



# PHYSICS





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# UTAH SCIENCE CORE CURRICULUM ALIGNMENT

## **STANDARD 1: STUDENTS WILL UNDERSTAND HOW TO MEASURE, CALCULATE, AND DESCRIBE THE MOTION OF AN OBJECT IN TERMS OF POSITION, TIME, VELOCITY, AND ACCELERATION.**

Objective 1: Describe the motion of an object in terms of position, time, and velocity.

- a) Calculate the average velocity of a moving object using data obtained from measurements of position of the object at two or more times.
- b) Distinguish between distance and displacement.
- c) Distinguish between speed and velocity.
- d) Determine and compare the average and instantaneous velocity of an object from data showing its position at given times.
- e) Collect, graph, and interpret data for position vs. time to describe the motion of an object and compare this motion to the motion of another object.

Objective 2: Analyze the motion of an object in terms of velocity, time, and acceleration.

- a) Determine the average acceleration of an object from data showing velocity at given times.
- b) Describe the velocity of an object when its acceleration is zero.
- c) Collect, graph, and interpret data for velocity vs. time to describe the motion of an object.
- d) Describe the acceleration of an object moving in a circular path at constant speed (i.e., constant speed, but changing direction).
- e) Analyze the velocity and acceleration of an object over time.

Objective 3: Relate the motion of objects to a frame of reference.

- a) Compare the motion of an object relative to two frames of reference.
- b) Predict the motion of an object relative to a different frame of reference (e.g., an object dropped from a moving vehicle observed from the vehicle and by a person standing on the sidewalk).
- c) Describe how selecting a specific frame of reference can simplify the description of the motion of an object.

Objective 4: Use Newton's first law to explain the motion of an object.

- a) Describe the motion of a moving object on which balanced forces are acting.
- b) Describe the motion of a stationary object on which balanced forces are acting.



- c) Describe the balanced forces acting on a moving object commonly encountered (e.g., forces acting on an automobile moving at constant velocity, forces that maintain a body in an upright position while walking).

## **STANDARD 2: STUDENTS WILL UNDERSTAND THE RELATION BETWEEN FORCE, MASS, AND ACCELERATION.**

Objective 1: Analyze forces acting on an object.

- a) Observe and describe forces encountered in everyday life (e.g., braking of an automobile - friction, falling rain drops - gravity, directional compass - magnetic, bathroom scale - elastic or spring).
- b) Use vector diagrams to represent the forces acting on an object.
- c) Measure the forces on an object using appropriate tools.
- d) Calculate the net force acting on an object.

Objective 2: Using Newton's second law, relate the force, mass, and acceleration of an object.

- a) Determine the relationship between the net force on an object and the object's acceleration.

- b) Relate the effect of an object's mass to its acceleration when an unbalanced force is applied.

- c) Determine the relationship between force, mass, and acceleration from experimental data and compare the results to Newton's second law.

- d) Predict the combined effect of multiple forces (e.g., friction, gravity, and normal forces) on an object's motion.

Objective 3: Explain that forces act in pairs as described by Newton's third law.

- a) Identify pairs of forces (e.g., action-reaction, equal and opposite) acting between two objects (e.g., two electric charges, a book and the table it rests upon, a person and a rope being pulled).

- b) Determine the magnitude and direction of the acting force when magnitude and direction of the reacting force is known.

- c) Provide examples of practical applications of Newton's third law (e.g., forces on a retaining wall, rockets, walking).

- d) Relate the historical development of Newton's laws of motion to our current understanding of the nature of science (e.g., based upon previous knowledge, empirical evidence, replicable observations, development of scientific law).

### **STANDARD 3: STUDENTS WILL UNDERSTAND THE FACTORS DETERMINING THE STRENGTH OF GRAVITATIONAL AND ELECTRIC FORCES.**

Objective 1: Relate the strength of the gravitational force to the distance between two objects and the mass of the objects (i.e., Newton's law of universal gravitation).

- a) Investigate how mass affects the gravitational force (e.g., spring scale, balance, or other method of finding a relationship between mass and the gravitational force).
- b) Distinguish between mass and weight.
- c) Describe how distance between objects affects the gravitational force (e.g., effect of gravitational forces of the moon and sun on objects on Earth).
- d) Explain how evidence and inference are used to describe fundamental forces in nature, such as the gravitational force.
- e) Research the importance of gravitational forces in the space program.

Objective 2: Describe the factors that affect the electric force (i.e., Coulomb's law).

- a) Relate the types of charge to their effect on electric force (i.e., like charges repel, unlike charges attract).
- b) Describe how the amount of charge affects the electric force.
- c) Investigate the relationship of distance between charged objects and the strength of the electric force.
- d) Research and report on electric forces in everyday applications found in both nature and technology (e.g., lightning, living organisms, batteries, copy machine, electrostatic precipitators).

## **STANDARD 4: STUDENTS WILL UNDERSTAND TRANSFER AND CONSERVATION OF ENERGY.**

Objective 1: Determine kinetic and potential energy in a system.

- a) Identify various types of potential energy (i.e., gravitational, elastic, chemical, electrostatic, nuclear).
- b) Calculate the kinetic energy of an object given the velocity and mass of the object.
- c) Describe the types of energy contributing to the total energy of a given system.

Objective 2: Describe conservation of energy in terms of systems.

- a) Describe a closed system in terms of its total energy.
- b) Relate the transformations between kinetic and potential energy in a system (e.g., moving magnet induces electricity in a coil of wire, roller coaster, internal combustion engine).
- c) Gather data and calculate the gravitational potential energy and the kinetic energy of an object (e.g., pendulum, water flowing downhill, ball dropped from a height) and relate this to the conservation of energy of a system.

- d) Evaluate social, economic, and environmental issues related to the production and transmission of electrical energy.

Objective 3: Describe common energy transformations and the effect on availability of energy.

- a) Describe the loss of useful energy in energy transformations.
- b) Investigate the transfer of heat energy by conduction, convection, and radiation.
- c) Describe the transformation of mechanical energy into electrical energy and the transmission of electrical energy.
- d) Research and report on the transformation of energy in electrical generation plants (e.g., chemical to heat to electricity, nuclear to heat to mechanical to electrical, gravitational to kinetic to mechanical to electrical), and include energy losses during each transformation.

## **STANDARD 5: STUDENTS WILL UNDERSTAND THE PROPERTIES AND APPLICATIONS OF WAVES.**

Objective 1: Demonstrate an understanding of mechanical waves in terms of general wave properties.

- a) Differentiate between period, frequency, wavelength, and amplitude of waves.
- b) Investigate and compare reflection, refraction, and diffraction of waves.
- c) Provide examples of waves commonly observed in nature and/or used in technological applications.
- d) Identify the relationship between the speed, wavelength, and frequency of a wave.
- e) Explain the observed change in frequency of a mechanical wave coming from a moving object as it approaches and moves away (i.e., Doppler effect).

- f) Explain the transfer of energy through a medium by mechanical waves.

Objective 2: Describe the nature of electromagnetic radiation and visible light.

- a) Describe the relationship of energy to wavelength or frequency for electromagnetic radiation.
- b) Distinguish between the different parts of the electromagnetic spectrum (e.g., radio waves and x-rays or visible light and microwaves).
- c) Explain that the different parts of the electromagnetic spectrum all travel through empty space and at the same speed.
- d) Explain the observed change in frequency of an electromagnetic wave coming from a moving object as it approaches and moves away (i.e., Doppler effect, red/blue shift).
- e) Provide examples of the use of electromagnetic radiation in everyday life (e.g., communications, lasers, microwaves, cellular phones, satellite dishes, visible light).



# WHY SCIENCE?

Many students equate science to learning vocabulary terms, labeling pictures, and memorizing facts. Science by nature is much more inclusive and loosely defined. Have you ever asked yourself questions about your surroundings and wondered how or why they are happening? This is science. Science works best when driven by curiosity and innovation. In order for you to experience science in its fullest sense you must take it beyond the textbook and into your everyday experience, but in order to be meaningful there are certain guidelines that can help us. Science is not constrained to Physics, but there are cross-cutting concepts threaded throughout all scientific disciplines. These include:

- **Patterns; i.e. *wave actions***
- **Cause and effect: Mechanism and explanation; i.e. *falling objects & gravity***
- **Scale, proportion, and quantity; i.e. *The bigger they are, the harder they fall.***
- **Systems and system models; i.e. *objects in motion***
- **Energy and matter: Flows, cycles, and conservation; i.e. *Energy transformations***
- **Structure and function; i.e. *architecture***
- **Stability and change; i.e. *Newton's first law***

When studying any specific scientific discipline you should attempt to keep these cross-cutting concepts in mind in order to gain a better perspective of the world as whole and the nature of science. Included in the concepts are the skills and practices that a scientist utilizes. When asking questions about the natural world there are certain skills and practices that can help you generate better conclusions, explanations and inferences.

These practices include:

- **Asking questions and defining problems**
- **Developing and using models**
- **Planning and carrying out investigations**
- **Analyzing and interpreting data**
- **Using mathematics and computational thinking**
- **Constructing explanations and designing solutions**
- **Engaging in argument from evidence**
- **Obtaining, evaluating, and communicating information**

While these practices and cross-cutting concepts are crucial to your overall success in science, in order to be most meaningful they do need some context. This is where the study of disciplinary core ideas are most impactful. If you study Physics or any other scientific discipline without the cross-cutting concepts and scientific practices then you limit yourself to fact memorization and miss how these concepts relate to our everyday life and our society as a whole. Studying individual scientific disciplines are the vehicle for understanding cross-cutting concepts and acquiring scientific skills. When individual disciplines are studied within the context of practices and cross-cutting concepts they become more meaningful and more impactful.

For example: *When looking for solutions to our current energy dependence, it is not a problem to be solved by chemists or physicists or geologists independently. It can only be solved when scientists come together with an understanding of how their independent research relates to the larger problem at hand. If we focus solely upon a few facts or cool phenomenon we can overlook how the study of science can really improve and impact our society and personal experiences.*







# **MOTION**

# CHAPTER 1

Vocabulary:

- displacement
- distance
- scalar
- vector

Standard 1: Students will understand how to measure, calculate, and describe the motion of an object in terms of position, time, velocity, and acceleration.

## **STANDARD 1, OBJECTIVE 1: DESCRIBE THE MOTION OF AN OBJECT IN TERMS OF POSITION, TIME, VELOCITY, AND ACCELERATION.**

### What is Motion?

- The motion of an object can be described by measurements of its position at different times.
- Velocity is a measure of the rate of change of position of an object over time.
- Acceleration is a measure of the rate of change of velocity of an object over time. This change in velocity may be a change in speed and/or direction.
- Motion is defined relative to the frame of reference from which it is observed. An object's state of motion will remain constant unless unbalanced forces act upon the object.
- This is Newton's first law of motion. [Utah State Core Curriculum – Physics Standard 1 Science Benchmark]
- Motion in terms of position, time, and velocity

### Objectives:

- Distinguish between distance and displacement.
- Distinguish between speed and velocity.
- Calculate the average velocity of a moving object using data obtained from measurements of position of the object at two or more times.
- Determine and compare the average and instantaneous velocity of an object from data showing its position at given times.

- Collect, graph, and interpret data for position vs. time to describe the motion of an object and compare this motion to the motion of another object.

## SECTION 1: DISTANCE VS. DISPLACEMENT

### Key Equations

$$\text{Symbols} \begin{cases} \Delta(\text{anything}) & \text{Final value - initial value} \\ \text{anything}_0 & \text{Value at time 0} \end{cases}$$

$$\text{Scalars} \begin{cases} t & \text{Time in seconds, s} \\ d = |\Delta x_1| + |\Delta x_2| & \text{Distance (in meters, m)} \\ v = |v| & \text{Speed (in meters per second, m/s)} \end{cases}$$

$$\text{Vectors} \begin{cases} x = x(t) & \text{Position} \\ \Delta x = x_f - x_i & \text{Displacement} \end{cases}$$

We begin our study of motion in the simplest terms we can: motion that takes place along a straight line, which is called one-dimensional motion. A car traveling east, west, north or south, is an example of such motion. When we imagine a car moving along a road we think of the car as represented by a “particle.” We define the position of a particle in the same way we would define the position of a point on a number line. Later on we will take up the case of two-dimensional motion; for example, the motion of baseball through the air.

### Scalars and Vectors

Consider the dashboard of a car shown in Figure below. It displays information about the motion of the car. The odometer shows the miles driven by the car during its lifetime. The speedometer shows the instantaneous speed of the car. These values describe “amount or size” or, as we say in physics, “magnitude,” but they include no information concerning the direction of the car’s motion. In order to describe the motion of an object

completely, two pieces of information are required: **magnitude** (for example, how far, or how fast) and direction.



The odometer (99,000 miles) shows the distance the car has traveled and the speedometer shows the instantaneous speed of the car (40 mph).

In physics a **scalar quantity** has only magnitude (numerical value): distance (30 miles) and speed (30 mph) are two examples of scalar quantities. We use the term **vector** to describe quantities that have both magnitude and direction. Vectors are represented by arrows: (displacement) 30 miles due west, (velocity) 30 mph due west, are two examples of vectors.

#### Check Your Understanding:

Which statement below describes a vector quantity?

- A race car moving at 110 mph
- A turtle strolling at 200 cm/min
- An SUV moving at 40 km/h east
- A wagon heading west

Answer: c, since both speed and direction are given. Speed is the 40 km/hr; east is the direction. Together, speed and direction become velocity.

## Position

We need to know where things are; this is true whether we are discussing daily life or the complexities of modern science. Physics defines the location of an object by assigning a position to it. Just as with mathematics, physics typically uses a coordinate system. The coordinate system must have a zero point or “origin” in order to properly reference position. Since we are discussing one-dimensional motion we will use the simplest coordinate system: a number line with a marked zero, negative values to the left of zero, and positive values to the right of zero. Similarly when using a coordinate system, you can define North as the positive direction and South as negative. You could also define East as positive and West as the negative direction.

When moving to the right and then to the left, we use simple arithmetic to add up the total distance covered. It is another matter to determine, at the end of the motion, how far and in which direction we are from the starting point; we call this quantity displacement.

**Distance** is a scalar quantity giving the positive length between two points. The total length for a series of distances can be computed by adding the absolute values of each length segment.

$$d = |\Delta x_1| + |\Delta x_2| + |\Delta x_3| + \dots$$

**Displacement** is the straight line distance in a given direction between the initial and final positions.

$\Delta x = x_f - x_i$ , where  $x_f$  is the final position of the object and  $x_i$  is the initial position of the object.

$$\Delta x = x_f - x_i$$

Successive displacements can be added together as vectors.

$$\text{Total Displacement} = \Delta x_1 + \Delta x_2 + \Delta x_3 + \dots$$

### Example 1

**Problem:** A car goes 120 m North, then 30 m South, then finally 60m North. How far has the car traveled (distance)? What is the car's net displacement?

#### **Solution:**

Distance is the total amount traveled. Thus distance = 120 + 30 + 60 m = 210 m

$$d = x_1 + x_2 + x_3$$

$$d = 120 \text{ m} + 30 \text{ m} + 60\text{m}$$

Displacement is the amount displaced from the starting position. Thus displacement = 120 - 30 + 60 m = 150 m.

$$\text{Displacement} = \Delta x_1 + \Delta x_2 + \Delta x_3$$

$$\Delta x = 120 \text{ m} + (-30 \text{ m}) + 60\text{m}$$

#### Check for Understanding

1. Write a paragraph explaining the difference between distance  $d$  and displacement  $\Delta x$ .
2. You're trying to predict how long it's going to take to get to Los Angeles for the long weekend. Do you care about the distance you'll travel or your displacement? Explain your answer.

# SPEED VS. VELOCITY

## Key Equation

Average Velocity

$$v_{avg} = \frac{\Delta x}{\Delta t}$$

## Average Speed and Instantaneous Speed

Suppose you are traveling along a long straight highway. You start driving, and an hour later, you are 100 km away. Your average speed is the 100 km/hr (100 kilometers per hour). The information you have is time and distance. You can calculate your average speed by dividing the distance you've traveled by the time of travel.

Average speed: Total distance traveled divided by total elapsed time

During the hour that this trip took, your speedometer may have had many different readings. You might have been traveling faster during the first part of the hour, and then slower in the second half. The reading on the speedometer is your **instantaneous speed**. **Instantaneous speed** is the speed at a specific time.

If you go back on a return trip, the calculation of the speed is the same. The result is still 100 km/hr. Like distance, discussed in the previous section, speed is a scalar quantity and thus always positive. The speedometer reading is the same no matter what direction you are driving in. Speed cannot provide information about direction.

## Average Velocity



Velocity is different than speed because velocity is a vector quantity and as such will have both a magnitude and a direction.

- Velocity is the combination of speed and direction.
- Velocity: Change in position divided by change in time.
- Change of position can be either positive or negative, so velocity can be positive or negative.

In the example above, the velocity on the outbound trip is +100 km/hr, while the velocity on the return trip is -100 km/hr (Figure below). See below for detailed calculations.



Velocity vectors on cars indicating direction and magnitude.

### Check Your Understanding

In the example above, the round trip speed and velocity are:

- a) the same
- b) different

*Answer: b*

The average speed for the entire trip is:

- a) 0 km/hr
- b) 100 km/hr
- c) 200 km/hr

*Answer: b. The speed is  $200 \text{ km} / 2 \text{ hrs} = 100 \text{ km/h}$*

The velocity for the round trip is: (Hint, consider the displacement.)

- a) 0 km/hr
- b) +100 km/hr
- c) -200 km/hr

*Answer: a. The displacement is zero, therefore  $0 \text{ km} / 2 \text{ hrs} = 0 \text{ km/hr}$ .*

## CALCULATE THE AVERAGE VELOCITY

### Determining average velocity

If the motion is always in the same direction, the average velocity will have the same numerical value as the average speed, except that a direction of motion must also be given.

If motion changes direction, the average velocity will be different than the average speed. Average velocity depends on the total displacement, defined as the line from the initial position to the final position. If we assign the zero position on the New Jersey side of the bridge, the displacement is:  $x_f + x_i = L - 0$ , traveling back from New York, the displacement is  $x_f + x_i = 0 - L$ . The total displacement is  $L + (-L) = 0$ , therefore, the average velocity for the round trip over the bridge is 0 mph.

### Check your understanding

A car moves due east at 30 mph for 45 min, turns around, and moves due west at 40 mph for 60 minutes. What is the average velocity for the entire trip?

Answers:

- East displacement:  $30 \times \frac{3}{4} = +22.5$  miles
- West displacement:  $-40(1) = -40$  miles

- Total displacement:  $-40 + (+22.5) = -17.5$  miles
- Min to Hour:  $(45 + 60)(1 \text{ hour}/60 \text{ min}) = 1.75$  hours
- Average velocity =  $-17.5 \text{ miles} / 1.75 \text{ hours} = -10.0 \text{ mph}$

### Example 1

Pacific loggerhead sea turtles migrate over 7,500 miles (12,000 km) between nesting beaches in Japan and feeding grounds off the coast of Mexico. If the average speed of a loggerhead is about 45 km/day, how long does it take for it to complete the distance of a one-way migration?

Question:  $t = ?$  [days]

Given:  $d = 12,000 \text{ km}$

$v_{avg} = 45 \text{ km/day}$

Equation:  $v_{avg} = \frac{d}{t}$  therefore  $t = \frac{d}{v_{avg}}$

Plug n' Chug:  $t = \frac{d}{v_{avg}} = \frac{12,000 \text{ km}}{45 \text{ km/day}} = 267 \text{ days}$

Answer: **267 days**

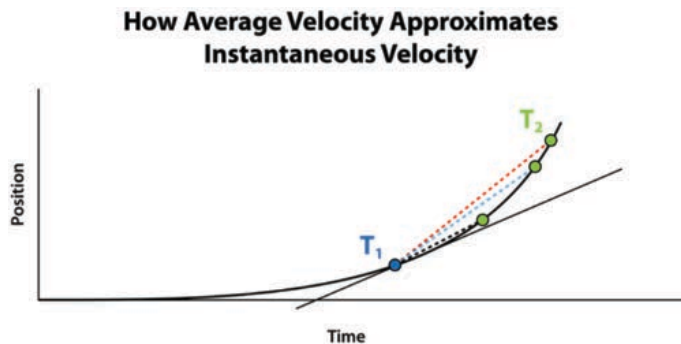
# AVERAGE VS. INSTANTANEOUS VELOCITY

As we said earlier, instantaneous speed is like the reading of a car's speedometer. It is the speed at any exact point in time. Instantaneous velocity refers to velocity at a specific time, such as  $t = 3.5$  s. It is like the reading of a speedometer combined with a pointer for current direction.

In practice, we cannot find a truly instantaneous velocity. Instead, we find an average velocity over smaller and smaller intervals of time. For example, a modern car speedometer works by measuring the fraction of a second it takes for the car's wheels to turn once. For driving, this is close to instantaneous. When we measure average velocity over a smaller and smaller intervals of time ( $\Delta t$ ), we get closer and closer to instantaneous velocity.

The diagram below shows the position of an object at the times  $t_2$ , 5.00 s and  $t_1$ , 3.00 s. If  $t_1$  is held fixed and  $t_2$  permitted to approach  $t_1$ , the slope of the line between  $t_2$  and  $t_1$  progressively comes closer to the slope of a tangent line through  $t_1$ . The slope of the line through  $t_1$  is called the instantaneous velocity at  $t_1$ . In general, the slope of the tangent line to a curve in a position-time graph gives the instantaneous velocity.

