'S SECOND LAW

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

Acceleration (m/sec²) → a; F ← *Force* (N); m ← *Mass* (kg)

Changes in motion involve acceleration Force is not necessary to keep an object in motion at constant speed. A moving object will keep going at a constant speed in a straight line until a force acts on it. Once a skater is moving, she will coast for a long time without any force to push her along. However, she does need force to speed up, slow down, turn, or stop. Changes in speed or direction always involve acceleration. *Force* causes *acceleration*, and *mass* resists *acceleration.*



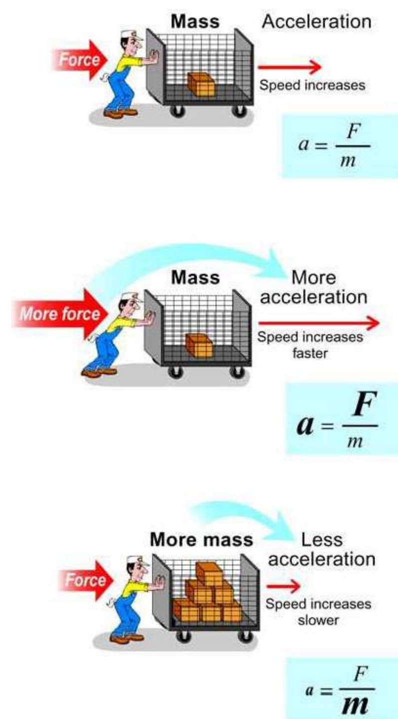


Figure 2.7: *Increasing the force increases the acceleration, and increasing the mass decreases the acceleration.*

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Applying the second law

Some guidelines To use Newton's second law properly, keep the following important ideas in mind. They are a good guideline for how to apply the second law to physics problems.

1. The *net* force is what causes acceleration.
2. If there is *no* acceleration, the net force *must* be zero.
3. If there *is* acceleration, there *must* also be a net force.
4. The force unit of newtons is based on kilograms, meters, and seconds.

Net force When two forces are in the same direction, the net force is the sum of the two forces. When two forces are in opposite directions the net force is the difference between them. To get the direction right we usually assign positive values to one direction and negative values to the other direction. Figure 2.8 shows how to calculate the net force for different forces.

Examples with and without acceleration Objects at rest or moving with constant speed have zero acceleration. This means the net force must also be zero. You can calculate unknown forces by using the knowledge that the net force must be zero. The motion of a kicked ball or a car turning a corner are examples where the acceleration is not zero. Both situations have net forces that are not zero.

Using newtons in calculations The newton is *defined* by the relationship between force, mass, and acceleration. A force of one newton is the exact amount of force needed to cause a mass of one kilogram to accelerate at one m/sec^2 (Figure 2.9). The newton is a useful way to measure force because it connects force directly to its effect on matter and motion. A net force of one newton will always accelerate a 1-kilogram mass at 1 m/sec^2 no matter where you are in the universe. In terms of solving problems, you should always use the following units when using force in newtons:

- mass in kilograms
- distance or position in meters
- time in seconds
- speed in m/sec
- acceleration in m/sec^2

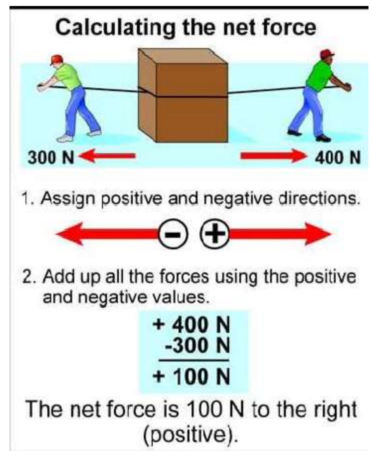

Figure 2.8: *Calculating the net force.*

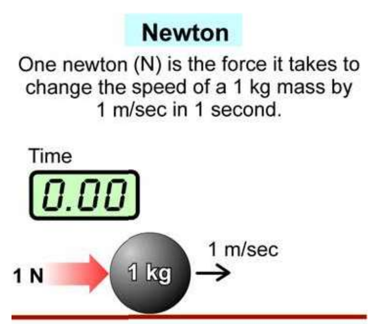

Figure 2.9: *The definition of a newton.*

Doing calculations with the second law

Writing the second law

The formula for the second law of motion uses *F*, *m*, and *a* to represent force, mass, and acceleration. The way you write the formula depends on what you want to know. Three ways to write the law are summarized below.