<http://bit.ly/1beTtlj>

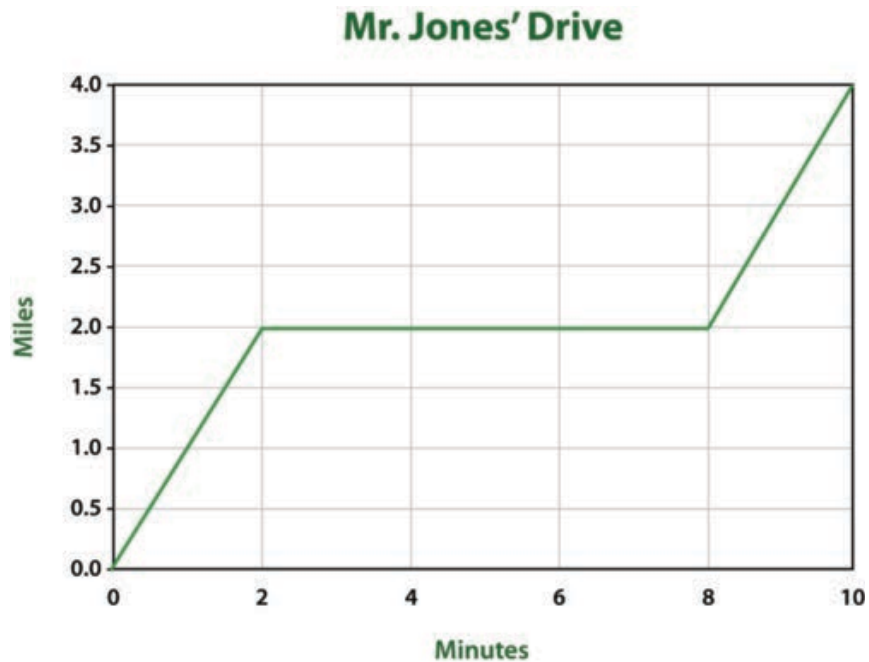


As  $T_2$  approaches  $T_1$  the tangent line through  $T_1$  is approximated.

## SECTION 1:5 DESCRIBE THE MOTION OF AN OBJECT

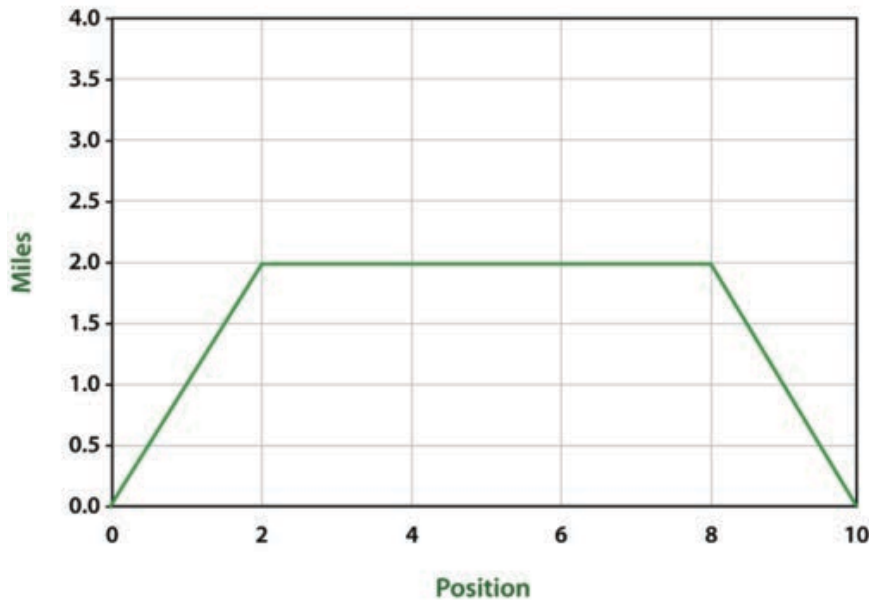
### Using Graphs to Distinguish Between Distance and Displacement

Mr. Jones lives on the same road as the high school where he works. During his morning commute, Mr. Jones drives two miles in two minutes, to reach the donut shop. He spends six minutes at the shop and while there, realizes he's forgotten his lunch at home. So he returns home, again covering two miles in two minutes. How should the data be graphed to represent the motion of Mr. Jones' car?



Graph 1. This graph shows what the odometer would display: Mr. Jones traveled four miles. What it does not display is the current location of Mr. Jones' car.

## Mr. Jones' Drive



Graph 2. This graph shows the location of the car. You can tell from reading the graph that the car has returned to where it started. However, determining the distance the car traveled from this graph is not that obvious.

Which graph is correct? Both are; they simply provide different information. Graph 1 in Figure above displays the distance traveled by the car as a function of time, while Graph 2 in Figure above displays the position of the car as a function of time. After ten minutes the car has traveled four miles (Graph 1 in Figure above), and it is back where it started (Graph 2 in Figure above).

Using Graph 2 in Figure above, the total distance the car traveled can be found by adding up the segments of its motion, while the final position of the car can immediately be read from the graph. Using Graph 1 in Figure above, the total distance the car traveled can immediately be read from the graph, but there is no way to determine the car's final position. Graph 2 in Figure above, the position versus time graph, is more useful.

### Check your understanding

Two bicyclists travel from House 1 to House 2 as in seen in the Figure below. Path A is a straight and Path B is a curved path. Which path has the greater displacement?

Answer: Consider the definition of displacement:  $\Delta x = x_f - x_i$

Since the initial and final positions for both paths are identical, the displacement must be the same for paths A and B.



### Position Time Graphs

If we continue with the story of Mr. Jones and use the data from his story to now discuss speed and velocity what can we find. A table was made to show Mr. Jones's movement from his home to the donut store and back home.

#### Mr. Jones' Travels

Time Interval (min)	Distance (miles)	Speed miles/min	Time Interval (min)	Displacement (miles)	Velocity miles/min
[0, 2]	2.0	1.0	[0, 2]	+2.0	+1
[2, 8]	0.0	0.0	[2, 8]	0.0	0
[8,10]	2.0	1.0	[8, 10]	-2.0	-1

Look back at the position vs. time graph for Mr. Jones. Mr. Jones' velocity during the time interval  $[0, 2]$  is calculated using the definition of velocity:  $\Delta x/\Delta t = (2.0-0)/(2-0)$ . What is the slope of the line for the interval  $[0, 2]$ ? A bit of thought would lead you to the conclusion that the slope is identical to the definition of velocity, as long as the units are included. In fact, the units of velocity are an aid in determining how to calculate velocity; miles "over" minutes imply division. This is a very important result: any slope in a

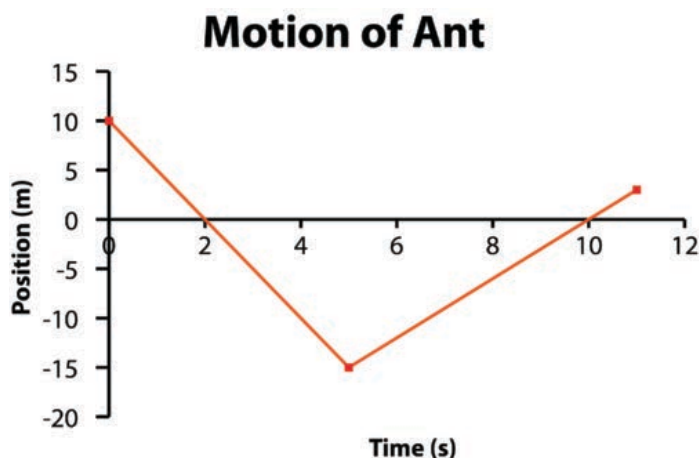
position vs. time graph has units of distance/time. Therefore, the slope of the line in a position-time graph is velocity. During the interval  $[8, 10]$ , the slope of the line is negative. We can immediately surmise that the motion is toward the left on a conventional number line. During the interval  $[2, 8]$ , the line is horizontal, so the slope is zero, which in turn indicates that the velocity is also zero. This conclusion makes sense physically; since Mr. Jones (and his car) are at the same position during the time interval  $[2, 8]$ . If his position is not changing, then of course, he's not moving. So his velocity must be zero.

Let's state some general conclusions regarding position-time graphs, using the sign conventions of a number line.

- A positive slope indicates positive velocity; motion is to the right.
- A negative slope indicates negative velocity; motion is to the left.
- A horizontal line indicates zero velocity, the position remains unchanged.

### Check Your Understanding

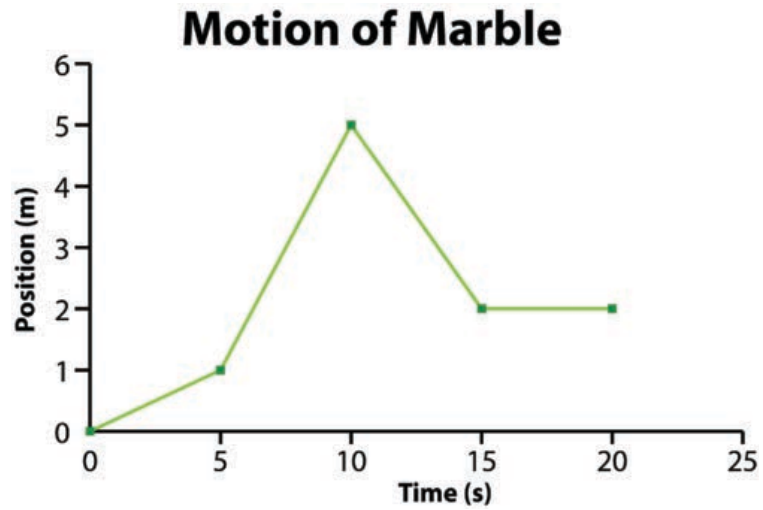
An ant travels with constant velocity from position  $+10$  m to position  $-15$  m for a time of  $5$  s; it instantaneously turns around, and moves from position  $-15$  m to position  $+3$  m with constant velocity, for a time of  $6$  s. Plot the ant's motion in a position-time graph and indicate the ant's velocity for each interval.





*Answer: The ant has a velocity of  $-5\text{ m/s}$  over the first five seconds and a velocity of  $+3\text{ m/s}$  over the last 6 seconds (Figure above).*

The motion of a rolling marble is represented in the position-time graph in Figure below.



Write a sentence or two that describes its motion.

*Answer: During the first 5 seconds the marble rolls to the right, slowly; during the next five seconds it continues rolling to the right but faster; during the next five seconds the marble rolls to the left a bit slower than during the previous five seconds; during last five seconds the marble is stationary.*

## **STANDARD 1, OBJECTIVE 2: ANALYZE THE MOTION OF AN OBJECT IN TERMS OF VELOCITY, TIME, AND ACCELERATION.**

How are velocity, time, and acceleration related?

Objectives:

- Determine the average acceleration of an object from data showing velocity at given times.
- Describe the velocity of an object when its acceleration is zero.
- Collect, graph, and interpret data for velocity vs. time to describe the motion of an object.
- Describe the acceleration of an object moving in a circular path at constant speed (i.e., constant speed, but changing direction).
- Analyze the velocity and acceleration of an object over time.

## **AVERAGE ACCELERATION**

Key Equation:

$$\vec{a}_{\text{avg}} = \frac{\Delta \vec{v}}{\Delta t}$$

In everyday life, we use “acceleration” to mean that an object is getting faster - i.e. greater speed. In physics, though, we use “acceleration” to mean any change in velocity. That means speeding up as well as slowing down or turning. Because velocity is a vector, it has direction. So a change in direction is a change in velocity. On a car, using the accelerator pedal is accelerating, but so is using the brakes or the steering wheel.

To see what a change of velocity means, it is best to representing an object's motion with a velocity-time graph. This is extremely useful in determining acceleration and displacement.

$$\vec{a}_{\text{avg}} = \frac{\Delta \vec{v}}{\Delta t}$$

Average acceleration is a change in velocity, divided by change in time. If the rate of change in velocity is uniform, the acceleration is uniform as well. Note: uniform and constant mean the same thing. We will only consider uniform acceleration unless otherwise stated.

### Check your understanding

How can braking provide for both negative and positive acceleration?

*Answer: If the brakes are applied while moving to the right the acceleration is to the left and therefore negative. If the breaks are applied while the car is traveling to the left the acceleration is to right and therefore positive.*

How can you have a negative acceleration without braking?

*Answer: Increase your velocity to the left.*

As common as the term acceleration is, there is a good deal of confusion surrounding the concept. An object can have any acceleration and simultaneously have a zero velocity. The velocity of an object at any instant (think of the speedometer in your car) gives no information in determining the object's acceleration, only the rate of change of velocity can be used to determine the object's acceleration.

### Thinking about acceleration

Suppose that a cheetah, starting from rest, has an acceleration of over 33 (km/hr/s), or kilometers per hour per second. So after one second, the cheetah has speed of 33 km/h, after two seconds, its speed is 66 km/h, and after three seconds, its speed is 99 km/h and 99 km/h is over 60 mph. So it takes a cheetah only 3 seconds to "go from zero to 60."

The cheetah increases its velocity by an average of 33 km/h every second. The units help to explain that acceleration depends upon the changing rate of velocity. 33 km/h is the same as 9.2 m/s (meters per second). So an acceleration of 33 km/h per second is 9.2 m/s per second. This is expressed as  $9.2 \text{ m/s}^2$ . Using dimensional analysis, we can see this from the formula for acceleration:

$$a = \frac{\Delta v}{\Delta t} = \left(\frac{m}{s}\right) \left(\frac{1}{s}\right) = \frac{m}{s^2}$$



The cheetah is the fastest land animal.

### Check your understanding

Thompson's gazelle can reach a speed of 65 km/h in four seconds. What is its acceleration in km/h/s and  $\text{m/s}^2$ ? (Use the conversion  $1 \text{ km/h} = 5/18 \text{ m/s}$ )

Check out the following link about acceleration:

<http://bit.ly/1jTUBG5>

*Answer: Using the given conversion,  $65 \text{ km/h} = 18 \text{ m/s}$ , and the acceleration is:*

$$a = \frac{\Delta v}{\Delta t} = \frac{18 \text{ m/s}}{4 \text{ s}} = 4.5 \text{ m/s}^2$$

A Thompson's gazelle has a maximum acceleration of  $4.5 \text{ m/s}^2$ . At this acceleration, how much time is required for it to reach a speed of  $40 \text{ km/h}$ ?

*Answer: Using our conversion from before,  $1 \text{ km/h} = 5/18 \text{ m/s}$ , we can make a conversion fraction for  $\text{km/h}$  to  $\text{m/s}$ .*

$$40 \text{ km/h} \times \frac{5 \text{ m/s}}{18 \text{ km/h}} = 11 \text{ m/s}$$

If the gazelle started from rest, and accelerates at  $4.5 \text{ m/s}^2$ , then after the first second its speed is  $4.5 \text{ m/s}$ , after the second second, its speed is  $9.0 \text{ m/s}$ , and after the third second its speed is  $13.5 \text{ m/s}$ . So we know the answer must be between 2 and 3 seconds. Using the definition of acceleration,  $a = \frac{\Delta v}{\Delta t}$ ; substitution gives:  $4.5 \text{ m/s}^2 = \frac{11 \text{ m/s}}{\Delta t}$ . Rearranging and solving, gives:

$$\Delta t = \frac{11 \text{ m/s}}{4.5 \text{ m/s}^2} = 2.4 \text{ s}$$

# VELOCITY VS. TIME & VELOCITY AT ZERO ACCELERATION

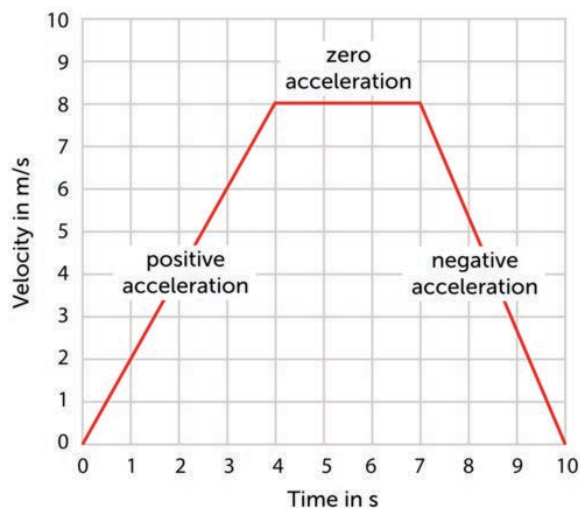


The sprinter in this image is just taking off from the starting blocks to run a short race down a straight track. She starts in a burst of speed and will pick up even more speed during the first few seconds of the race. She'll keep running at top speed until she crosses the finish line. Only then will she slow down.

Velocity is a measure of both speed and direction of motion. A change in velocity is called acceleration. In the case of the sprinter, she accelerates as she runs down the track because her speed is changing even though her direction stays the same. If you need a review of acceleration, watch the musical video at this URL:

## Plotting Velocity vs Time

The changing velocity of the sprinter—or of any other moving person or object—can be represented by a velocity-time graph like the one in the Figure below for the sprinter. A velocity-time graph shows how velocity changes over time. The sprinter's velocity increases for the first 4 seconds of the race, it remains constant for the next 3 seconds, and it decreases during the last 3 seconds after she crosses the finish line.



### Acceleration and Slope

In a velocity-time graph, acceleration is represented by the slope, or steepness, of the graph line. If the line slopes upward, like the line between 0 and 4 seconds in the graph above, velocity is increasing, so acceleration is positive. If the line is horizontal, as it is between 4 and 7 seconds, velocity is constant and acceleration is zero. If the line slopes downward, like the line between 7 and 10 seconds, velocity is decreasing and acceleration is negative. Negative acceleration is called deceleration. Remember slope is rise divided by run.

Q: Assume that another sprinter is running the same race. The other runner reaches a top velocity of 9 m/s by 4 seconds after the start of the race. How would the first 4 seconds of the velocity-time graph for this runner be different from the graph above?

A: *The graph line for this runner during seconds 0–4 would be steeper (have a greater slope). This would show that acceleration is greater during this time period for the other sprinter.*

### Check your understanding

Describe a velocity-time graph. What does the slope of the graph line represents?

*Answer: The positive slope on a velocity-time graph shows positive acceleration. A slope of zero on a velocity-time graph shows no acceleration and constant speed. A negative slope shows negative acceleration or slowing down.*

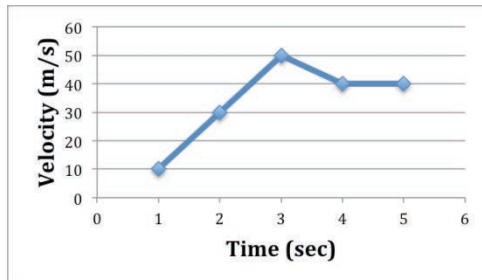
In the velocity-time graph above, the sprinter reaches a velocity of 2 m/s in just 1 second. At a constant rate of acceleration, how long does it take for her to double this velocity? What is her acceleration during this time period?

*Answer: Looking at the graph she reaches double the velocity of 2 m/s or 4 m/s at 2 seconds. Her acceleration would be  $2 \text{ m/s}^2$ .  $4 \text{ m/s} / 2 \text{ s} = 2 \text{ m/s/s}$  or  $2 \text{ m/s}^2$ .*

Create a velocity-time graph by plotting the data in the Table below.

Velocity (m/s)	Time (s)
10	1
30	2
50	3
40	4
40	5

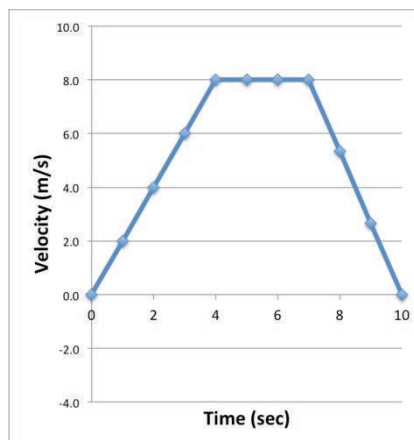
Answer:



Some helpful sites for motion graphs: <http://bit.ly/1fsNDnC>

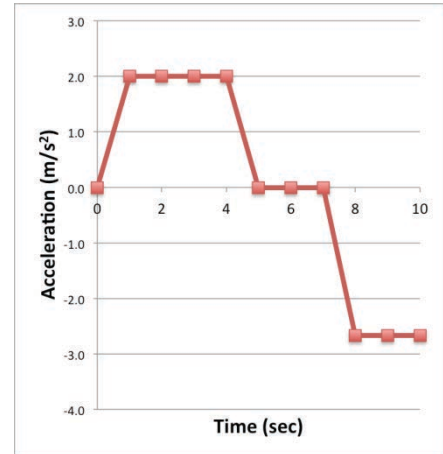
## ANALYSIS OF VELOCITY AND ACCELERATION OVER TIME

In section 2.2 we discussed graphing velocity over time by looking at a sprinter. The velocity over time graph clearly shows positive or negative acceleration. We learned if the graph shows a positive slope then there is positive acceleration. If the slope is negative then there is negative acceleration. When the slope is zero there is no acceleration and velocity stays the same.

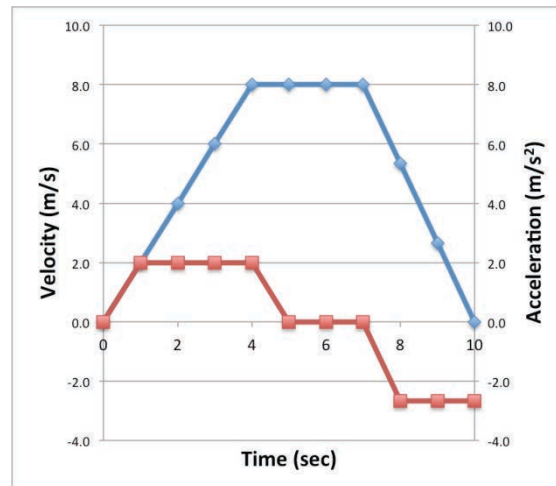




The same information showing acceleration over time looks extremely different (see graph right). A positive slope on a graph showing positive acceleration over time will show an increase in acceleration or the sprinter is increasing the rate of speeding up. A negative slope on the graph shows a negative acceleration over time or the sprinter is increasing the rate of slowing down. A slope of 0 shows that there is a constant increase or decrease of speed depending on if the value is positive or negative. For the sprinter a slope of 0 means she is increasing or decreasing speed at a constant rate.



A graph showing both at the same time helps to clearly see what is happening to velocity and speed over time.



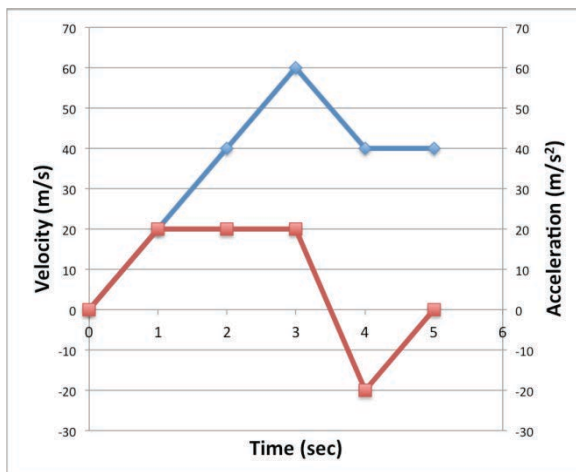
### Check your Understanding

A racecar that is racing on a straight road for starts from a stopped positions and increases his velocity to 60 m/s in three seconds. He then decreases his velocity to 40 m/s for the next second and maintains that velocity for the next second (see the data table below for his velocity). Complete the table filling in the acceleration for each second of the racecars movement and then graph both velocity and acceleration over time.

Time (s)	Velocity (m/s)	Acceleration (m/s <sup>2</sup> )
0	0	
1	20	
2	40	
3	60	
4	40	
5	40	

Answer:

Time (s)	Velocity (m/s)	Acceleration (m/s <sup>2</sup> )
0	0	0
1	20	20
2	40	20
3	60	20
4	40	-20
5	40	0



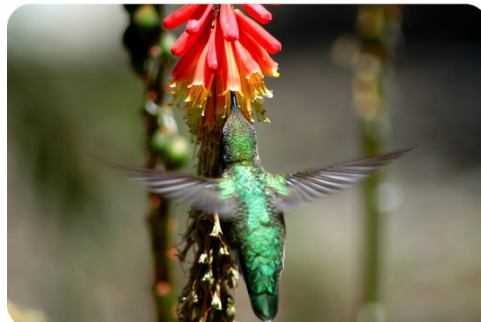
What is frame of reference and what does it have to do with motion?

## **STANDARD 1, OBJECTIVE 3: RELATE THE MOTION OF OBJECTS TO A FRAME OF REFERENCE.**

Objectives:

- Compare the motion of an object relative to two frames of reference.
- Predict the motion of an object relative to a different frame of reference (e.g., an object dropped from a moving vehicle observed from the vehicle and by a person standing on the sidewalk).
- Describe how selecting a specific frame of reference can simplify the description of the motion of an object.

### **SECTION 3.1 – FRAME OF REFERENCE**



<http://bit.ly/1n3lqoH>

The wings of this hummingbird are moving so fast that they're just a blur of motion. You can probably think of many other examples of things in motion. If you can't, just look around you. It's likely that you'll see something moving, and if nothing else, your eyes will be moving. So you know from experience what motion is. No doubt it seems like a fairly simple concept. However, when you read this article, you'll find out that it's not quite as simple as it seems.

## Defining Motion

In science, motion is defined as a change in position. An object's position is its location. Besides the wings of the hummingbird in opening image, you can see other examples of motion in the Figure below. In each case, the position of something is changing.



**Q:** In each picture in the Figure above, what is moving and how is its position changing?

**A:** *The train and all its passengers are speeding straight down a track to the next station. The man and his bike are racing along a curving highway. The inchworm is slowly inching its way along a branch. The meteor is shooting through the atmosphere toward Earth, burning up as it goes.*

## Frame of Reference

There's more to motion than objects simply changing position. You'll see why when you consider the following example. Assume that the school bus pictured in the Figure below passes by you as you stand on the sidewalk. It's obvious to you that the bus is moving, but what about to the children inside the bus? The bus isn't moving relative to them, and if they look at the other children sitting on the bus, they won't appear to be moving either. If the ride is really smooth, the children may only be able to tell that the bus is moving by looking out the window and seeing you and the trees whizzing by.



When a bus passes someone standing on the sidewalk, it momentarily blocks the person's view of objects across the street. This helps the outside observer detect the bus's motion.



If the ride is smooth enough, these children may not even realize that the bus is moving unless they look out the windows.

This example shows that how we perceive motion depends on our frame of reference. Frame of reference refers to something that is not moving with respect to an observer that can be used to detect motion. For the children on the bus, if they use other children riding the bus as their frame of reference, they do not appear to be moving. But if they use objects outside the bus as their frame of reference, they can tell they are moving. The video at the URL below illustrates other examples of how frame of reference is related to motion.

**<http://bit.ly/1iVI71U>**

Q: What is your frame of reference if you are standing on the sidewalk and see the bus go by? How can you tell that the bus is moving?

*A: Your frame of reference might be the trees and other stationary objects across the street. As the bus goes by, it momentarily blocks your view of these objects, and this helps you detect the bus' motion.*

## SECTION 3.2 – PREDICTIONS WITH FRAME OF REFERENCE

### Inertial Frames

There are endless examples of relative motion. Suppose that you're in an elevator that is rising with a constant speed of 2 m/s relative to the ground. If you release a ball while in this reference frame, how will the motion of the ball differ than had you dropped the ball while standing on the ground?

Had you been asleep in this reference frame and woke after the compartment was in motion, you would have no idea whatsoever you were in motion. There is no experiment that can be performed to detect constant velocity motion. If you've ever traveled in a jet moving 1000 km/h (about 600 mph) with no air turbulence, then you know from firsthand experience that you felt motionless. After the brief acceleration period you can no longer sense the motion of the elevator. The ball will move as if it has been released in the reference frame of the Earth.

As a general statement, we consider all constant velocity reference frames to be equivalent. This idea is known as The Galilean Principle of Relativity. Constant-velocity reference frames are called inertial frames of reference. An "at-rest" reference frame is an arbitrary construct. If you're traveling with a constant velocity in your car, the reference frame of the car is an at-rest frame. The elevator compartment moving 2 m/s is an at-rest frame with respect to the compartment. And, you sitting and reading this firmly placed on the earth consider yourself to be in an at-rest reference frame. But you know the Earth itself is in motion. It rotates about its axis with a speed of about 1600 km/h (1000 mph) at the equator, and it orbits the sun with an average speed of 108,000 km/h (67,000 mph). In fact, the earth isn't even an inertial frame of reference since it rotates about its axis and its orbital speed varies. (Remember, velocity is constant only if its magnitude and direction do not change—objects in circular motion do not qualify!) We usually approximate the earth as an inertial frame of reference since we do not readily sense the earth's acceleration. Objects on the Earth's surface have a maximum acceleration due to its rotation of about  $0.03 \text{ m/s}^2$  — which we don't typically concern ourselves with since the acceleration due to gravity is  $10 \text{ m/s}^2$ .

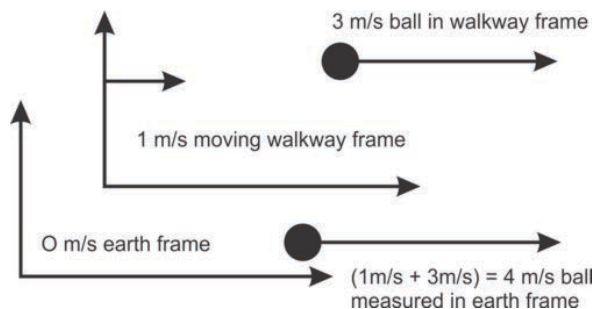
### Relative Motion

Figure below, a moving walkway, provides us with an example of relative motion. Let us consider two Cartesian coordinate systems. One is attached to the “stationary” earth. The other is attached to a walkway moving with a constant horizontal velocity of 1 m/s with respect to the earth. If a ball is thrown with an initial horizontal velocity of 3 m/s in the direction the walkway is moving by a person standing on the walkway, what horizontal velocity does a person standing on the ground measure for the ball? The person in the earth frame sees the ball having a combined velocity of 4 m/s. The person in the “moving frame” will measure it as 3 m/s. According to The Principle of Galilean Relativity, the velocity,  $V$ , seen from the at-rest frame is additive, that is,  $V = 1 \text{ m/s} + 3 \text{ m/s}$ . See Figure below.



[http://www.flickr.com/photos/paul\\_lowry/4914284947/](http://www.flickr.com/photos/paul_lowry/4914284947/)

<http://bit.ly/1n3luVf>



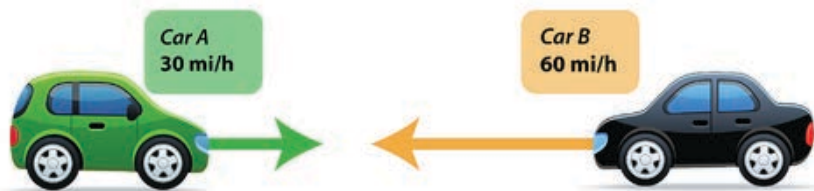
Author: CK-12 Foundation - Ira Nirenberg License: CC-BY-NC-SA 3.0

All motion is measured with respect to a reference frame (coordinate system attached to the earth) when defining the velocity of each car in questions 2 and 3.

2. Two cars are headed toward each other: Car A moves with a velocity of 30 mph due east and Car B with a velocity of 60 mph due west, relative to “at-rest” earth. See Figure below.

Part a: Passengers in Car A’s reference frame assume they are motionless.

Part b: Passengers in Car B’s reference frame assume they are motionless.



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a. What is the velocity of car B relative to car A?

We define motion to the east is positive (+30 mph), and motion to the west is negative (-60 mph).



From our previous statements regarding relative velocity we can “feel” that the relative velocity is greater than either speed: If we define the relative velocity (the velocity of car B relative to the velocity of car A) as:  $\vec{V}_{ba} = \vec{V}_b - \vec{V}_a$ , then  $-60 - 30 = -90$  mph, a person in car A sees car B moving west at 90 mph. The person in car A sees himself as “motionless” while car B is moving toward him with car B’s speed and his own speed which he does not perceive.

b. What is the velocity of car A relative to the velocity of car B is? This means we are assuming car B is our “at rest” coordinate system.

$\vec{V}_{ab} = \vec{V}_a - \vec{V}_b = 30 \text{ mph} - (-60 \text{ mph}) = +90 \text{ mph}$ . A person in car B sees car A moving east at 90 mph.

The person in car B sees himself as motionless while car A is moving toward him with car A’s speed and his own speed which he does not perceive.

Note: The “at-rest” frame sees its motion reversed in the “moving frame.”

3. Car A is moving due east with a speed of 30 mph and Car B is moving due north with a speed of 30 mph.

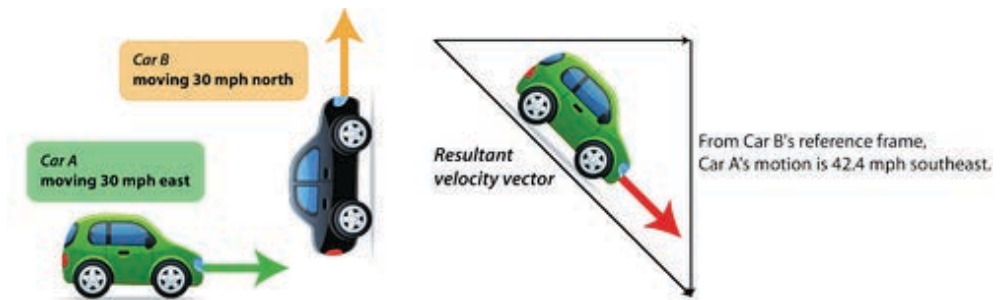


Diagram for 3a Author: Image copyright lana rinck, 2012; modified by CK-12 Foundation - Christopher Auyeng, Raymond Chou License: Used under license from Shutterstock.com Source: <http://www.shutterstock.com>

a. What is the velocity of car A relative to car B?

$\vec{V}_{ab} = \vec{V}_a - \vec{V}_b$  The two vectors are not along the same line so we'll use their components

$\vec{V}_a = (+30, 0)$  and  $\vec{V}_b = (0, +30)$ , where east is +X and north is +Y.  
 $-\vec{V}_b = (0, -30)$ , therefore,  $\vec{V}_a - \vec{V}_b = (30 + 0, 0 - 30) = (30, -30)$ . The components are directed east and south, so the direction is southeast. Since both components have the same magnitude, the angle must be  $45^\circ$ . But since the vector is in the southeast direction it is in the 4th quadrant so the angle is  $315^\circ$ , and the magnitude is the Pythagorean sum  $(30^2 + 30^2)^{\frac{1}{2}} = 42.4 \text{ mph}$

Thus:  $\vec{V}_{ab} = 42.4 \text{ mph}$  in direction  $315^\circ$

b. What is the velocity of car B relative to car A?

The magnitude of the relative speed is the same but the direction is reversed:

Thus:  $\vec{V}_{ba} = 42.4 \text{ mph}$  in direction  $135^\circ$

## **SECTION 3.3**

# **SELECTING A FRAME OF REFERENCE CAN SIMPLIFY THE DESCRIPTION**

Velocity is always measured relative to something. We measure how fast a person runs or how fast a car drives relative to the ground. However, we know from astronomy that the Earth itself is both turning around its axis and going around the Sun. As we've discussed a reference frame is a fixed point and directions from it that we measure relative to.

If you are on a bus going north at 60 mph, then the person seated across the aisle from you has velocity 60 mph north relative to the ground and velocity zero relative to you. If the bus is going at a steady speed, you can toss a coin across to them, and it works the same as if you were standing on solid ground. In the bus frame of reference, you and the other passenger have velocity zero, and the coin has a slight velocity east (say 20 mph). In this frame of reference, someone standing to the side of the road would have a velocity 60 mph south.

In the ground frame of reference, you and the other passenger are both moving 60 mph north, while the coin is moving diagonally northeast. The coin's velocity vector is 60 mph north and 20 mph east added together.

Both of these frames of reference are correct. You can solve any problems using either one, as long as you use it consistently. Some problems, though, are easier in one frame of reference than in another. If you wanted to solve how long it would take for the coin to go across the aisle, then the bus frame of reference is much simpler.

An airplane is flying straight and level at 550 miles per hour, 35,000 feet above the ground. What is the net force on the airplane?

## **STANDARD 1, OBJECTIVE 4: USE NEWTON'S FIRST LAW TO EXPLAIN THE MOTION OF AN OBJECT.**

### **NEWTON'S FIRST LAW**

Objectives:

- Describe the motion of a stationary object on which balanced forces are acting.
- Describe the motion of a moving object on which balanced forces are acting.
- Describe the balanced forces acting on a moving object commonly encountered (e.g., forces acting on an automobile moving at constant velocity, forces that maintain a body in an upright position while walking).

#### **Newton's First Law**

The First Law is about inertia; an object at rest will remain at rest. An object in motion will remain in motion, at a constant speed, in a constant direction until acted on by an outside force. Prior to Newton and Galileo, the prevailing view on motion was still Aristotle's. According to his theory the natural state of things is at rest; force is required to keep something moving at a constant rate. This made sense to people throughout history because on earth, friction and air resistance slow moving objects to a stop. When there is no friction, a situation approximated in space, Newton's first law is much more evident.

**Inertia** is the property of an object that resists a change in its state of motion. An object's inertia is simply the mass of the object. The more massive an object is, the more difficult it is to start it moving or to change its speed or direction once it is moving. Mass and Weight are two different things. Mass (typically in units of kg or grams) is basically a measure of what comprises an object. Weight is the measure of how much the force of

gravity is pulling on the object. In fact, instead of saying 'I weigh 80 lb.', one could say that 'the force of gravity is pulling on me with a force of 80 lb.' The metric unit for weight (and force) is the Newton.

Watch this Explanation about Newton's First Law of Motion here:

<http://bit.ly/1aNHRhz>

### Simulation

Try the following simulation to apply these principles.

<http://bit.ly/1bdPKaH>

### Practice Problems

1. When hit from behind in a car crash, a passenger can suffer a neck injury called whiplash. Explain in terms of inertia how this occurs, and how headrests can prevent the injury.
2. A cheetah can outrun a gazelle in a short straight race, but the gazelle can escape with its life by zigzagging. The cheetah is more massive than the gazelle – explain how this strategy works.
3. If your hammer develops a loose head, you can tighten it by banging it on the ground. But – it's better to bang the hammer head up rather than head down. Explain, using inertia.
4. If a man weighs 140 lb. on Earth, what is his weight in Newtons and his mass in kg?

## Answers

*The passenger's head will remain at rest for the split second when the seat exerts a big force on the passenger's back causing a "whiplash" on your neck. This is an example of Newton's first law because your head is not acted on by an unbalanced force while the rest of your body is. A head rest causes your head to accelerate with the rest of your body.*

*The cheetah must exert a bigger force to change directions than the gazelle because the cheetah has more inertia. This extra force needed for the cheetah to change directions allows the gazelle to get away.*

*The head of the hammer has more inertia than the tail. So when you bang the hammer "head up" the head exerts a large force on the rest of the hammer in order to come to a stop.*

*620 N, 62 kg (using 10 m/s/s for acceleration of gravity)*

## VOCABULARY

acceleration - a change in velocity, divided by change in time.

average velocity – average displacement divided by time in which the displacement occurred

balanced forces – when the net sum of all forces acting on a body cancel out to zero

displacement - the difference between final and initial positions

distance - a scalar quantity giving the positive length between two points frame of reference

instantaneous velocity – the velocity at a specific time

position – location of an object, usually relative to where movement started or ended.

rate – measurement of units over a period of time

scalar – a description of motion referring only to magnitude (e.g. distance, speed)

speed - Total distance traveled divided by total travel time

time – measurement of a period in which something occurred, is occurring, or will occur

vector – a description of motion referring to both magnitude and direction (e.g. displacement, velocity)

velocity - Change in position divided by change in time







# **FORCE, MASS + ACCELERATION**

# CHAPTER 2

How does a rider move the scooter through its tricks?

Standard 2: Students will understand the relation between force, mass, and acceleration.

## **STANDARD 2, OBJECTIVE 1: ANALYZE FORCES ACTING ON AN OBJECT.**

STD 2.1a, 2.1c



### **Force**

Carson has been riding a scooter for almost as long as he can remember. As you can see, he's really good at it. He can even do tricks in the air. It takes a lot of practice to be able to control a scooter like this. Carson automatically applies just the right forces to control his scooter.

### **Defining Force**

Std 2.2b, 2,2c

Force is defined as a push or pull. There are several fundamental forces in the universe, including the force of gravity, electromagnetic force, and weak and strong nuclear forces. When it comes to the motion of everyday objects, however, the forces of interest include mainly gravity, friction, and applied force. Applied force is force that a person or thing applies to an object.

**Q:** What forces act on Carson's scooter?

*A: Gravity, friction, and applied forces all act on Carson's scooter. Gravity keeps pulling both Carson and the scooter toward the ground. Friction between the wheels of the scooter and the ground prevent the scooter from sliding but also slow it down. In addition, Carson applies forces to his scooter to control its speed and direction.*

## Force and Motion

Forces cause all motions. Every time the motion of an object changes, it's because a force has been applied to it. Force can cause a stationary object to start moving or a moving object to change its speed or direction or both. A change in the speed or direction of an object is called **acceleration**. Look at Carson's little brother Colton in the Figure below. He's getting his scooter started by pushing off with his foot. The force he applies to the ground with his foot starts the scooter moving in the opposite direction. The harder he pushes against the ground, the faster the scooter will go.

Isaac Newton stated the relationship between force, mass and acceleration in his comprehensive treatise called the Principia. He organized this particular idea into three laws of motion. A modern translation would be something like this:



**Newton's first law of motion** – an object at rest will remain at rest. An object in motion will remain in motion, at a constant speed, in a constant direction until acted on by an outside force.

**Newton's second law of motion** – an outside force will produce an acceleration that is proportional to the force and inversely proportional to the mass being accelerated. In simpler words, force equals mass times acceleration. Just remember the equation  $F = ma$ .