Table 2.1: *Three forms of the second law*

Use . . .	. . . if you want to find . . .	. . . and you know . . .
a=*F*/*m*	acceleration (*a*)	force (*F*) and mass (*m*)
F=*ma*	force (*F*)	acceleration (*a*) and mass (*m*)
m=*F*/*a*	mass (*m*)	acceleration (*a*) and force (*F*)

Net force

Remember, when using the second law, the force that appears is the net force. Consider all the forces that are acting and add them up to find the net force before calculating any accelerations. If you work in the other direction, calculating force from mass and acceleration, it is the net force that you get from the second law. You may have to do additional work if the problem asks for a specific force and there is more than one force acting.

Units and the second law

When using *F* = *ma*, the units of force (newtons) must equal the units of mass (kilograms) multiplied by the units of acceleration (m/sec^2). How is this possible? The answer is that 1 newton is 1 kg·m/sec^2. The unit "newton" was created to be a shortcut way to write the unit of force. It is much simpler to say 5 N rather than 5 kg·m/sec^2.

Newton's second law

A car has a mass of 1,000 kg. If a net force of 2,000 N is exerted on the car, what is its acceleration?

1. Looking for: You are asked for the car's acceleration.

2. Given: You are given its mass in kilograms and the net force in newtons.

3. Relationships: $a = \frac{F}{m}$

4. Solution:

$$a = \frac{2000\text{ N}}{1000\text{ kg}} = \frac{2\text{kg}\bullet\text{m}/\text{sec}^2}{\text{kg}} = 2\text{ m/sec}^2$$

Your turn...

a. What is the acceleration of a 1,500-kilogram car if a net force of 1,000 N is exerted on it? **Answer:** 1.5 m/sec^2

b. As you coast down the hill on your bicycle, you accelerate at 0.5 m/sec^2. If the total mass of your body and the bicycle is 80 kg, with what force is gravity pulling you down the hill? **Answer:** 40 kg·m/sec^2 or 40 N

c. You push a grocery car with a force of 30 N and it accelerates at 2 m/sec^2. What is its mass? **Answer:** 15 kg

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Force and energy

Energy moves through force Force is the action through which energy moves. This important idea will help you understand why forces occur. Consider a rubber band that is stretched to launch a car. The rubber band has energy because it is stretched. When you let the car go, the energy of the rubber band is transferred to the car. The transfer of energy from the stretched rubber band to the car occurs through the force that the rubber band exerts on the car (Figure 2.10).

Energy differences create force Forces are created any time there is a difference in energy. A stretched rubber band has more energy than a rubber band lying relaxed. The difference in energy results in a force that the rubber band exerts on whatever is holding it in the stretched shape.

An example of energy difference Energy differences can be created in many ways. A car at the top of a hill has more energy than when the car is at the bottom. This tells you there must be a force that pulls the car toward the bottom of the hill. You can predict that a downhill force must exist even though you may not know the cause of that force.

An important idea Suppose there is an energy difference between one arrangement of a system (car at the top) and another arrangement (car at the bottom). Some force will *always* act to bring the system from the higher energy arrangement to the lower energy one. We will find many examples of this important principle throughout the course. The principle is true in all of science, not just physics. It is true in chemistry, earth science, and biology, too.

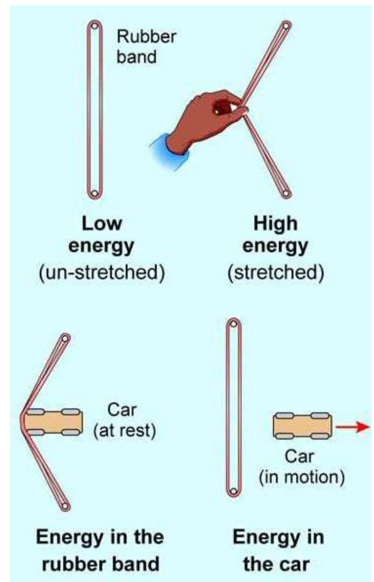

Figure 2.10: *Energy differences cause forces to be created. The forces can transfer energy from one object to another.*

2.2 Section Review

1. List three units in which acceleration can be measured.
2. According to Newton's second law, what causes acceleration? What resists acceleration?
3. An 8,000 kg helicopter's speed increases from 0 m/sec to 25 m/sec in 5 seconds. Calculate its acceleration and the net force acting on it.
4. Define the term "net force."
5. Describe the conceptual relationship between energy and force.

2.3 Gravity and Free Fall

Imagine dropping a baseball out of a second-floor window. What happens? Of course, the ball falls toward the ground. Is the speed constant or does the ball accelerate? If it accelerates, at what rate? Do all objects fall at the same rate? You will learn the answers to these questions in this section.

Vocabulary

free fall, acceleration due to gravity, velocity, weight, air resistance, terminal speed

Objectives

- ✓ Describe the motion of an object in free fall.
- ✓ Calculate speed and distance for an object in free fall.
- ✓ Distinguish between mass and weight.
- ✓ Explain how air resistance affects the motion of objects.

The acceleration due to gravity

The definition of free fall

An object is in **free fall** if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped baseball is in free fall from the instant it leaves your hand until it reaches the ground. A ball thrown upward is also in free fall after it leaves your hand. Although you might not describe the ball as “falling,” it is still in free fall. Birds, helicopters, and airplanes are *not* normally in free fall because forces other than gravity act on them.

The acceleration of gravity

Objects in free fall on Earth accelerate downward at 9.8 m/sec^2, the **acceleration due to gravity**. Because this acceleration is used so frequently in physics, the letter g is used to represent its value. When you see the letter *g* in a physics question, you can substitute the value 9.8 m/sec^2.

Speed in free fall

If you know the acceleration of an object in free fall, you can predict its speed at any time after it is dropped. The speed of a dropped object will increase by 9.8 m/sec every second (Figure 2.11). If it starts at rest, it will be moving at 9.8 m/sec after one second, 19.6 m/sec after two seconds, 29.4 m/sec after three seconds, and so on. To calculate the object’s speed, you multiply the time it falls by the value of g. Because the units of *g* are m/sec^2, the speed must be in m/sec and the time must be in seconds.

FREE FALL SPEED
(starting at rest)

$$v = gt$$

Speed (m/sec) → v; *Acceleration due to gravity* (m/sec^2) → g; *Time* (sec) → t

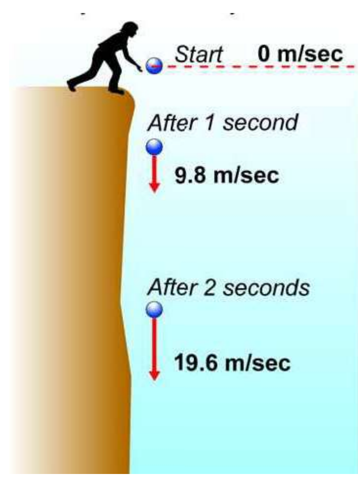

Figure 2.11: *The speed of a ball in free fall increases by 9.8 m/sec every second.*

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Upward launches

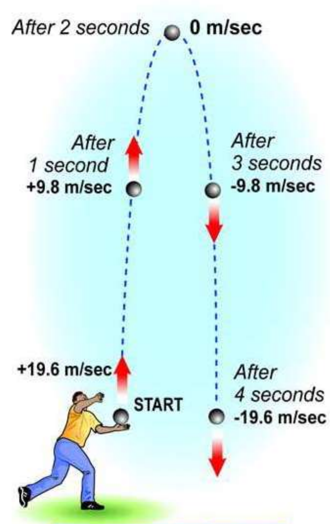
Throwing a ball upward When an object is in free fall, it accelerates *downward* at 9.8 m/sec^2. Gravity causes the acceleration by exerting a downward force. So what happens if you throw a ball *upward*? The ball will slow down as it moves upward, come to a stop for an instant, and then fall back down. As it moves upward, the speed *decreases* by 9.8 m/sec every second until it reaches zero. The ball then reverses direction and starts falling down. As it falls downward, the speed *increases* by 9.8 m/sec every second.