**Newton's third law of motion** – for every action there's an equal and opposite reaction. This idea means that forces always come in pairs. If there is one force there are two. They are equal in magnitude and opposite in direction.

How much an object accelerates when a force is applied to it depends not only on the strength of the force but also on the object's mass. For example, a heavier scooter would be harder to accelerate. Colton would have to push with more force to start it moving and move it faster. You can explore the how force, mass, and acceleration are related by doing the activity at this URL:

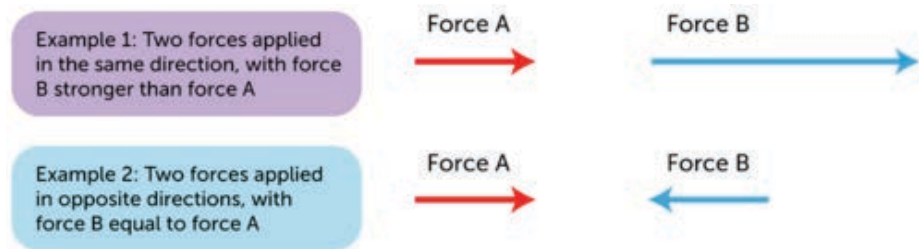
<http://bit.ly/1deF3o1>

Q: What units do you think are used to measure force?

A: The SI unit for force is the Newton (N). A Newton is the force needed to cause a mass of 1 kilogram to accelerate at  $1 \text{ m/s}^2$ , so a Newton equals  $1 \text{ kg} \cdot \text{m/s}^2$ . The Newton was named for the scientist Sir Isaac Newton, who is famous for his laws of motion and gravity.

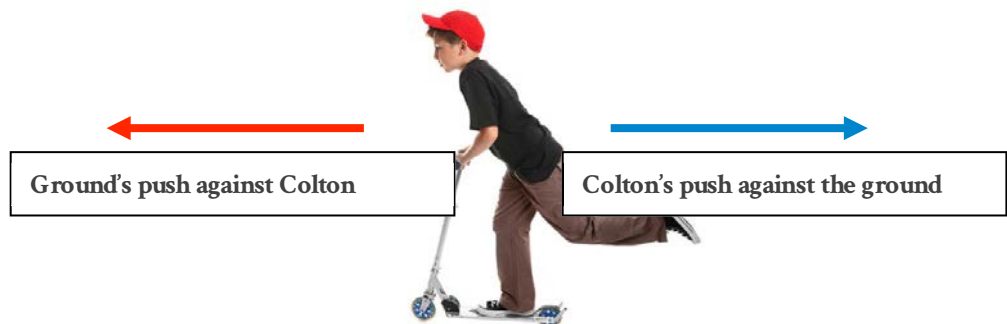
### Force as a Vector

Force is a vector, or a measure that has both size and direction. For example, Colton pushes on the ground in the opposite direction that the scooter moves, so that's the direction of the force he applies. He can give the scooter a strong push or a weak push. That's the size of the force. Like other vectors, a force can be represented with an arrow. You can see some examples in the Figure below. The length of each arrow represents the strength of the force, and the way the arrow points represents the direction of the force.



Q: How could you use arrows to represent the forces that start Colton's scooter moving?

A: Colton pushes against the ground behind him (to the right in the Figure above). The ground pushes back with equal force to the left, causing the scooter to move in that direction. Force arrows A and B in example 2 above could represent these forces.



## SUMMARY

- Force is defined as a push or pull acting on an object. Forces include gravity, friction, and applied force.
- Force causes changes in the speed or direction of motion. These changes are called acceleration.
- The SI unit for force is the Newton (N).
- Force is a vector because it has both size and direction. Like other vectors, it can be represented by an arrow.

## PRACTICE

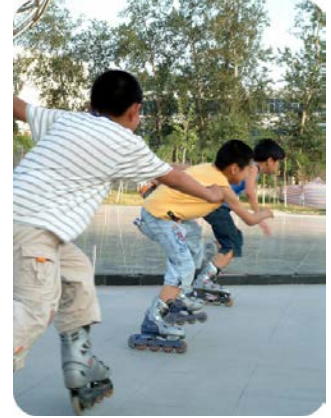
Apply different types of forces to materials in the interactive animated lab at the following URL. Then answer the questions below.

<http://bit.ly/1nx7d6u>

1. What is compression, and how does it affect materials?
2. What is tension? What is a real-life example?
3. Describe shear as a force.
4. What is torsion?

Why is the biggest, strongest kid not always the fastest?

## **STANDARD 2, OBJECTIVE 2: USING NEWTON'S SECOND LAW, RELATE THE FORCE, MASS, AND ACCELERATION OF AN OBJECT.**



Newton's Second Law

Key Equation:

$$F = ma$$

(Force = mass X acceleration)

These boys are racing around the track at Newton's Skate Park. The boy who can increase his speed the most will win the race. Tony, who is closest to the camera in this picture, is bigger and stronger than the other two boys, so he can apply greater force to his skates.

Q: Does this mean that Tony will win the race?

A: *Not necessarily, because force isn't the only factor that affects acceleration.*

### **Force, Mass, and Acceleration**

An object accelerates whenever it speeds up, slows down, or changes direction.

Remember any change in directions is acceleration even if the speed remains constant.

Acceleration occurs whenever an unbalanced force acts on an object. Two factors affect the acceleration of an object: the net force acting on the object and the object's mass.

Newton's second law of motion describes how force and mass affect acceleration. The law states that the acceleration of an object equals the net force acting on the object divided by the object's mass. This can be represented by the equation:

$$\text{Acceleration} = \frac{\text{Net force}}{\text{Mass}}$$

or

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

This is commonly written as  $F = ma$



**Q:** While Tony races along on his rollerblades, what net force is acting on the skates?

**A:** Tony exerts a backward force against the ground, as you can see in the Figure below, first with one skate and then with the other. This force pushes him forward. Although friction partly counters the forward motion of the skates, it is weaker than the force Tony exerts. Therefore, there is a net forward force on the skates.

### Direct and Inverse Relationships

Newton's second law shows that there is a direct relationship between force and acceleration. The greater the force that is applied to an object of a given mass, the more the object will accelerate. For example, doubling the force on the object doubles its acceleration. At the following URL, you can simulate pushing a 2000-kilogram elephant on skates, using different amounts of force. Do the simulation to see how changing force while holding mass constant changes the acceleration of the skating elephant.

<http://bit.ly/1aNH8x3>

The relationship between mass and acceleration is different. It is an inverse relationship. In an inverse relationship, when one variable increases, the other variable decreases. The greater the mass of an object, the less it will accelerate when a given force is applied. For



example, doubling the mass of an object results in only half as much acceleration for the same amount of force.

**Q:** Tony has greater mass than the other two boys he is racing above. How will this affect his acceleration around the track?

*A: Tony's greater mass will result in less acceleration for the same amount of force.*

## SUMMARY

- Newton's second law of motion states that the acceleration of an object equals the net force acting on the object divided by the object's mass.
- According to the second law, there is a direct relationship between force and acceleration and an inverse relationship between mass and acceleration.

## PRACTICE PROBLEMS

1. At the following URL, use the simulator to experiment with force, mass, and acceleration. First keep force constant at 1 N, and vary mass from 1–5 kg. Next keep mass constant at 1 kg, and vary force from 1–5 N. In each simulation, record the values you tested and the resulting acceleration. Finally, make two line graphs to plot your results. On one graph, show acceleration when force is constant and mass changes. On the other graph, show acceleration when mass is constant and force changes. Describe in words what the two graphs show.

<http://bit.ly/1ihOdFS>

## REVIEW

2. State Newton's second law of motion.
3. How can Newton's second law of motion be represented with an equation?
4. If the net force acting on an object doubles, how will the object's acceleration be affected?
5. Tony has a mass of 50 kg, and his friend Sam has a mass of 45 kg. Assume that both friends push off on their rollerblades with the same force. Explain which boy will have greater acceleration.

## STANDARD 2, OBJECTIVE 3: EXPLAIN THAT FORCES ACT IN PAIRS AS DESCRIBED BY NEWTON'S THIRD LAW.

### Newton's Third Law

It was Newton who realized singular forces could not exist: they must come in pairs. In order for there to be an “interaction” there must be at least two objects, each “feeling” the other's effect. Newton's Third Law states: Whenever two objects interact they must necessarily place equal and opposite forces upon each other.

Mathematically, Newton's Third law is expressed as:  $F_{AB} = -F_{BA}$ , where the subscript “AB” means, the force exerted on A by B and the subscript “BA” means, the force exerted on B by A. Forces  $F_{AB}$  and  $F_{BA}$  are identical forces and never act upon the same object. A Newton's Third Law pair of forces never acts upon the same object. Forces that are equal and opposite and do act upon the same object are not a pair.

### Problem Solving

We use Newton's laws to solve “dynamics” problems. Dynamics, unlike kinematics, considers the forces acting upon objects. Whether it is a system of stars gravitationally bound together or two colliding automobiles, we can use Newton's laws to analyze and quantify their motion. Of Newton's three laws, the major mathematical “workhorse” used to investigate these and endless other physical situations is Newton's Second Law (N2L):  $\sum F = Ma$ .

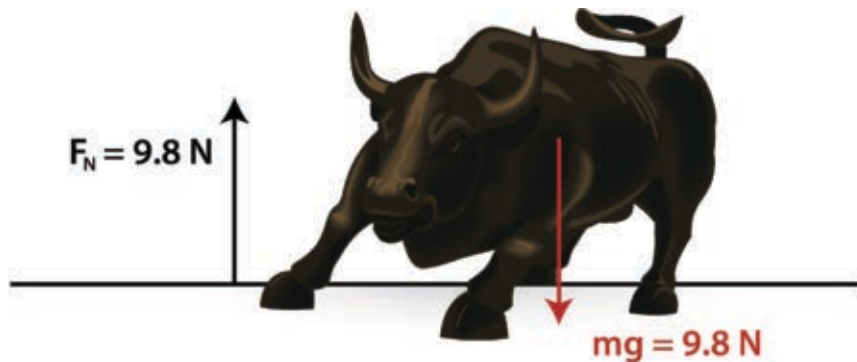
In using Newton's laws we assume that the acceleration is constant in all of the examples in the present chapter. Newton's laws can certainly deal with situations where the acceleration is not constant, but, for most part, such situations are beyond the level of this book. As a last simplification we assume that all forces act upon the center of mass of an object. The center of mass of an object can be thought of as that point where all of the mass of an object is concentrated. It is the point at which if your finger were placed the object would remain balanced, at the 50 cm point of a meter stick for example.

## FREE-BODY-DIAGRAMS

A Diagram showing those forces that act upon a body is called a Free-Body-Diagram (FBD). The forces in a FBD show the direction each force acts, and, when possible, the relative magnitude of the each force by the length of the force vector. Each force in a FBD must be labeled appropriately so it is clear what each arrow represents.

### *Example 1: Sitting Bull*

In the Figure below a 1.0 kg bull statue is resting on a mantelpiece. Analyze the forces acting on the bull and their relationship to each other. There are two vertical forces that act upon the bull: The earth pulling down on the center of mass of the bull with a force of  $W = mg = (1.0)(9.8) = 9.8 \text{ N}$  and the floor pushing back against the weight of the bull, with a “normal” force  $F_N$ . The term “normal” force comes from mathematics where normal means: perpendicular to a surface. The normal force vector (often stated as “the normal”) is drawn perpendicular to the surface that the bull rests upon. Normal forces are usually associated with a push upon an object not a pull.



Author: Image copyright Bistrafic, 2012 License: Used under license from Shutterstock.com by CK-12.

Using Newton’s Second Law we write:  $\sum F = Ma$ , where  $\sum F = F_N - mg = ma = 0$ , where  $a=0$ . The negative sign ( $-mg$ ) indicates that the earth pulls downward on the statue. Usually, when solving problems with N2L, forces that point down and to the left are expressed negatively and forces that point up and to the right are expressed positively. These are just conventions and any consistent set of conventions is permissible. It is also important (when enough information is provided) to draw the length of a vector in

proportion to its magnitude. In the diagram above,  $F_N$  and  $mg$  are drawn the same length, reflecting the fact that they have the same magnitude. Important: in the diagrams, the arrows must originate inside the object, pointing “outward”

The statue is stationary so it has zero acceleration. This reduces the problem to  $F_N = mg$ , which intuitively seems reasonable. When the problem is solved, it shows the magnitudes of the forces are equal. It must be kept in mind that their directions are opposite, and that they are not a N3L pair.

*Example 2: Hanging Loose*

In the diagram below Mr. Joe Loose is hanging from a rope for dear life. Joe’s mass is 75 kg.

Use  $g = 9.8\text{m/s}^2$ .

2a. Draw Joe’s FBD



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2b. What is the tension in the rope?

We assume the mass of the rope is negligible. Including the mass of the rope is not particularly difficult, but we’re just starting out!

Labeling: A tension force is transmitted through a string, cord or rope. The convention in physics is to use label T, for “tension”.

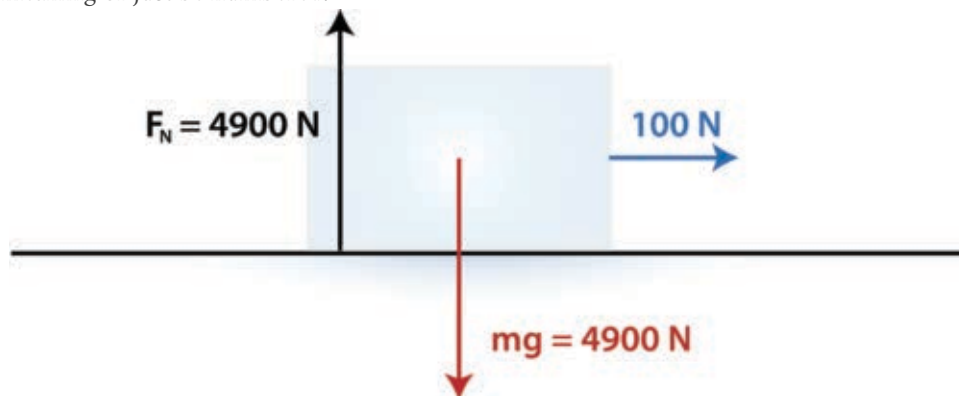
Once again, we apply:  $\sum F = Ma$ , where  $\sum F = T - mg = ma = 0$  since  $a=0$ .

*Example 3: Sliding Away*

A 4900 N block of ice, initially at rest on a frictionless horizontal surface, has a horizontal force of 100 N applied to it.

Always begin by drawing a FBD of the problem.

Labeling: Typically, applied forces are either written as F. If there are multiple forces, depending on the wording of the problem, each force may have a subscript that reflects its meaning or just be numbered.



Questions and answers:

3a. Find the mass of the block of ice in Figure above, use  $g = 9.8\text{m/s}^2$ .

3b. Find the acceleration of the block of ice in Figure above.

$$\sum F = Ma, \quad \sum F = F_{ap} = ma$$

$$100 \text{ N} = (500 \text{ kg})a, \quad a = 0.20 \text{ m/s}^2$$

3c. Find the velocity of the block at  $t=100$  sec.

$$V_f = at + V_i, \quad (0.20)(100) + 0 = 20 \text{ m/s}$$

3d. Find the displacement of the block at  $t = 100$  sec.

$$\Delta x = \frac{1}{2}(V_i + V_f)t = \frac{1}{2}(0 + 20)(100) = 1000 \text{ m}$$

#### Example 4: A Touching Story

In Figure below Block A has a mass of 10 kg and Block B has a mass of 6 kg. Both blocks are in contact with each other, with Block A experiencing an applied 70 N force to the right as shown. Note: both blocks rest on a frictionless surface and have the same acceleration.

Note: When referring to more than one mass we often use the word “system.”

4a. Draw the FBD's for Block A and Block B.

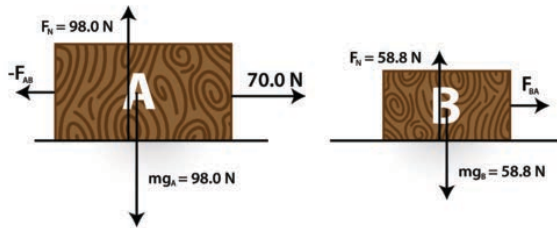
Answer:

As Block A moves to the right it experiences a force from Block B to the left.

This force is labeled:  $-F_{AB}$  (force on A by B)



Block B is pushed to the right with the same force that it exerts upon Block A, according to N3L. This force is labeled:  $F_{BA}$  (force on B by A); the magnitudes of  $-F_{AB}$  and  $F_{BA}$  are, of course, equal, according to N3L.



4b. Find the acceleration of the system.

Answer:

Both masses will have the same acceleration.

So we will find the acceleration of the system using  $F = ma$ .

$$a = F/m \quad \text{so, } a = 70 \text{ N}/16\text{kg} = 4.375 \text{ m/s}^2$$

4c. What is the magnitude of the force between Block A and Block B ( $F_{AB}$  or  $F_{BA}$ )?

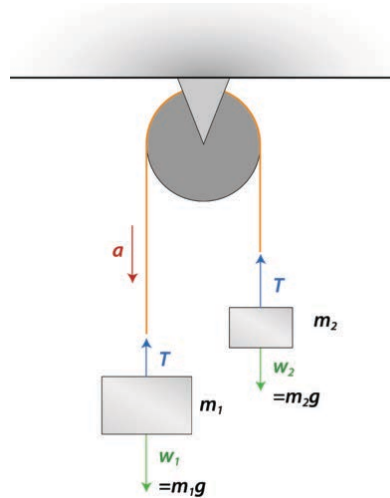
Answer:

This is answered by finding the force necessary to accelerate block b at the rate of acceleration found previously.  $F = 6.00(4.375) = 26.25 = 26.3 \text{ N}$

Example 4: One end of the rope in Figure below is attached to a 3.2-kg mass,  $m_1$  and the other end is attached to a 2kg mass  $m_2$ . Assume the system is frictionless and the rope has negligible mass.

4a. Draw FBDs for the  $m_1$  and  $m_2$ .





4b. Determine the acceleration of the system. Use  $g=9.8\text{m/s}^2$ .

Answer:

Before we begin, we decide in which direction the system accelerates. Since the mass of the  $m_2$  is smaller than the mass of  $m_1$ ,  $m_2$  will accelerate up and  $m_1$  will accelerate down. Therefore the tension in the rope is greater than the weight of  $m_1$  but smaller than the weight of  $m_2$ . Using N2L we write the equations of motion for  $m_1$  and  $m_2$ .

$$\sum F = (3.2)(9.8) - T = 32a \quad (\text{since } T < mg_1, a > 0)$$

$$\sum F = T - (2.0)(9.8) - T = 2.0a \quad (\text{since } T < mg_2, a > 0)$$

The equations are set up so that the acceleration has a consistent sign.

Had we chosen the direction of the acceleration incorrectly, our answer would have been a negative number, informing us of our error.

Solving the system of equations we have:

$$(3.2)(9.8) - (2.0)(9.8) = 5.2a, \text{ solving for the acceleration gives:}$$

$$a = 2.26 \text{ m/s}^2 = 2.3 \text{ m/s}^2.$$

4c. Find the tension in the rope.

Again, either equation will provide the answer. Using the second equation above we have:

$$T = (2.0)(9.8) + (2.0)(2.26) = 24.12 \text{ N} = 24 \text{ N}$$

One possible check on the problem is to insure that:

$$mg_2 < T < mg_1$$

$$mg_{ax} = (2.0)(9.8) = 19.6 \text{ N} = 20 \text{ N} \text{ and}$$

$$mg_{log} = (3.2)(9.8) = 31.36 \text{ N} = 31 \text{ N}$$

Therefore:  $20 < 24 < 31$ .

It is always wise to check your results for consistency.

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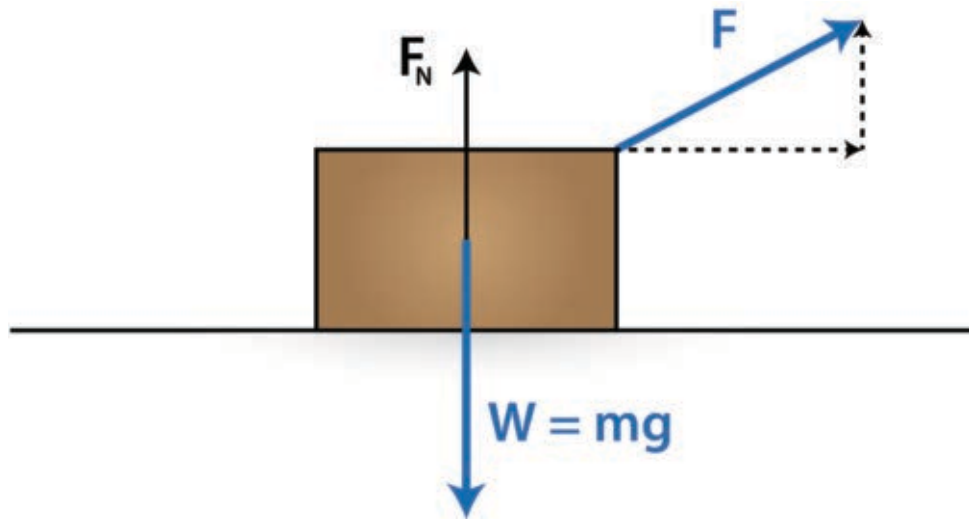
## FRICION AND NORMAL FORCE

### INTRODUCTION

Just as velocity and acceleration are vectors that can point in any direction, force is also a vector that has both a magnitude and a direction.

### THE NORMAL FORCE

A normal force is the force exerted by the ground or other object that prevents other objects from going through it. In the Figure below, a block that rests upon the ground is pulled in a diagonal direction up and to the right. Just as velocity and acceleration can have x and y components, forces can have x and y components. We will need the same skills in resolving the force vector in the Figure below.



Author: CK-12 Foundation - Christopher Auyeung, Raymond Chou License: CC-BY-NC-SA 3.0

The applied force,  $F$ , acts at an angle to the horizontal. Knowing the value of the angle is not necessary to understand the effect on the normal force. Recall that the normal force,  $F_N$ , is the reaction force to the force that the block exerts on the ground. The applied force,  $F$ , has two components. One component acts toward the right (the  $x$  component) and the other component acts upward (the  $y$  component). Consider the effect that the  $y$  component has on the normal force. Since the  $y$  component of the force  $F$  acts in the upward direction it effectively “eases” some of the block’s weight off the ground. If the  $y$  component were equal in magnitude to the weight of the block, the ground would not experience any force upon it due to the weight of the block. We can see that upward forces reduce the reaction force on the block. Thus, upward forces acting on the block reduce the normal force.

### CHECK YOUR UNDERSTANDING

In the Figure above, the weight,  $mg$ , of the block is 100 N and the force,  $F$ , has a  $y$  component,  $F_y$ , of 25 N.

1. What normal force,  $F_N$ , does the ground exert upon the block?

Answer: We know that gravity and the normal force act only in the  $y$  direction, and that the block is not moving (velocity and acceleration zero). We can use Newton's Third Law, which can be applied to the net force in the  $y$  direction and the acceleration in the  $y$  direction.

$$\sum_y F = F_N + F_y - mg = ma_y = 0$$

Therefore,  $F_N = 100 - 25 = 75 \text{ N}$

### Illustrative Examples

2a. A 25.0 kg block experiences an applied force  $F$  of 100 N acting at an angle  $30^\circ$  above the horizontal. What is the normal force,  $F_N$ , on the block?

$$F_x = F \cos \theta = F \cos 30^\circ = 100 \cos 30^\circ = 86.6 \text{ N}$$

$$F_y = F \sin \theta = F \sin 30^\circ = 100 \sin 30^\circ = 50.0 \text{ N}$$

Answer: The first thing to do is to resolve the applied force into its  $x$  and  $y$  components:

$$W = mg = (25.0\text{kg})(10\text{m/s}^2) = 250 \text{ N}$$

Next, since we were given the mass of the block, we need to find its weight:

$$\sum F_y = F_N + 50\text{N} - 250\text{N} = ma_y = 0$$

The question concerns the forces in the y direction.

Therefore,

$$F_N = 200 \text{ N}$$

2b. What is the horizontal acceleration of the block in question 2a?

This question concerns the forces in the x direction.

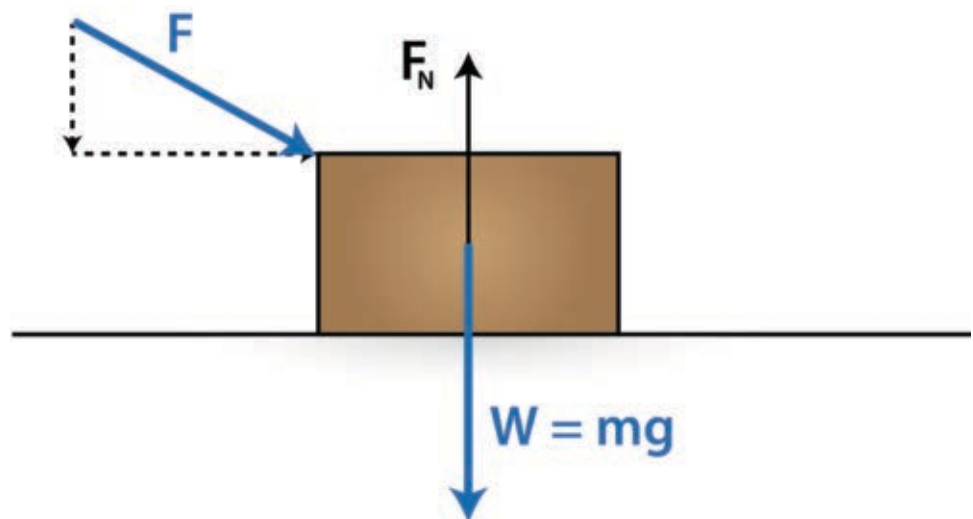
$$\sum F_x = 86.6 \text{ N} = ma_x = (25.0\text{kg})a_x$$

Therefore,

$$a = 3.46 \text{ m/s}^2$$

## CHECK YOUR UNDERSTANDING

Had the applied force been directed as shown in this diagram, what effect do you think it would have had on the normal force? See diagram below.



- (a) The normal force is greater than the weight of the block.
- (b) The normal force is less than the weight of the block.
- (c) The normal force equals the weight of the block.

*Answer: The answer is a. See if you can convince yourself that the normal force in this situation would be 295 N if the values of all the given quantities were the same as in question 2 but with the direction of  $F$  as shown above.*

## Friction

Friction is a force that opposes two objects sliding against each other, and is a contact force like the normal force. While the normal force acts perpendicular to the flat surface, friction acts in a direction along the flat surface of an object.

We generally speak of two kinds of friction: kinetic friction and static friction. We will begin our discussion of friction with kinetic friction.

## KINETIC FRICTION

“Kinetic” means moving. Kinetic friction means friction between two objects sliding against each other, such as: 1. Sliding a book across a desktop. 2. Your foot slipping on an icy pavement. The force from kinetic friction is abbreviated  $f_k$ . (Friction forces by convention use a lower case  $f$ .)

We know a force must exist on the book because it eventually stops moving. Newton’s Second Law implies there must be some force acting on the book to slow it down and eventually bring it to rest. We call this force, kinetic friction. Friction arises because no matter how smooth the surface of the book may look or feel, or the surface it is in contact with, microscopically the two surfaces are rough. The smallest unevenness of the surfaces acts to impede the motion of the book. In fact, a force must be applied to the book just to overcome this “roughness” before it can be set into motion. The force that acts on the book before it is set into motion is called the static friction force, which we will discuss after dealing with kinetic friction.

We know that kinetic friction follows three basic rules:

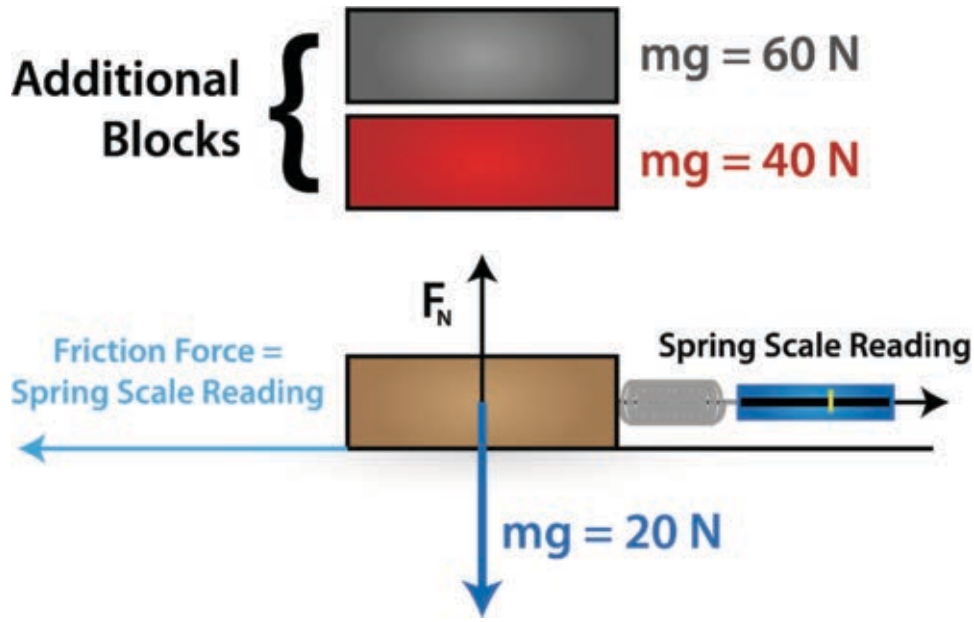
6. The frictional force is independent of the relative velocity between the two surfaces for conventional speeds.
7. The frictional force is independent of contact surface area. If you slide a book lying flat or turn it on edge, the force of friction is the same.
8. The frictional force,  $f_k$ , is directly proportional to the normal force the two objects press against each other with,  $F_N$ , and also directly proportional to the roughness or stickiness of the surface, called its coefficient of friction. We write this as  $f_k = \mu_k F_N$ , where  $\mu_k$  is the coefficient of friction. The symbol,  $\mu$ , is the Greek letter mu and pronounced “myoo” in English. The rougher or stickier the contact between two surfaces, the larger the value of  $\mu_k$ . A frictionless surface would have  $\mu_k = 0$ .

As you well know, it’s easier to push an object from one point to another than to carry it from one point to another. We usually just accept this observation as obvious. But why is this so?

The observation leads to the conclusion that the force of kinetic friction is usually less than the weight of the object to be moved. If not, why push when you could more easily lift?

The coefficients of friction,  $\mu_k$ , are measured experimentally. A typical experimental setup, which is often encountered in school physics laboratories, is to use a spring scale to pull increasing weights at a constant velocity, Figure below. Since the velocity is constant, the force that the spring scale exerts is equal to the magnitude of the kinetic friction. As the weight that is pulled increases, so too does the minimum force required to set the weight in motion. But as noted above, we would expect the force reading on the spring scale, to be smaller than the weight being pulled. The ratio of the force on the spring scale to the weight of the object is found to be constant, and is  $\mu_k$ .

The set-up:



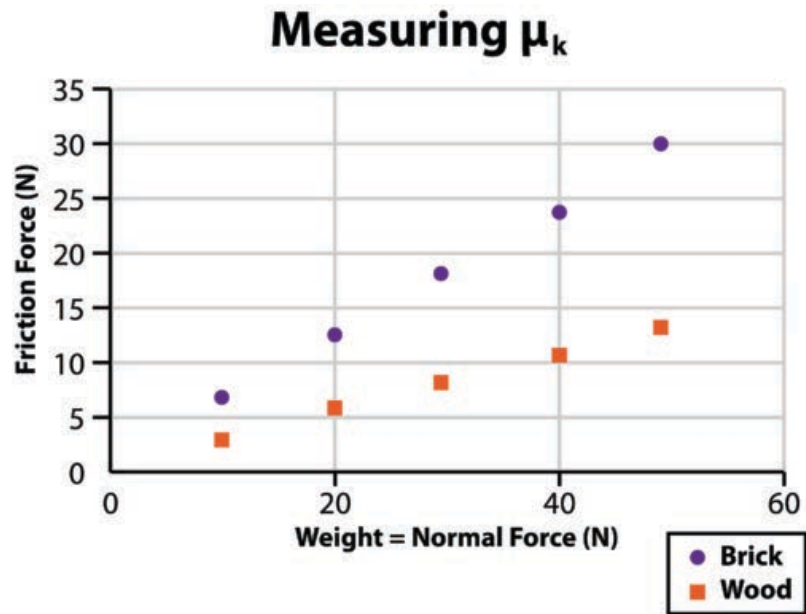
$mg = 20 \text{ N}$

Weight (N)	Spring reading = friction force (N)
20	10
40	20
60	30

If we graph kinetic friction force vs. weight, we would find a straight line with the slope of 0.5. The slope of this graph represents the coefficient of friction,  $\mu_k$ . Notice that friction is measured in newtons since it is a force. What are the units of  $\mu_k$ ?



Figure below shows two experiments measuring the coefficient of kinetic friction for brick and wood on polished oak.



#### CHECK YOUR UNDERSTANDING

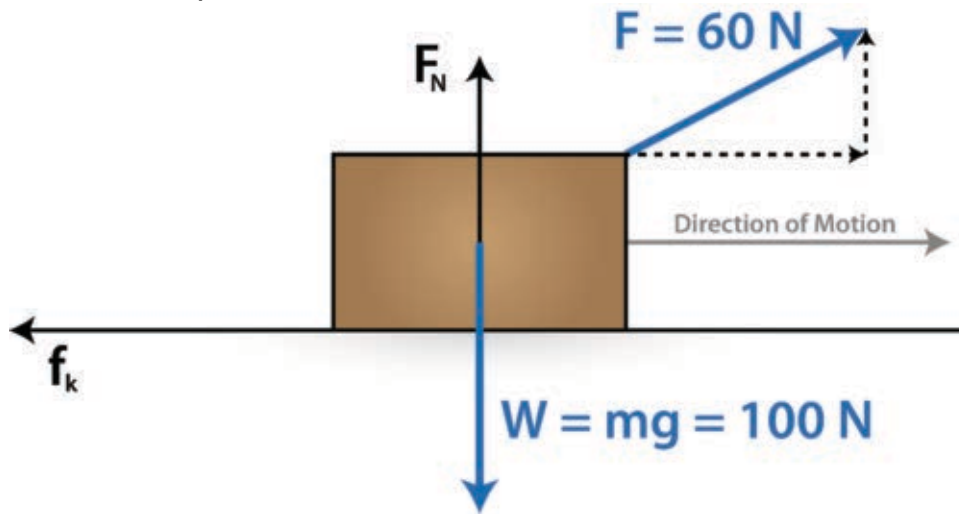
1. What are the units of  $\mu_k$ ?

Since  $\mu_k$  is defined as the ratio  $\frac{f_k}{F_N}$  it must be a “pure” number. It has no units since it is a ratio of force units: N/N which “cancel out.”

2. It is typically stated that  $\mu_k$  is less than 1 for common materials. There are exceptions, of course; sliding rubber on rubber can result in  $\mu_k > 1$ . How can  $\mu_k = 1$  be interpreted if the motion takes place along a horizontal surface?

*Answer: The force needed to slide the object is the same as the force needed to lift the object. Since  $\mu_k$  is usually found to be less than 1, it substantiates the notion that it's easier to push (or drag) an object than lift it!*

Illustrative Example 1



In Figure above a force  $F$  of 60 N acts at an angle of 30 degrees above the horizontal upon a block of weight 100 N moving it with constant velocity.

- Draw the Free Body Diagram (FBD) for the problem.
- Determine the friction force between the block and the surface.
- Determine the normal force on the block.
- Determine the coefficient of kinetic friction,  $\mu_k$ .

Answers:

(a) See Figure above. Notice how the friction force is represented in FBDs. It is drawn as an “interface” vector.

(b) Since the block moves at constant velocity  $\sum_x F = 0$ .

Therefore  $\sum_x F = F \cos \theta - f_k = 0, 60 \cos 30^\circ = f_k; f_k = 51.96 = 52 \text{ N}$

(c) We assume the block has no vertical motion therefore,  $\sum_y F = 0$

$\sum_y F = F_N + F \sin \theta - mg = 0; F_N = mg - F \sin \theta = 100 - 60 \sin 30^\circ = 70 \text{ N}$

(d) Since  $f_k = \mu_k F_N; \mu_k = \frac{f_k}{F_N} = \frac{52}{70} = 0.74; \mu_k = 0.74$

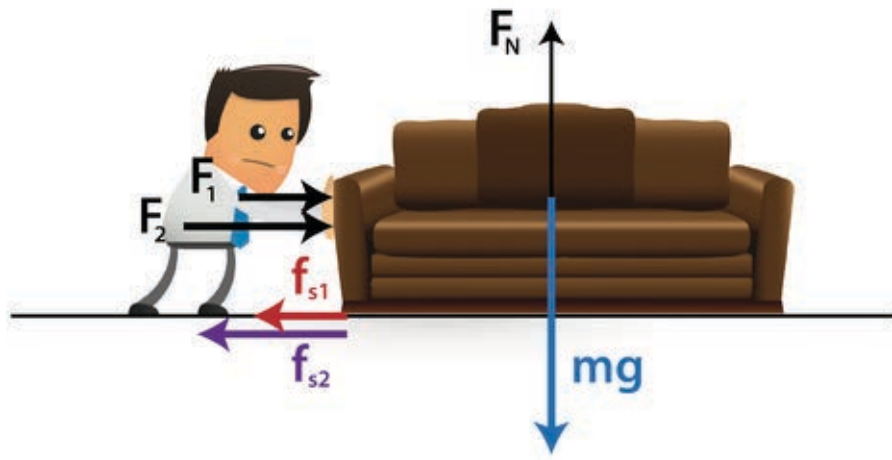
## STATIC FRICTION

The original meaning of “static” is “not moving”. Static friction,  $f_s$ , exists when the contact surfaces do not slide relative to one another. Two examples would be:

1. A coin on an inclined surface that remains stationary.
2. Exerting a force on heavy couch that refuses to move.

For a given pair of surfaces, the coefficient of static friction  $m_s$  is larger than the coefficient of kinetic friction,  $m_k$ . Put simply: There is less friction when objects are in motion. We mentioned earlier in the section that regardless of how smooth the surfaces of two objects appear, at the microscopic level they are very rough. Atoms actually interact along the irregular contact areas between the surfaces forming electrical bonds. As soon as there is relative motion between the surfaces the bonds begin to break. Heat due to friction continues to aid in breaking the bonds, making it easier to maintain motion; hence kinetic friction is smaller than static friction; and  $m_k < m_s$ .

Consider Figure below.



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The man in the figure is trying to slide a heavy couch. He exerts a force  $F_1$  that is insufficient to set the couch in motion; he then applies a greater force  $F_2$  and the couch still does not move. In each case, since a force was placed upon the couch, and it remained stationary, an equal and opposite force must have acted upon the couch ( $f_{s1}$  and  $f_{s2}$  respectively) such that the net force on the couch remained zero, and the couch remained at rest. We call this force, static friction. But unlike kinetic friction, the static friction force is not confined to one value. For example, if  $f_1$  was 100 N and  $f_2$  was 150 N in Figure above, then the static friction forces were  $f_{s1} = 100\text{N}$  and  $f_{s2} = 150\text{N}$ , respectively. In fact, the static friction force can take on any value greater than or equal to zero up to the maximum force at which the couch is set into motion. At the point the couch is set into motion, static friction is gone and kinetic friction begins. Because static friction can take on any value up to the point of motion, we define static friction using an inequality: The coefficient of static friction,  $\mu_s$ , is found by determining the maximum force,  $f_{s\text{max}}$ , just before the instant an object is set into motion. We will generally drop the subscript on the static friction force when the context is clear.

$$f_s \leq \mu_s F_N$$

#### Illustrative Example 2

The couch in Figure above just begins to move when a force of 175 N is applied to it.

- What is the maximum static friction force,  $f_s$ , between the couch and the floor?
- What is the coefficient of static friction,  $\mu_s$ , if the couch weighs 1000 N?

Solutions:

(a) Since the maximum force applied before the couch moves is 175 N this must be the maximum static friction;  $f_s = 175\text{ N}$

(b)  $\mu_s = \frac{f_s}{F_N} = \frac{175\text{N}}{1000\text{N}} = 0.175$

Notice that the coefficient of static friction,  $\mu_s$ , is a pure number (it has no units) just as the coefficient of kinetic friction,  $\mu_k$ . This is because the coefficient of static friction,  $\mu_s$ , depends upon the nature of the materials in contact and it is a ratio of two forces, as is the coefficient of kinetic friction,  $\mu_k$ .

### Kinetic and Static Friction Oppose Motion

Friction acts to oppose the motion caused by an applied force; thus opposing the relative motion between two surfaces. If you attempt to accelerate your car and there is insufficient static friction between the tires and the road (say, you're on ice), the tires would spin and the car would gain no additional speed. Kinetic friction would oppose the motion of the tires, even on ice, and you'd "burn rubber." However, during those moments when your tires made contact with the asphalt static friction would oppose the applied force your tires put upon the road and send the car forward. At the area of contact between the tire and the road, the tire pushes back on the pavement and the pavement pushes on the tire in the forward direction (Newton's 3rd law in action!) The force of static friction is responsible for pushing the car forward. The force of static friction opposes the motion of the tire relative to the road but has the same direction as the velocity of the car.

## CHECK YOUR UNDERSTANDING

1. How does the magnitude of the force of friction change as the angle of from the horizontal increases?

*Answer: As the angle increases, the normal force decreases so the friction force must also decrease. If the normal force goes to zero, so does the friction force.*



<http://www.flickr.com/photos/aaronschmidt/3296165247/>

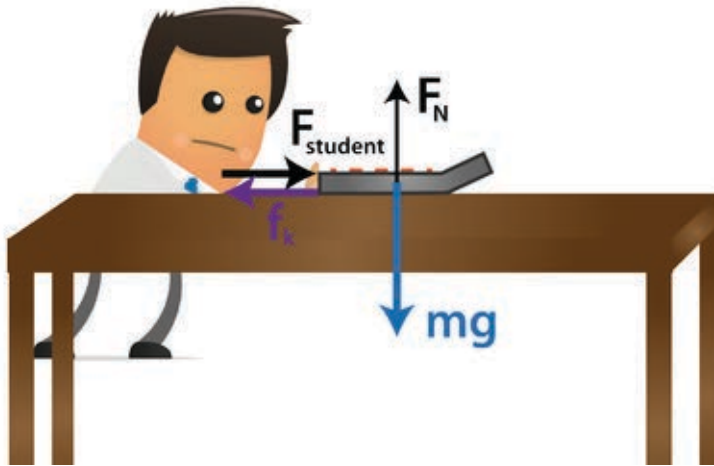
2. If the man in the picture were taller, and he applied a force of the same magnitude to the weight, how would the normal force on the weight change?