Velocity When an object's direction is important, we use the *velocity* instead of the speed. **Velocity** is speed with direction. In Figure 2.12, the ball's initial velocity is +19.6 m/sec and its velocity four seconds later is -19.6 m/sec. The positive sign means upward and the negative sign means downward.

Speed The acceleration of the ball is -9.8 m/sec^2 ($-g$). That means you subtract 9.8 m/sec from the speed every second. Figure 2.12 shows what happens to a ball launched upward at 19.6 m/sec. The speed decreases for two seconds, reaches zero, and then increases for two seconds. *The acceleration is the same all the time* (-9.8 m/sec^2) even though the ball is slowing down as it goes up and speeding up as it comes back down. The acceleration is the same because the change in speed is the same from one second to the next. The speed always changes by -9.8 m/sec every second.

Stopping for an instant Notice the ball's speed is 0 m/sec at the top of its path. If you watch this motion, the ball looks like it stops, because it is moving so slowly at the top of its path. To your eye it may look like it stops for a second, but a slow-motion camera would show the ball's speed immediately reverses at the top and does not stay zero for any measurable amount of time.

Acceleration You may want to say the acceleration is zero at the top, but only the *speed* is zero at the top. Speed and acceleration are not the same thing, remember — just like 60 miles and 60 miles per hour are not the same thing. The force of gravity causes the ball's acceleration. The force of gravity stays constant; therefore, the acceleration is also constant and cannot be zero while the ball is in the air.



Time (sec)	Velocity (m/sec)
0.0	19.60
1.0	9.80
2.0	0.00
3.0	-9.80
4.0	-19.60

Figure 2.12: *The motion of a ball launched upward at 19.6 m/sec.*

Free fall and distance

Changing speeds In chapter 1, you used $d = vt$ to calculate distance. You cannot calculate distance in the same simple way when speed is not constant, as happens in free fall. An object in free fall increases its speed by 9.8 m/sec each second (or 9.8 m/sec^2), so it moves a greater distance each second.

Average speed One way to calculate distance is to use the *average speed*. In free fall and other situations of *constant* acceleration, the average speed is the average of the starting or initial speed (v_i) and the final speed (v_f). Taking the average accounts for the fact that the speed is not constant. Be careful when doing this calculation. The average speed may *not* be ($v_f + v_i$) ÷ 2, if the acceleration is not constant.

AVERAGE SPEED

$$V_{avg} = \frac{v_f + v_i}{2}$$

Average speed (m/sec) → V_{avg}; *Final speed* (m/sec) → v_f; *Initial speed* (m/sec) → v_i

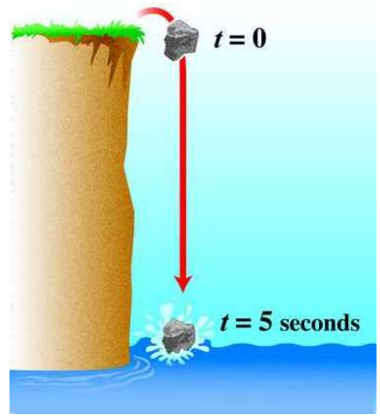


Figure 2.13: *What is the average speed of a rock that falls for 5 seconds?*

Average speed

A rock falls off a cliff and splashes into a river 5 seconds later (Figure 2.13). What was the rock's average speed during its fall?

1. Looking for: You are asked for the average speed in meters per second. You need to find the final speed in meters per second.