*Answer: The taller he is, the more vertical is the force, so the normal force would decrease.*

3. A student pushes a calculator along a table with a horizontal force of 1 N but the calculator remains motionless.

(a) What is the magnitude of the static friction force on the calculator?

(b) Can the static friction force ever be smaller or larger than 1 N?



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<http://bit.ly/1hZnux2>

Answers:

2a. Since the calculator remains stationary, the force of static friction and the force that the student exerts must be equal and opposite.

2b. The static force can easily be smaller. Any force less than 1 N that the student exerts upon the calculator will be equal and opposite to the static friction force. The static friction can take on an infinite number of values below the threshold force that sets the calculator in motion. The static friction force may possibly be larger than 1 N if the student applies a bit more force and the calculator remains motionless. The force at which the calculator just begins to move is the maximum force that static friction can provide.







**GRAVITATIONAL AND ELECTRONIC FORCES****CHAPTER 3**

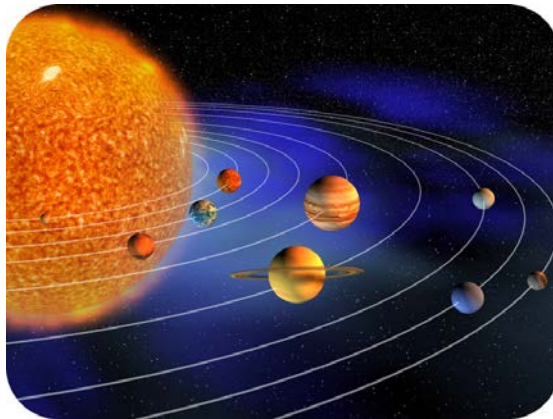
Standard 3: Students will understand the factors determining the strength of gravitational and electric forces.

**STANDARD 3, OBJECTIVE 1: RELATE THE STRENGTH OF THE GRAVITATIONAL FORCE TO THE DISTANCE BETWEEN TWO OBJECTS AND THE MASS OF THE OBJECTS (I.E., NEWTON'S LAW OF UNIVERSAL GRAVITATION).**

**SECTION 3.1: GRAVITATIONAL FORCE (NEWTON'S LAW OF UNIVERSAL GRAVITATION)**

Objective:

- Students will relate the strength of the gravitational force to the distance between two objects and the mass of the objects.



Long, long ago, when the universe was still young, an incredible force caused dust and gas particles to pull together to form the objects in our solar system. From the smallest moon to our enormous sun, this force created not only our solar system, but all the solar systems in all the galaxies of the universe. The force is gravity.

## Defining Gravity

Gravity has traditionally been defined as a force of attraction between things that have mass. According to this conception of gravity, anything that has mass, no matter how small, exerts gravity on other matter. Gravity can act between objects that are not even touching. In fact, gravity can act over very long distances. However, the farther two objects are from each other, the weaker is the force of gravity between them. Less massive objects also have less gravity than more massive objects.

## Earth's Gravity

You are already very familiar with Earth's gravity. It constantly pulls you toward the center of the planet. It prevents you and everything else on Earth from being flung out into space as the planet spins on its axis. It also pulls objects that are above the surface—from meteors to skydivers—down to the ground. Gravity between Earth and the moon and between Earth and artificial satellites keeps all these objects circling around Earth. Gravity also keeps Earth and the other planets moving around the much more massive sun.

Q: There is a force of gravity between Earth and you and also between you and all the objects around you. When you drop a paper clip, why doesn't it fall toward you instead of toward Earth?

A: *Earth is so much more massive than you that its gravitational pull on the paper clip is immensely greater.*

## Mass and Weight

In everyday usage, the mass of an object is often referred to as its weight though these are in fact different concepts and quantities. In scientific contexts, mass refers loosely to the amount of "matter" in an object (though "matter" may be difficult to define), whereas weight refers to the force experienced by an object due to gravity. Mass is considered by scientists to be more fundamental that is mass does not change from place to place in the universe. One kilogram of mass is one kilogram on the surface of the Moon, Mars, a Neutron Star or orbiting the hypothesized black hole at the center of our Milky Way Galaxy. Mass is immutable meaning it does not change from place to place. In other words, an object with a mass of 1.0 kilograms will weigh 9.8 Newtons (Newton is the unit

of force, while kilogram is the unit of mass) on Earth (its mass multiplied by the acceleration due to gravity). Its weight will be less on Mars (where gravity is weaker), more on Saturn, and negligible in space when far from any significant source of gravity, but it will always have the same mass. In order to define weight we often overlook the fact that the definition of weight requires a support force from a solid surface. The astronauts in the International Space station are weightless because the wall, ceiling, or floor do not provide support but are falling around the Earth with the astronaut. If the space station stopped moving tangentially around the Earth it would fall like a rock toward the center of the Earth. The space station is gravitationally attracted to the Earth. From: [http://en.wikipedia.org/wiki/Mass\\_versus\\_weight](http://en.wikipedia.org/wiki/Mass_versus_weight)

Weight measures the force of gravity pulling downward on an object. The SI (System International) unit for weight, like other forces, is the Newton (N). On Earth, a mass of 1 kilogram has a weight of about 10 Newtons because of the pull of Earth's gravity. On the moon, which has 1/6 the amount of gravity (due to its lower mass), the same mass would weigh 1.6 N. Weight is measured with a scale, like the spring scale shown in the figure below. The scale measures the force with which gravity pulls an object downward. To delve a little deeper into weight and gravity, watch this video:

**<https://www.khanacademy.org/science/physics/newton-gravitation/gravity-newtonian/v/mass-and-weight-clarification>**

## SUMMARY

- Gravity has traditionally been defined as a force of attraction between things that have mass. The strength of gravity between two objects depends on their mass and their distance apart.
- Earth's gravity constantly pulls matter toward the center of the planet. It also keeps the Moon and satellites orbiting Earth and Earth orbiting the sun.
- Weight measures the force of gravity pulling on an object. The SI unit for weight is the Newton (N).

The mass of an object is a measurement of the amount of matter it is made of.

## PRACTICE

At the following URL, read about gravity and tides. Watch the animation and look closely at the diagrams. Then answer the questions below.

<http://www.mmscrusaders.com/newscirocks/tides/tideanim.htm>

1. What causes tides?
2. Which has a greater influence on tides, the moon or the sun? Why?
3. Why is there a tidal bulge of water on the opposite side of Earth from the moon?
4. When are tides highest? What causes these tides to be highest?
5. When are tides lowest? What causes these tides to be lowest?

## REVIEW

6. What is the traditional definition of gravity?
7. Identify factors that influence the strength of gravity between two objects.
8. Define weight. What is the SI unit for weight?
9. Explain why an astronaut would weigh less on the moon than on Earth.

### Vocabulary

- Mass: amount of matter in an object
- Weight: another name for the force of gravity, but you need a supporting surface to measure weight.



<http://www.flickr.com/photos/wxmom/1359996991/>, CC BY-SA.

You may have heard a story about Isaac Newton coming up with the idea of gravity when an apple fell out of a tree and hit him in the head. The story isn't true, but seeing how things like apples fall to Earth helped Newton form his ideas about gravity, the force of attraction between things that have mass. Of course, people had known about the effects of gravity for thousands of years before Newton came along. After all, they constantly experienced gravity in their daily lives. They observed over and over again that things always fall toward the ground. However, it wasn't until Newton developed his law of gravity in the late 1600s that people knew gravity applies to everything in the universe that has mass.

## **NEWTON'S LAW OF UNIVERSAL GRAVITATION**

Newton was the first one to suggest that gravity is universal and affects all objects in the universe. That's why Newton's law of gravity is called the law of universal gravitation. Universal gravitation means that the force that causes an apple to fall from a tree to the ground is the same force that causes the moon to keep moving around Earth. Universal gravitation also means that while Earth exerts a pull on you, you exert a pull on Earth (remember Newton's 3<sup>rd</sup> Law). In fact, there is gravity between you and every mass around you—your desk, your book, your pen. Even tiny molecules of gas are attracted to

one another by the force of gravity. You can learn more about Newton's law of gravity and how he developed it in the video at this URL:

<http://www.guardian.co.uk/science/interactive/2012/mar/12/newton-law-gravity-audio-slideshow>

Q: Newton's law of universal gravitation had a huge impact on how people thought about the universe. A force that acts across a distance was unheard of while contact forces that push or pull on an object are easy to observe. Why do you think it was so important?

A: Newton's law was the first scientific law that applied to the entire universe. It explains the motion of objects not only on Earth but in outer space as well.

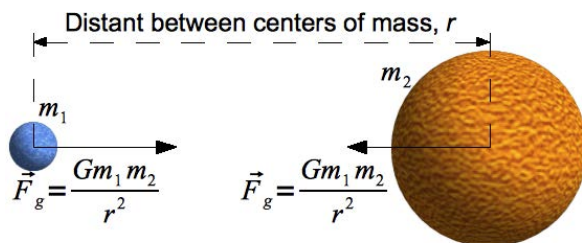
## LAW OF UNIVERSAL GRAVITATION EQUATION

### UNIVERSAL GRAVITY

Using astronomical data, Newton was able to formulate his ideas into an equation. This equation tells us the strength of the force of gravity between any two objects anywhere in the universe. Newton discovered that any two objects in the universe, with masses  $m_1$  and  $m_2$  with their centers of mass at a distance  $r$  apart will experience a force of mutual attraction along the line joining their centers of mass equal to:

$$F = G \frac{m_1 m_2}{r^2}$$

Here is an illustration of this law for two objects, for instance the earth and the sun:





### Factors that Influence the Strength of Gravity

Newton's law also states that the strength of gravity between any two objects depends on two factors: the masses of the objects and the distance between them. According to this equation, the force of gravity is directly proportional to the masses of the two objects and inversely proportional to the square of the distance between them. This means that:

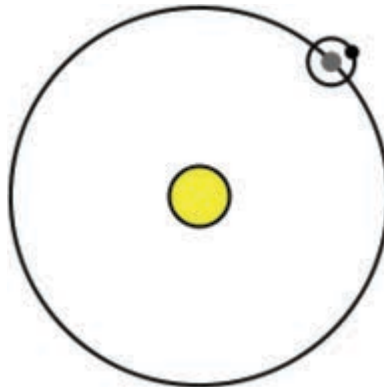
Objects with greater mass have a stronger force of gravity between them. For example, because Earth is so massive, it attracts you and your desk more strongly than you and your desk attract each other. That's why you and the desk remain in place on the floor rather than moving toward one another.

For example, if you double the mass of one of the objects, the force will also double.

If you triple the mass of one of the objects, the force will triple.

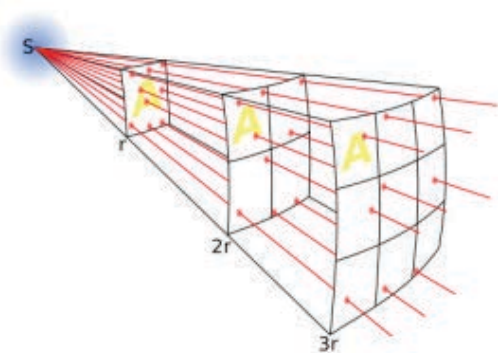
If you double the mass of one object and triple the mass of the other, the force will become six times ( $2 \times 3 = 6$ ) stronger.

Objects that are closer together have a stronger force of gravity between them. For example, the moon is closer to Earth than it is to the more massive sun, so the force of gravity is greater between the moon and Earth than between the moon and the sun. That's why the moon circles around Earth rather than the sun. You can see this in the Figure below.



## Inverse Square Law

In physics, an inverse-square law is any physical law stating that a specified physical quantity or intensity is inversely proportional to the square of the distance from the source of that physical quantity. As an example, let's look at an image which shows how the intensity of light decreases according to the inverse square law.

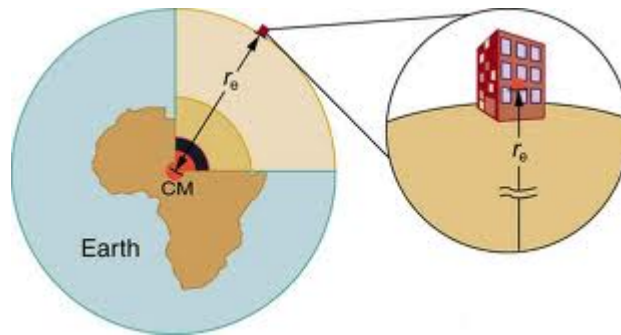


Because the light spreads out over an area, every time we double the distance, the light intensity decreases by  $\frac{1}{4}$ . If we triple the distance, the light intensity will decrease by  $\frac{1}{9}$ . Both the law of Universal Gravitation and the Coulomb's Law (discussed in the next section) obey the inverse square law for distance. See if you can fill in the missing values in the table below.

Distance	Inverse	Inverse Square
1(D)	1/1	1(F)
2(D)	$\frac{1}{2}$	$\frac{1}{4}$ (F)
$\frac{1}{2}$ (D)	2	4(F)
3(D)		___(F)
$\frac{1}{4}$ (D)		____(F)
___(D)	$\frac{5}{6}$	____(F)
___(D)	$\frac{8}{7}$	____(F)
___(D)	$\frac{9}{10}$	____(F)
___(D)		$\frac{4}{9}$ (F)
___(D)		$\frac{49}{16}$ (F)
___(D)		0.36(F)

## GRAVITY ON THE EARTH'S SURFACE

On the surface of a planet—such as earth—the  $r$  in formula is very close to the radius of the planet, since a planet's center of mass is—usually—at its center. It also does not vary by much: for instance, the earth's radius is about 6,000,000 m. Even the height of Mt. Everest is only 8,800 m, so we can say that for objects near the surface of the earth, the  $r$  in formula is constant and equal to the earth's radius. This allows us to say that gravity is more or less constant on the surface of the earth. Here's an illustration:



<http://cnx.org/content/m42143/latest/>

For any object near the surface of the earth, the force of gravity may be expressed as:

$$F_G = G \frac{m_{Earth} m_{Object}}{r^2}$$

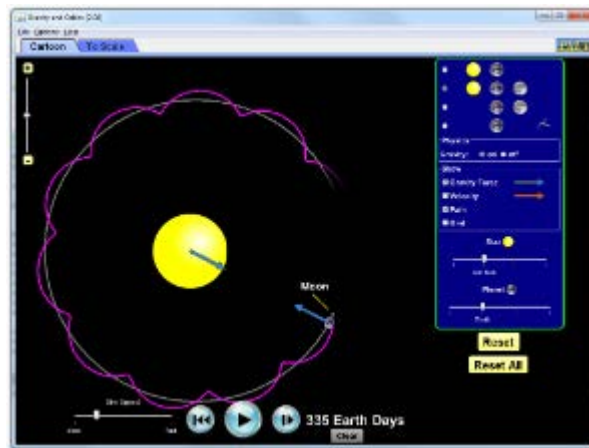
$$F_G = G \frac{m_{Earth} m_{Object}}{r^2} = m_{object} g$$

$$g_{Earth} = G \frac{m_{Earth}}{r^2}$$

In fact, an object's weight is the magnitude of the gravitational force on it. To find the weight of an object on another planet, star, or moon, use the appropriate values in the formula for the force of gravity.

# SIMULATION

Gravity and Orbits (PhET Simulation)  
[http://phet.colorado.edu/sims/gravity-and-orbits/gravity-and-orbits\\_en.jnlp](http://phet.colorado.edu/sims/gravity-and-orbits/gravity-and-orbits_en.jnlp)



## Key Equations

$F_G = \frac{Gm_1m_2}{r^2}$ ; the force of gravity between an object with mass  $m_1$  and another object of mass  $m_2$  and a distance between them of  $r$ .

$G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$ ; the universal constant of gravity  
 $g = \frac{Gm}{r^2}$ ; gravitational field strength or gravitational acceleration of a planet with mass  $m$  and radius  $r$ . Note that this is not really a separate equation but comes from Newton's second law and the law of universal gravitation.

Some data needed for the problems:

- The radius of the Earth is  $6.4 \times 10^6 \text{ m}$
- The mass of the Earth is about  $6.0 \times 10^{24} \text{ kg}$
- The mass of the Sun is about  $2.0 \times 10^{30} \text{ kg}$
- The Earth-Sun distance is about  $1.5 \times 10^{11} \text{ m}$
- The Earth-Moon distance is about  $3.8 \times 10^8 \text{ m}$

## Guidance

When using the Universal Law of Gravity formula and the constant  $G$  above, make sure to use units of meters and kilograms.

The direction of the force of gravity is in a straight line between two objects. It is always attractive.

Newton invented calculus in order to prove that for a spherical object (like Earth) one can assume all of its mass is at the center of the sphere (thus in his formula, one can use the radius of Earth for the distance between a falling rock and Earth).

Newton's Laws apply to all forces; but when he developed them only one was known: gravity. Newton's major insight—and one of the greatest in the history of science—was that the same force that causes objects to fall when released is also responsible for keeping the planets in orbit.

EXAMPLE 1: Determine the force of attraction between a 15.0 kg box and a 63.0 kg person if they are 3.45 m apart.

Assume that the distance I have been given is the distance between the two centers of the objects.

$$F_g = \frac{Gm_1m_2}{r^2} = \frac{6.67 \times 10^{-11} (15.0 \text{ kg})(63.0 \text{ kg})}{(3.45 \text{ m})^2}$$

$$F_g = 5.30 \times 10^{-9} \text{ N}$$

EXAMPLE 2: Determine the force of attraction between the sun and the Earth.

$$F_g = \frac{G m_1 m_2}{r^2} = \frac{6.67 \times 10^{-11} (2.0 \times 10^{30})(6.0 \times 10^{24})}{(1.5 \times 10^{11})^2} = 3.6 \times 10^{22} \text{ N}$$

## SUMMARY

- Newton's law of universal gravitation states that the force of gravity affects everything with mass in the universe.
- Newton's law also states that the strength of gravity between any two objects depends on the masses of the objects and the distance between them.

## PRACTICE

Watch the short video about Newton's law of gravity at the following URL, and then answer the questions below.

<http://www.youtube.com/watch?v=Jk5E-CrE1zg>

1. What equation did Newton use to represent the force of gravity between two objects? What does each letter in the equation stand for? Which letter stands for a value that never changes?
2. Based on the equation, how does the force of gravity between two objects change when the mass of one of the objects doubles?
3. If the distance between the two objects doubles, how does this affect the force of gravity between them?
4. If you double one mass and quadruple the other mass, how does that affect the force of gravity between 2 objects?
5. If you double one mass, AND triple the distance between the two masses, how does that affect the force between the two objects?
6. What is Newton's law of universal gravitation?
7. Describe the relationship between the masses of two objects and the force of gravity between them.

Prove  $g$  is approximately  $10 \text{ m/s}^2$  on Earth by following these steps:

8. Calculate the force of gravity between a falling object (for example an apple) and that of Earth. Use the symbol  $m_o$  to represent the mass of the falling object.
9. Now divide that force by the object's mass to find the acceleration  $g$  of the object.

### Vocabulary

- Gravitational Force: the force of attraction between all masses in the universe
- law of universal gravitation: Law stating that gravity is a force of attraction between all objects in the universe and that the strength of gravity is greater when masses of objects are greater or distances between objects are shorter.

## REVIEW

10. Which is greater – the gravitational force that the Sun exerts on the moon, or the force the Earth exerts on the moon?
11. Does the moon orbit the Earth or the Sun? Explain
12. Use Newton's Law of Universal Gravitation to explain why even though Jupiter has 300 times the mass of the earth, on the "surface" of Jupiter you'd weigh only 3 times what you weigh on earth. What other factor has to be considered here?
13. How does the gravitational force change when one mass is doubled and the distance between the masses is doubled?
14. How does the gravitational force change when both masses are doubled and the distance between the masses is tripled?
15. Graph the gravitational force vs distance squared from the given chart.

<u>Force</u>	<u>distance</u>
<u>1N</u>	<u>1m</u>
<u>4N</u>	<u>5m</u>
<u>2N</u>	<u>7m</u>
<u>0.7N</u>	<u>12m</u>

Why do some charges attract and some charges repel?

**STANDARD 3, OBJECTIVE 2: DESCRIBE THE FACTORS THAT AFFECT THE ELECTRIC FORCE (I.E., COULOMB'S LAW).**

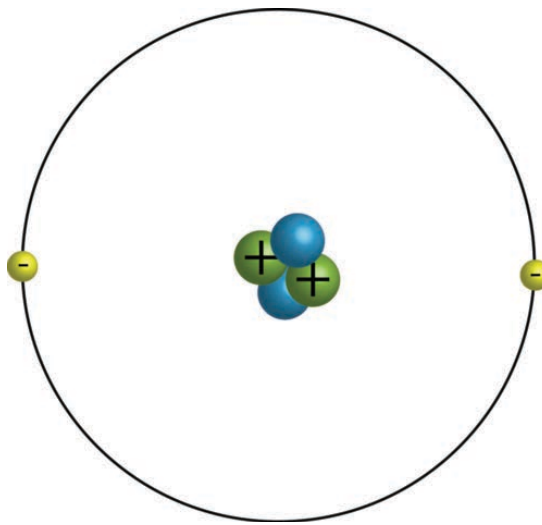


A lightning bolt is like the spark that gives you a shock when you touch a metal doorknob. Of course, the lightning bolt is on a *much* larger scale. But both the lightning bolt and spark are a sudden transfer of electric charge.



### Introducing Electric Charge

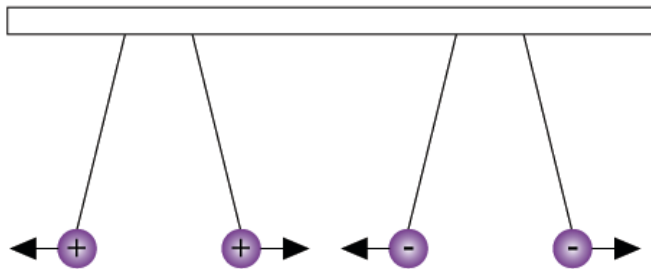
Electric charge is a physical property of particles or objects that causes them to attract or repel each other without touching. All electric charge is based on the protons and electrons in atoms. A proton has a positive electric charge, and an electron has a negative electric charge. In the Figure [below](#), you can see that positively charged protons (+) are located in the nucleus of the atom, while negatively charged electrons (-) move around the nucleus.



### Electric Force

When it comes to electric charges, opposites attract, so positive and negative particles attract each other. You can see this in the diagram below. This attraction explains why negative electrons keep moving around the positive nucleus of the atom. Like charges, on the other hand, repel each other, so two positive or two negative charges push apart. This is also shown in the diagram. The attraction or repulsion between charged particles is called electric force. The strength of electric force depends on the amount of electric charge on the particles and the distance between them. Larger charges or shorter distances result in greater force. You can experiment with electric force with the animation at the following URL.

**[http://www.colorado.edu/physics/2000/waves\\_particles/wavpart2.html](http://www.colorado.edu/physics/2000/waves_particles/wavpart2.html)**



Q: How do positive protons stay close together inside the nucleus of the atom if like charges repel each other?

A: Other, stronger forces in the nucleus hold the protons together.

## SUMMARY

Electric charge is a physical property of particles or objects that causes them to attract or repel each other without touching.

Particles that have opposite charges attract each other. Particles that have like charges repel each other. The force of attraction or repulsion is called electric force.

## PRACTICE

Read the first four boxes of text at the following URL. Then write a concise paragraph explaining why direction E is the correct answer to the quick

quiz. <http://www.physics.wisc.edu/undergrads/courses/208-f07/Lectures/lect6.pdf>

## REVIEW

1. What is electric charge?
2. Make a simple table summarizing electric forces between charged particles.

### Vocabulary

- electric charge: Physical property of particles or objects that causes them to attract or repel each other without touching; may be positive or negative.
- electric force: Force of attraction or repulsion between charged particles.

Students will learn the inner workings of electrostatics: Why certain objects repulse, why certain objects attract and how to calculate the number of excess electrons or protons in an object.

## SIMULATION

**Balloons (PhET Simulation)**  
<http://phet.colorado.edu/en/simulation/balloons>



### Key Equations

$q = Ne$  Any object's charge is an integer multiple of an electron's charge.

$q$  = total charge on an object, measured in units of Coulombs

$n$  = number of extra or missing electrons

$e$  = fundamental charge unit,  $1.6 \times 10^{-19} \text{ C}$

### Guidance

Opposite charges attract and like charges repel.

The charge of an electron( $e$ ) and proton is  $1.6 \times 10^{-19} \text{ C}$ . This is called the fundamental charge unit. One can determine the number of excess electrons (or protons if positive charge) by dividing the object's charge by the fundamental charge.

Most objects are electrically neutral (equal numbers of electrons and protons). This enables gravitational force to dominate on a macro scale.

### EXAMPLE 1

Question If an object has  $+0.003 \text{ C}$  of charge, how many excess protons does the object have?

Answer:  $N = 1.875 \times 10^{16}$  protons

Answer:  $q = ne$   $0.003 \text{ C} = n(-1.6 \times 10^{-19} \text{ C})$   $n = 1.875 \times 10^{16}$  protons

## TIME FOR PRACTICE

After sliding your feet across the rug, you touch the sink faucet and get shocked. Explain what is happening.

What is the net charge of the universe? Of your toaster?

As you slide your feet along the carpet, you pick up a net charge of  $+4 \text{ mC}$ . Which of the following is true?

You have an excess of  $2.5 \times 10^{16}$  electrons

You have an excess of  $2.5 \times 10^{19}$  electrons

You have an excess of  $2.5 \times 10^{16}$  protons

You have an excess of  $2.5 \times 10^{19}$  protons

You rub a glass rod with a piece of fur. If the rod now has a charge of  $-0.6 \mu\text{C}$ , how many electrons have been added to the rod?

$3.75 \times 10^{18}$

$3.75 \times 10^{12}$

6000

$6.00 \times 10^{12}$

## BIG PICTURE

### Electrostatics

All objects have positive and negative charges inside them. If the number of positive and negative charges are equal, as they most often are, then the object is neutral. Charged objects are objects with more positive charges than negative ones, or vice versa. Opposite charges attract, and similar charges repel. Electric fields are created by a net charge and point away from positive charges and towards negative charges. Many macroscopic forces can be attributed to the electrostatic forces between molecules and atoms.



Charles-Augustin de Coulomb  
(1736-1806)

### Key Terms

**Charge:** Charge is carried by protons and electrons. Charge is always conserved in a closed system. SI unit: C

**Coulomb's Law:** Coulomb's law states that the force between two charges is proportional to the value of the two charges and inversely proportional to the square of the distance between them.

### Coulomb's Law

There are two types of charge: positive and negative.

- Electrons have negative charge.
- Protons have positive charge.
- Magnitude of the charge is the same for electrons and protons:  $e = 1.6 \times 10^{-19} \text{ C}$
- Coulomb's law is used to calculate the force between two charged particles: where  $k$  is a constant,  $q$  is the charge, and  $r$  is the distance between the charged particles.

The force can be attractive or repulsive depending on the charges:

- Like charges (charges with the same sign) repel
- Charges with opposite signs attract

## Guidance

The Coulomb Force Law states that any two charged particles ( $q_1, q_2$ ) --- with charge measured in units of Coulombs --- at a distance  $r$  from each other will experience a force of repulsion or attraction along the line joining them equal to:

$$F = k \frac{q_1 q_2}{r^2}$$

This looks a lot like the Law of Universal Gravitation, which deals with attraction between objects with mass. It depends on the product of the two charges and obeys the inverse square law for distance.

For example, if you double the charge on one of the objects, the force will also double. If you triple the charge on one of the objects, the force will triple.

If you double the charge on one object and triple the charge on the other, the force will become six times ( $2 \times 3 = 6$ ) stronger.

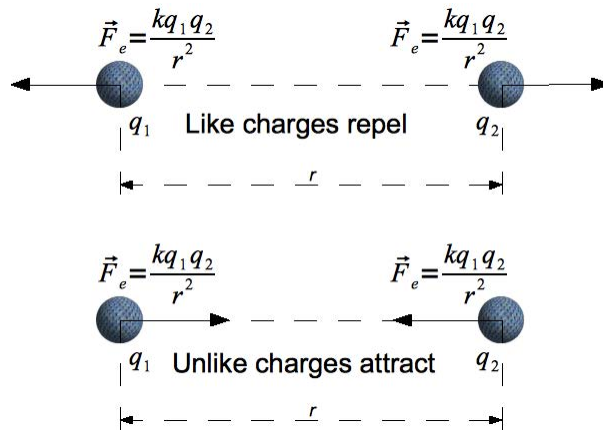
If we double the distance, the force decreases by  $1/4$ . If we triple the distance, the force will decrease by  $1/9$ .

Q: What do you think would happen if the distance between the charges was cut in half?

A: The inverse of  $1/2$  is  $2/1=2$ . The inverse SQUARE is  $2^2=4$ . The force would become four times stronger.

### WHAT'S THE DIFFERENCE?

The big difference is that while any two masses experience mutual *attraction*, two charges can either attract or repel each other, depending on whether the signs of their charges are alike:



- The sign of the force can tell you whether the two particles attract or repel.
- If the force between two charged particles is positive, then we can say the force is repulsive.
- For example, if the two charges are both positive, say +2 C and +3 C, the product of the charges will be positive.
- If the two charges are both negative, say -2 C and -3 C, the product of the charges will be also be positive.
- If the force between two charged particles is negative, then we can say the force is attractive.
- For example, if one charge is positive and the other is negative, say +2 C and -3 C, the product of the charges will be negative.

Like gravitational (and all other) forces, Coulomb forces add as vectors. Thus to find the force on a charge from an arrangement of charges, one needs to find the vector sum of the force from each charge in the arrangement.

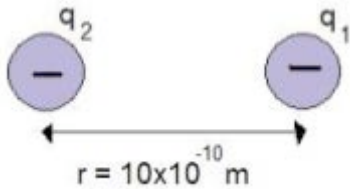
### Sample calculations

taken from <https://share.ehs.uen.org/node/9191>

#### EXAMPLE 1

An electron is located  $1.00 \times 10^{-10}$  m to the right of another electron. What is the force on the first electron from the second electron,  $F_{e1}$ ? What is the force on the second electron from the first electron,  $F_{e2}$ ? What if these are protons instead?

It is useful to draw a picture just to visualize the problem. The first electron is  $1.00 \times 10^{-10}$  m to the right of the second electron, so the appropriate drawing is:



We want to first find the force on  $q_1$  from  $q_2$ .

To solve this problem, we need to use Coulomb's Law and merely substitute in the appropriate values. The magnitude of Coulomb's law is:

$$F_e = \frac{k_e q_1 q_2}{r^2}$$

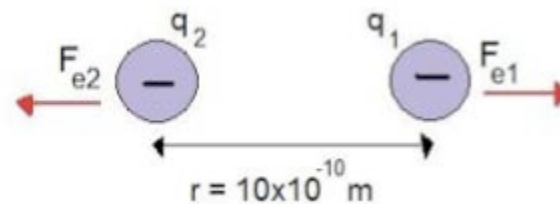
We know that  $k_e = 8.99 \times 10^9 \text{ Nm}^2/\text{C}^2$ ,  $r$  is given in the problem as  $1.00 \times 10^{-10}$  m. You probably don't recall, but we previously learned that the charge of an electron is  $e^- = -1.602 \times 10^{-19}$  C. So plugging these in we get:

$$F_e = \frac{k_e (e^-)^2}{r^2} = \frac{\left(8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}\right) (-1.602 \times 10^{-19} \text{ C})^2}{(1.00 \times 10^{-10} \text{ m})^2} = 2.31 \times 10^{-8} \text{ N}$$



This gives us the magnitude of the force. The sign of our answer, positive, tells us that the force is repulsive. So, the force on  $q_1$  is directed away from  $q_2$ , or to the right. Finally, our answer is:

$$F_{e1} = 2.31 \times 10^{-8} \text{ N to the right}$$



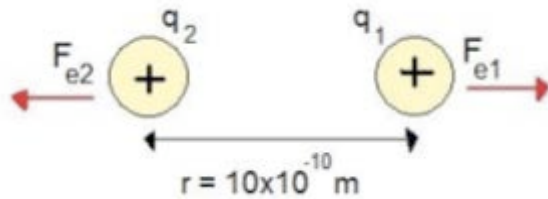
The force on  $q_2$  is equal and opposite (remember Newton's third law?). Therefore

$$F_{e2} = 2.31 \times 10^{-8} \text{ N to the left}$$

Now consider the question, “What if these are protons instead?”

Most of the numbers are the same. The only difference is that the charge of a proton is  $e^+ = 1.602 \times 10^{-19} \text{ Nm}^2/\text{C}^2$ . So, plugging these in gives us

$$F_e = \frac{k_e (e^+)^2}{r^2} = \frac{\left(8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}\right) (1.602 \times 10^{-19} \text{ C})^2}{(1.00 \times 10^{-10} \text{ m})^2} = 2.31 \times 10^{-8} \text{ N}$$



Which is again a positive number. So the force is repulsive, and will be directed away from the other proton. Or

Notice that the answer is the same, although the charges are different.

$$F_{e1} = 2.31 \times 10^{-8} \text{ N to the right}$$

$$F_{e2} = 2.31 \times 10^{-8} \text{ N to the left}$$

## PRACTICE

1. What equation did Coulomb use to represent the force of electrical attraction or repulsion between two objects? What does each letter in the equation stand for? Which letter stands for a value that never changes?
2. Based on the equation, how does the electrical force between two objects change when the mass of one of the objects doubles?
3. If the distance between the two objects is tripled, how does this affect the overall strength of the electric force between them?
4. If you triple one charge and quadruple the other charge, how does that affect the strength of the electric force between 2 objects?
5. The force between two charged particles is + 50 Newtons. What could the signs of the charges be on each object? Is the electric force attractive or repulsive? How do you know?
6. List the similarities and differences between Coulomb's law and Newton's law of gravitation.
7. State Coulomb's law. Explain what each symbol in it stands for, and use it to find the force between a 0.002-C charge and a 0.006-C charge that are 10 meters apart. ( $k = 9 \times 10^9 \text{ Nm}^2/\text{C}^2$ )

## EXAMPLES OF ELECTROSTATICS IN REAL LIFE

### The Van de Graaff Generator



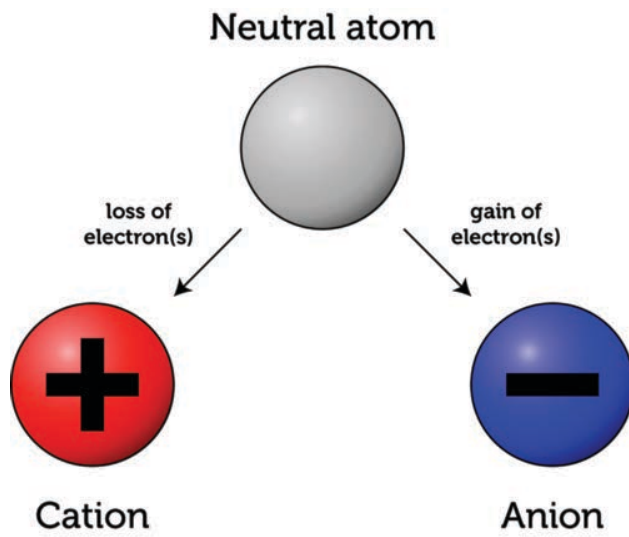
What explains this shocking photo? The man in the picture is touching a device called a van de Graaff generator. The dome on top of the device has a negative electric charge. When the man places his hand on the dome, he becomes negatively charged as well—right down to the tip of each hair! You can see a video demonstrating a van de Graff generator at this URL:<http://www.youtube.com/watch?v=SREXQWAIJk>

Q: Why is the man's hair standing on end?

*A: All of the hairs have all become negatively charged, and like charges repel each other. Therefore, the hairs are pushing away from each other, causing them to stand on end.*

## Transferring Electrons

The man pictured above became negatively charged because electrons flowed from the van de Graaff generator to him. Whenever electrons are transferred between objects, neutral matter becomes charged. This occurs even with individual atoms. Atoms are neutral in electric charge because they have the same number of negative electrons as positive protons. However, if atoms lose or gain electrons, they become charged particles called ions. You can see how this happens in the Figure [below](#). When an atom loses electrons, it becomes a positively charged ion.. When an atom gains electrons, it becomes a negative charged ion.



## Conservation of Charge

Like the formation of ions, the formation of charged matter in general depends on the transfer of electrons, either between two materials or within a material. Three ways this can occur are referred to as conduction, polarization, and friction. All three ways are described below. However, regardless of how electrons are transferred, the total charge always remains the same. Electrons move, but they aren't destroyed. This is the law of conservation of charge.

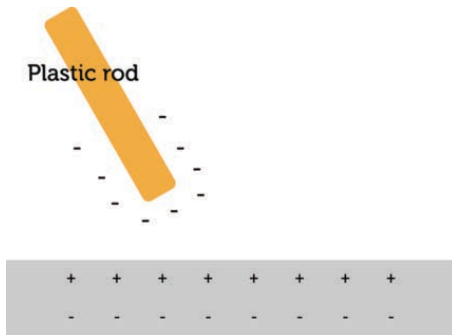
## Conduction

The transfer of electrons from the van de Graaff generator to the man is an example of conduction. Conduction occurs when there is direct contact between materials that differ in their ability to give up or accept electrons. A van de Graff generator produces a negative charge on its dome, so it tends to give up electrons. Human hands are positively charged, so they tend to accept electrons. Therefore, electrons flow from the dome to the man's hand when they are in contact.

You don't need a van de Graaff generator for conduction to take place. It may occur when you walk across a wool carpet in rubber-soled shoes. Wool tends to give up electrons and rubber tends to accept them. Therefore, the carpet transfers electrons to your shoes each time you put down your foot. The transfer of electrons results in you becoming negatively charged and the carpet becoming positively charged.

## Polarization

Assume that you have walked across a wool carpet in rubber-soled shoes and become negatively charged. If you then reach out to touch a metal doorknob, electrons in the neutral metal will be repelled and move away from your hand before you even touch the knob. In this way, one end of the doorknob becomes positively charged and the other end becomes negatively charged. This is called polarization. Polarization occurs whenever electrons within a neutral object move because of the electric field of a nearby charged object. It occurs without direct contact between the two objects. The Figure opposite models how polarization occurs.



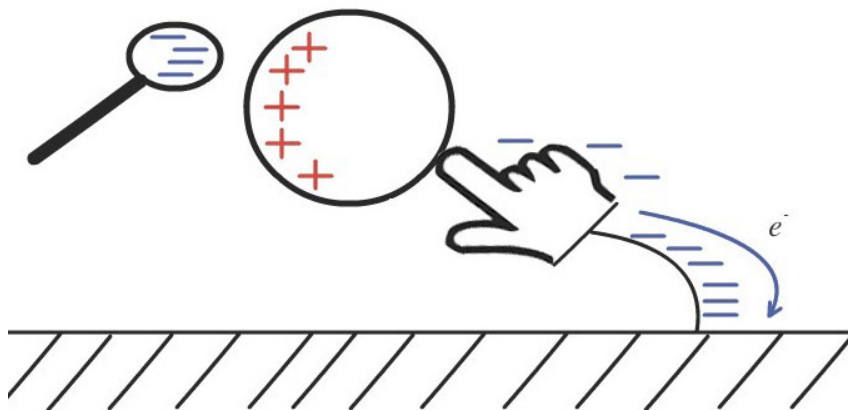
Q: What happens when the negatively charged plastic rod in the diagram is placed close to the neutral metal plate?

A: Electrons in the plate are repelled by the positive charges in the rod. The electrons move away from the rod, causing one side of the plate to become positively charged and the other side to become negatively charged.

Charging by induction is when we charge an object without touching it. There are many methods for charging objects by induction, but here is one process for charging a single object by induction.

1. First touch one finger to the neutral object to ground the object.
2. Then, bring a charged object (we'll assume it's negatively charged, but it can be either) close to the neutral object. This causes negative charges in the neutral object to be repelled through your body to the ground.
3. When the finger is removed, the neutral object will be positively charged. When charging by induction, the originally neutral object will always end up with the opposite charge.

Below is a diagram illustrating this process. When charge moves, electrons are always the ones that move. Protons cannot move between atoms.



### Friction

Did you ever rub an inflated balloon against your hair? Friction between the balloon and hair cause electrons from the hair to “rub off” on the balloon. That’s because a balloon attracts electrons more strongly than hair does. After the transfer of electrons, the balloon becomes negatively charged and the hair becomes positively charged. The individual hairs push away from each other and stand on end because like charges repel each other. The balloon and the hair attract each other because opposite charges attract.

Electrons are transferred in this way whenever there is friction between materials that differ in their ability to give up or accept electrons. Watch the animation “Balloons and Static Electricity” at the following URL to see how electrons are transferred by friction between a sweater and a balloon.

**[http://www.cabrillo.edu/~jmccullough/Physics/Electric\\_Forces\\_Fields.html](http://www.cabrillo.edu/~jmccullough/Physics/Electric_Forces_Fields.html)**

Q: If you rub a balloon against a wall, it may stick to the wall. Explain why.

*A: Electrons are transferred from the wall to the balloon, making the balloon negatively charged and the wall positively charged. The balloon sticks to the wall because opposite charges attract.*

## SUMMARY

- Whenever electrons are transferred between objects, neutral matter becomes charged. For example, when atoms lose or gain electrons they become charged particles called ions.
- Three ways electrons can be transferred are conduction, friction, and polarization. In each case, the total charge remains the same. This is the law of conservation of charge.
- Conduction occurs when there is direct contact between materials that differ in their ability to give up or accept electrons.
- Polarization is the movement of electrons within a neutral object due to the electric field of a nearby charged object. It occurs without direct contact between the two objects.
- Electrons are transferred whenever there is friction between materials that differ in their ability to give up or accept electrons.