2. Given: You may assume zero initial speed and are given the air time in seconds.

3. Relationships: $v_f = gt$ and $v_{avg} = \frac{v_i + v_f}{2}$ where $g = 9.8$ m/sec^2

4. Solution: $v_f = (9.8 \text{ m/sec}^2)(5 \text{ sec}) = 49 \text{ m/sec}$ $\quad v_{avg} = \frac{0 + 49 \text{ m/sec}}{2} = 24.5 \text{ m/sec}$

Your turn...

a. What is the average speed of a baseball dropped from rest that falls for 2 seconds? **Answer:** 9.8 m/sec

b. What is the average speed of a ball with an initial downward speed of 10 m/sec that falls for 2 seconds? **Answer:** 14.8 m/sec

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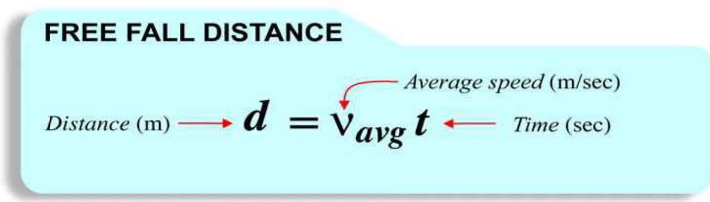
Calculating distance Now that you know how to calculate the average speed for an object in free fall, you can use the average speed to find out the distance it falls.



Calculating free-fall speed and distance

A skydiver falls for 6 seconds before opening her parachute. Calculate her actual speed at the 6-second mark and the distance she has fallen in this time.

1. Looking for: You are asked to find the final speed and the distance.

2. Given: You may assume zero initial speed and are given the time in seconds.

3. Relationships: $v_f = gt \qquad v_{avg} = \frac{v_i + v_f}{2} \qquad d = v_{avg} t$

4. Solution:

$v_f = (9.8 \text{ m/sec}^2)(6 \text{ sec}) = 58.8 \text{ m/sec}$

The speed after 6 seconds is 58.8 m/sec.

$v_{avg} = \frac{0 + 58.8 \text{ m/sec}}{2} = 29.4 \text{ m/sec}$

$d = (29.4 \text{ m/sec})(6 \text{ sec}) = 176.4 \text{ m}$

The skydiver falls 176.4 meters.

Your turn...

a. Calculate the final speed and distance for a skydiver who waits only 4 seconds to open his parachute. **Answer:** 39.2 m/sec and 78.4 m

b. An apple falls from the top branch of a tree and lands 1 second later. How tall is the tree? **Answer:** 4.9 m

Another way to calculate free-fall distance

Using the average speed to calculate the distance traveled by an object in free fall requires multiple steps. If you are only given the air time, you must first find the final speed, then you must calculate the average speed, and finally you can find the distance. These three steps can all be combined into one formula. The general version of the formula is more complicated than the scope of this book, but can be simplified if the object starts at rest ($v_i = 0$).

1) If the initial speed is zero and the object falls for t seconds, then the final speed is gt.

2) The average speed is half the final speed or $\frac{1}{2}gt$.

3) The distance is the average speed multiplied by the time or $\frac{1}{2}gt^2$.

The general formula is therefore:

$$d = \frac{1}{2} g t^2$$

Remember, this formula only works when the object starts at rest and is in free fall.

Gravity and weight

Gravity's force depends on mass

The force of gravity on an object is called **weight**. The symbol F_g stands for "force of gravity" and is used to represent weight. At Earth's surface, gravity exerts a force of 9.8 N on every kilogram of mass. That means a 1-kilogram mass has a weight of 9.8 N, a two-kilogram mass has a weight of 19.6 N, and so on. On Earth's surface, the weight of any object is its mass multiplied by 9.8 N/kg. Because weight is a force, it is measured in units of force such as newtons and pounds.

Weight and mass

We all tend to use the terms *weight* and *mass* interchangeably. Heavy objects have lots of mass and light objects have little mass. People and things such as food are "weighed" in both kilograms and pounds. If you look on the label of a bag of flour, it lists the "weight" in two units: 5 pounds in the English system and 2.3 kilograms in the metric system. As long as we are on Earth, where g = 9.8 N/kg a 2.3-kilogram object will weigh 5 pounds. But on the moon, g = 1.6 N/kg, so a 2.3 kilogram object will weigh only 0.8 pounds (Figure 2.14).

Weight and the second law

You should recognize that the value of 9.8 N/kg is the same as g (9.8 m/sec^2) but with different units. This is no coincidence. According to the second law, a force of 9.8 newtons acting on one kilogram produces an acceleration of 9.8 m/sec^2. For this reason the value of g can also be used as 9.8 N/kg. Which units you choose depends on whether you want to calculate acceleration or the weight force. Both units are actually identical: 9.8 N/kg = 9.8 m/sec^2.

WEIGHT

$$F_g = mg$$

Weight or force of gravity (N) → F_g; Mass (kg) → m; Strength of gravity (9.8 N/kg) → g

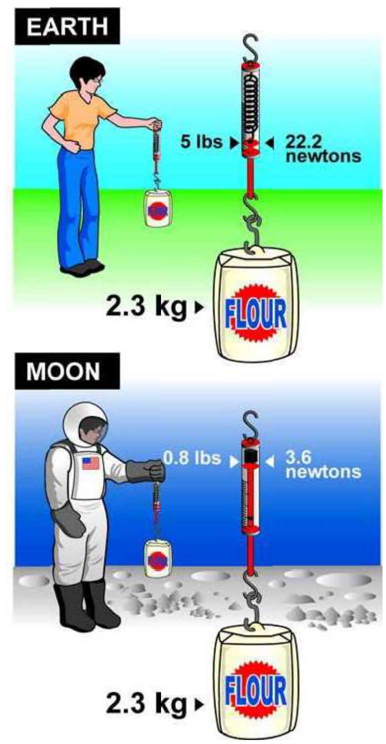


Figure 2.14: *An object that weighs 5 pounds on Earth weighs only 0.8 pounds on the moon. It has the same mass but different weights because gravity is stronger on Earth.*

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Mass is fundamental

Although mass and weight are related quantities, always remember the difference when doing physics. Mass is a fundamental property of an object measured in kilograms (kg). Weight is a *force* measured in *newtons (N)* that depends on mass and gravity. A 10-kilogram object has a mass of 10 kilograms no matter where it is in the universe. A 10-kilogram object's weight, however, can vary greatly depending on whether the object is on Earth, on the moon, or in outer space.

Weight and mass

Legend has it that around 1587 Galileo dropped two balls from the Leaning Tower of Pisa to see which would fall faster. Suppose the balls had masses of 1 kilogram and 10 kilograms.
a. Use the equation for weight to calculate the force of gravity on each ball.
b. Use your answers from (a) and Newton's second law to calculate each ball's acceleration.

1. Looking for: You are asked to find the force of gravity (weight) and the acceleration.

2. Given: You are given each ball's mass in kilograms.

3. Relationships: $W=mg$ $a=F/m$

4. Solution:

For the 1-kg ball:
a) $W = (1\text{ kg})(9.8\text{ m/sec}^2)$ $W = 9.8$ N
b) $a = (9.8\text{ N})/(1\text{ kg})$ $a = 9.8\text{ m/sec}^2$

For the 10-kg ball:
a) $W = (10\text{ kg})(9.8\text{ m/sec}^2)$ $W = 98$ N
b) $a = (98\text{ N})/(10\text{ kg})$ $a = 9.8\text{ m/sec}^2$ Both balls have the same acceleration.

Your turn...

a. Calculate the weight of a 60-kilogram person (in newtons) on Earth and on Mars ($g = 3.7\text{ m/sec}^2$). **Answer:** 588 N, 222 N
b. A 70-kg person travels to a planet where he weighs 1,750 N. What is the value of g on that planet? **Answer:** 25 m/sec^2

Why accelerations are the same

The example problem shows the weight of a 10-kilogram object is 10 times the weight of a 1-kilogram object. However, the heavier weight produces only one-tenth the acceleration because of the larger mass. The increase in force (weight) is exactly compensated by the increase in inertia (mass). As a result, the acceleration of all objects in free fall is the same.