## REVIEW

1. How is charge transferred by a van de Graaff generator?
2. Compare and contrast the formation of cations and anions.
3. State the law of conservation of charge.
4. Explain how conduction and polarization occur, using the example of walking across a wool carpet in rubber-soled shoes and then reaching out to touch a metal doorknob.
5. Predict what will happen to the charges of a plastic comb and a piece of tissue paper if you rub the tissue paper on the comb. (*Hint* Plastic tends to accept electrons and tissue paper tends to give up electrons.)

### Vocabulary

- law of conservation of charge: Law stating that charges are not destroyed when they are transferred between two materials or within a material, so the total charge remains the same.





You're a thoughtful visitor, so you wipe your feet on the welcome mat before you reach out to touch the brass knocker on the door. Ouch! A spark suddenly jumps between your hand and the metal, and you feel an electric shock.

**Q:** Why do you think an electric shock occurs?

*A:* An electric shock occurs when there is a sudden discharge of static electricity.

### **What Is Static Electricity?**

Static electricity is a buildup of electric charges on objects. Charges build up when negative electrons are transferred from one object to another. The object that gives up electrons becomes positively charged, and the object that accepts the electrons becomes negatively charged. This can happen in several ways.

One way electric charges can build up is through friction between materials that differ in their ability to give up or accept electrons. When you wipe your rubber-soled shoes on the wool mat, for example, electrons rub off the mat onto your shoes. As a result of this transfer of electrons, positive charges build up on the mat and negative charges build up on you.

Once an object becomes electrically charged, it is likely to remain charged until it touches another object or at least comes very close to another object. That's because electric charges cannot travel easily through air, especially if the air is dry.

Q: You're more likely to get a shock in the winter when the air is very dry. Can you explain why?

A: When the air is very dry, electric charges are more likely to build up objects because they cannot travel easily through the dry air. This makes a shock more likely when you touch another object.

### Static Discharge

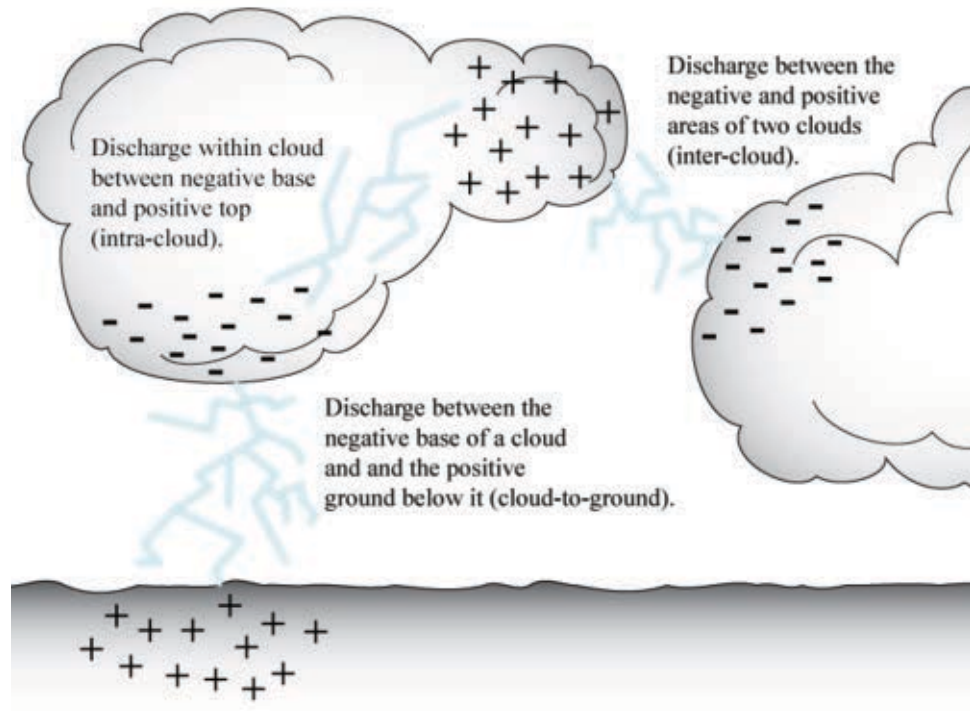
What happens when you have become negatively charged and your hand approaches the metal doorknocker? Your negatively charged hand repels electrons in the metal, so the electrons move to the other side of the knocker. This makes the side of the knocker closest to your hand positively charged. As your negatively charged hand gets very close to the positively charged side of the metal, the air between your hand and the knocker also becomes electrically charged. This allows electrons to suddenly flow from your hand to the knocker. The sudden flow of electrons is static discharge. The discharge of electrons is the spark you see and the shock you feel. Watch the animation "John Travoltage" at the following URL to see an example of static electricity and static discharge.

**[http://www.cabrillo.edu/~jmccullough/Physics/Electric\\_Forces\\_Fields.html](http://www.cabrillo.edu/~jmccullough/Physics/Electric_Forces_Fields.html)**

### How Lightning Occurs

Another example of static discharge, but on a much larger scale, is lightning. You can see how it occurs in the following diagram and animation as you read about it below.

**<http://micro.magnet.fsu.edu/electromag/java/lightning/index.html>**



During a rainstorm, clouds develop regions of positive and negative charge due to the movement of air molecules, water drops, and ice particles. The negative charges are concentrated at the base of the clouds, and the positive charges are concentrated at the top. The negative charges repel electrons on the ground beneath them, so the ground below the clouds becomes positively charged. At first, the atmosphere prevents electrons from flowing away from areas of negative charge and toward areas of positive charge. As more charges build up, however, the air between the oppositely charged areas also becomes charged. When this happens, static electricity is discharged as bolts of lightning. At the URL below, you can watch an awesome slow-motion lightning strike. Be sure to wait for the real-time lightning strike at the end of the video. You'll be amazed when you realize how much has occurred during that split-second discharge of static electricity.

**<http://www.youtube.com/watch?v=Y8oN0YFAXWQ&feature=related>**

## SUMMARY

Static electricity is a buildup of electric charges on objects. It occurs when electrons are transferred from one object to another.

A sudden flow of electrons from one charged object to another is called static discharge.

Examples of static discharge include lightning and the shock you sometimes feel when you touch another object.

## PRACTICE

Watch the video at the following URL. Then answer the discussion questions. Read the background essay if you need help with any of the questions.

**<http://www.teachersdomain.org/resource/phy03.sci.phys.mfe.zsnap/>**

1. What is static electricity?
2. How does static discharge occur?
3. Explain why a bolt of lightning is like the spark you might see when you touch a metal object and get a shock.

## VOCABULARY

Force: a push or pull; an interaction between two objects

Electric Force: attractive or repulsive interaction between any two charged objects

Electric Charge: the amount of excess electricity in a body (either positive or negative) depending whether there is a deficiency or excess of electrons

Friction: the rubbing of one body against another; while it often opposes motion, that is not always the case

Gravitational Force: the *force* of attraction between all masses in the universe

Mass: amount of matter in an object

Net Force: the overall force on an object when all the individual forces acting on the object are added together

Normal Force: support force exerted upon an object that is in contact with another stable object

static discharge: Sudden flow of electrons from an object that has a buildup of charges.

static electricity: Buildup of charges on an object that occurs through induction.

Weight: another name for the force of gravity

Vector: a quantity that has a direction and a magnitude

Vector Diagram: (also sometimes called a force diagram or free-body diagram) a sketch showing all of the forces acting on an object; used by physicists and engineers to analyze the forces acting on a body

# ENERGY

# CHAPTER 4

How is energy determined and transferred?

Standard 4: Students will understand transfer and conservation of energy.

## **STANDARD 4, OBJECTIVE 1: DETERMINE KINETIC AND POTENTIAL ENERGY IN A SYSTEM.**



Some chemistry reactions can be very calm and boring, while other reactions release a great deal of energy. Dynamite is a chemical that can explode violently. Here we see dynamite being used to move boulders to clear a path for a road. The chemical reactions involved here release tremendous amounts of energy very quickly.

Dynamite was invented by Alfred Nobel in 1866. Nitroglycerin, a very unstable explosive, was already known. Nobel mixed the nitroglycerin with silica to stabilize it and form a solid material. He made a fortune with this discovery and established the Nobel Foundation, which funds the Nobel Prizes every year.

# WHAT CHEMICAL BONDS DO YOU FIND IN ENERGY?

## ENERGY IN CHEMICAL BONDS

Chemical reactions either require energy or release energy. The amount of energy needed or released depends upon the structure of the molecules that are involved in the reaction. Some reactions need to be heated for long periods in order for change to take place. Other reactions release energy, allowing heat to be given off to the surroundings. This energy can be used in a variety of ways.

### HEATING

Coal, natural gas, oil—these materials can be burned to produce heat. The reaction with oxygen releases a great deal of energy that can warm homes and offices. Wood is another example of a chemical (yes, a very complicated one) that will release energy when burned.

### TRANSPORTATION

A major use for petroleum products is fuel for cars, trucks, airplanes, trains, and other vehicles. The chemicals used are usually a mixture of compounds containing several carbon atoms in a chain. When the material is ignited, a massive amount of gas is created almost instantaneously. This increase in volume will move the pistons in an internal combustion engine to provide power. A jet plane works on a similar principle. Air comes into the front of the engine and mixes with the jet fuel. This mixture is ignited and the gases formed create a lot of pressure to push the plane forward. The idea can be seen even more clearly in the case of a rocket launch. The ignition of the fuel (either solid-state or liquid) creates gases produced under great pressure that pushes the rocket up.





## BATTERIES

A major source of energy produced by chemical reactions involves batteries. There are many types of batteries that operate using a variety of chemical reactions. The general principle behind these reactions is the release of electrons that can then flow through a circuit, producing an electrical current.



Car battery.

Batteries are used in a wide variety of applications, such as:

- A. flashlights
- B. watches
- C. computers
- D. cars
- E. hybrid vehicles – provide some power to wheels
- F. cell phones

Batteries in cars, computers, cell phones, and other devices are usually rechargeable. An electric current is passed through the battery to provide electrons that reverse (at least partially) the chemical reactions originally used to create the electric current. However, eventually the system can no longer be recharged and the battery has to be discarded.

## HAND-WARMERS

Hikers, campers, and other outdoor folks take advantage of chemical reactions to keep their hands warm. Small containers of chemicals can undergo reaction to generate heat that can be used to avoid frostbite. Some products, such as hand-warmers, contain iron filings that will react with air to release thermal energy. These types of hand-warmers cannot be reused. Other systems rely on heat being released when certain chemicals crystallize. If the warmer containing sodium acetate is placed in very hot water after use, the system can be regenerated.

## **SUMMARY**

- Some chemical reactions release energy
- This energy can be used in a variety of ways

## **REVIEW**

1. What kind of energy is released when we burn natural gas?
2. How does burning gasoline power a car?
3. How do batteries create energy?
4. Explain how a hand-warmer works.

# FORMS OF ENERGY

## What are the forms of energy?

This rock musician's electric guitar wails at a concert, as colored lights wash over the band. It's hot on stage because of the lights, but they really add to the show. The fans are thrilled and screaming with excitement. The exciting concert wouldn't be possible without several different forms of energy. Do you know what they are?

### Forms of Energy

Energy or the ability to do work can exist in many different forms. The two main types of energy that we study are kinetic and potential energies. Kinetic energy is the energy of motion; any moving object possesses kinetic energy. An object at rest (relative to the observer) has no kinetic energy. There is only one type of kinetic energy.

Potential energy is a little more complicated. The word "potential" roughly means "ability". If you have the "potential" to get straight A's, you have the ability to get good grades. Whether you do or not depends on your work ethic, study habits, performance on tests and other factors, but the ability is there. In the same way, potential energy has the ability to do work on an object. Whether the work is actually done depends on the situation, but the ability is there.

Sometimes, potential energy is called "energy in storage" and that is a good way to think of it. Think of your bedroom—there are lots of places where you can store things: a closet, a dresser, under your bed, etc. Objects can store energy in different ways as well. What



determines the method of storage is the force acting on the object. Potential energies include (but are not limited to):

- A. Gravitational Potential Energy – When you lift something up off the ground, you are giving the object gravitational potential energy. The object now has the potential to fall. The higher the object is lifted, the more gravitational potential energy it has.
- B. Elastic Potential Energy – When you change the shape of an object, you are giving the object elastic potential energy. A rubber band is an excellent example: as you stretch the rubber band, the elastic potential energy is waiting for you to let go so it can snap the rubber band back to its original shape. The more deformed you make an object, the more elastic potential energy it will have.
- C. Chemical Potential Energy – Atoms form bonds to create molecules. The bonds contain chemical potential energy. To form stronger bonds, more chemical potential energy is needed to be stored. When those bonds are broken (for example, when you eat you are breaking the bonds in your food) that chemical potential energy is released to give you energy to live.
- D. Electrostatic Potential Energy – Remember that charges attract or repel each other. If you bring two charges next to each other, there is a potential for these charges to attract (unlike charges) or repel (like charges). This electrostatic potential energy is what provides the energy for the charges to move closer or further away from each other.
- E. Nuclear Potential Energy – In the nucleus of an atom, protons are very close together. We know that two protons will repel, so in order to stop that from happening, each nucleus contains an amount of nuclear potential energy to “bind” the protons together and keep the nucleus intact. When people talk about “splitting the atom” they are referring to the nuclear potential energy that is released in the process.

Energy can also change from one form to another. The previous photo of the guitar player represents six forms of energy: mechanical, chemical, electrical, light, thermal, and kinetic energy of air molecules (sound) energy. Another form of energy not shown in the picture is nuclear energy.

Q: Can you find the six different forms of energy in the photo of the guitar player on page 131?

## **SUPPLEMENTAL LINKS**

For an introduction to forms of energy, go to this URL:

**<http://bit.ly/1ihO05v>**

For an interactive animation about different forms of energy:

**<http://bit.ly/1ihOtVa>**

Check your knowledge of forms of energy URL:

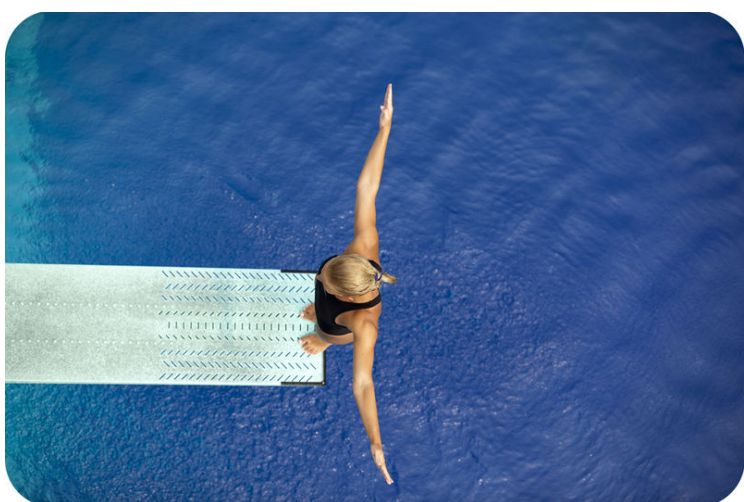
**<http://bit.ly/1bdPyZ5>**

## **REVIEW**

Make a table of forms of energy. In your table, list and define five of the forms of energy described in this article. State whether the form of energy is kinetic or potential. Include an example of each form.

## HOW IS ENERGY CONSERVED?

### STANDARD 4, OBJECTIVE 2: DESCRIBE CONSERVATION OF ENERGY IN TERMS OF SYSTEMS.



#### Potential Energy

This diver is standing at the end of the diving board, ready to dive. After she dives and is falling toward the water, she'll have kinetic energy, or the energy of moving matter. But even as she stands motionless high above the water, she has energy. Do you know why?

#### Stored Energy

The diver has energy because of her position high above the pool. The type of energy she has is called potential energy. Potential energy is energy that is stored. Often, an object has potential energy because of its position or shape.

Q: What is it about the diver's position that gives her potential energy?

## Gravitational Potential Energy

Potential energy due to the position of an object above Earth's surface is called gravitational potential energy. Like the diver on the diving board, anything that is raised up above Earth's surface has the potential to fall because of gravity. You can see an example of people with gravitational potential energy in the figure below.



Gravitational potential energy depends on an object's weight and its height above the ground. It can be calculated with the equation:

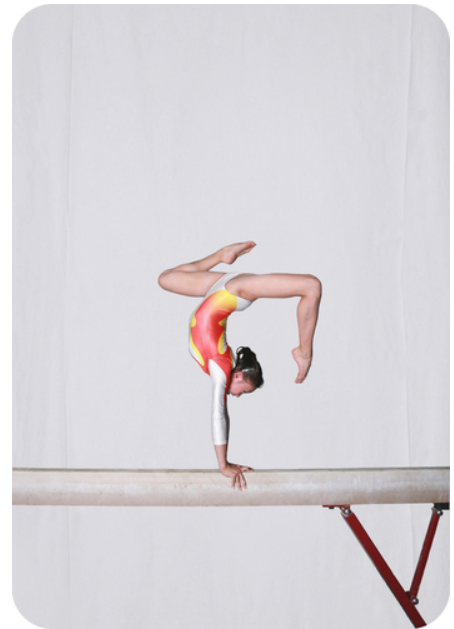
$$\text{Gravitational potential energy (GPE)} = \text{weight} \times \text{height}$$

Consider the little girl on the sled, pictured above. She weighs 140 Newtons, and the top of the hill is 4 meters higher than the bottom of the hill. As she sits at the top of the hill, the child's gravitational potential energy is:

$$\text{GPE} = 140 \text{ N} \times 4 \text{ m} = 560 \text{ N m}$$

Notice that the answer is given in Newton meters (N m), which is the SI unit for energy. A Newton meter is the energy needed to move a weight of 1 Newton over a distance of 1 meter. A Newton meter is also called a joule (J).

Q: The gymnast on the balance beam in the picture weighs 360 Newtons. If the balance beam is 1.2 meters above the ground, what is the gymnast's gravitational potential energy?



### Elastic Potential Energy

Potential energy due to an object's shape is called elastic potential energy. This energy results when an elastic object is stretched or compressed. The farther the object is stretched or compressed, the greater its potential energy is. A point will be reached when the object can't be stretched or compressed any more. Then it will forcefully return to its original shape.



Look at the pogo stick in the picture. Its spring has elastic potential energy when it is pressed down by the girl's weight. When it can't be compressed any more, it will spring back to its original shape. The energy it releases will push the pogo stick—and the girl—off the ground.

Q: The girl below is giving the elastic band of her slingshot potential energy by stretching it. She's holding a small stone against the stretched band. What will happen when she releases the band?

### Electrostatic Energy

Electrostatic Potential Energy is also known as electric potential energy. It results from electric charges or groups of charges that are held at a distance from each other. This results in a form of potential energy that changes with the configuration of the charges within a system. Batteries take advantage of converting chemical potential energy into electrical energy.



### Other Forms of Potential Energy

All of the examples of potential energy described above involve movement or the potential to move.

The form of energy that involves movement is called mechanical energy. Other forms of energy also involve potential energy, including chemical energy and nuclear energy. Chemical energy is stored in the bonds between the atoms of compounds. For example, food and batteries both contain chemical energy. Nuclear

energy is stored in the nuclei of atoms because of the strong forces that hold the nucleus together. Nuclei of radioactive elements such as uranium are unstable, so they break apart and release the stored energy.



## SUPPLEMENTAL LINKS

A cartoon introduction to gravitational potential energy URL:

<http://bit.ly/1iVljxX>

A pogo stick spring compresses and then returns to its original shape in this animation

<http://bit.ly/1aNHVy5>

<http://bit.ly/1fiuRxE>

## SUMMARY

- Potential energy is energy that is stored.
- Gravitational potential energy is due to the position of an object above Earth's surface. The object has the potential to fall due to gravity. Gravitational potential energy depends on an object's weight and its height above the ground ( $GPE = \text{weight} \times \text{height}$ ).
- Elastic potential energy is due to an object's shape. It results when an elastic object is stretched or compressed. The more it is stretched or compressed, the greater its elastic potential energy is.
- Chemical energy and nuclear energy are other forms of potential energy.

## REVIEW

1. What is potential energy?
2. Compare and contrast gravitational and elastic potential energy, and give an example of each.
3. The diver on the diving board in the opening picture weighs 500 Newtons. The diving board is 5 meters above the ground. What is the diver's gravitational potential energy?
4. Why does food have potential energy?

- Vocabulary
- potential energy:  
Stored energy an  
object has  
because of its  
position or shape.

## WHAT IS KINETIC ENERGY?



What could these four photos possibly have in common? Can you guess what it is? All of them show things that have kinetic energy.

### Defining Kinetic Energy

Kinetic energy is the energy of moving matter. Anything that is moving has kinetic energy—from atoms in matter to stars in outer space. Things with kinetic energy can do work. For example, the spinning saw blade in the photo above is doing the work of cutting through a piece of metal.

### Calculating Kinetic Energy

The amount of kinetic energy in a moving object depends directly on its mass and velocity. An object with greater mass or greater velocity has more kinetic energy. You can calculate the kinetic energy of a moving object with this equation:

$$\text{Kinetic Energy (KE)} = \frac{1}{2} \text{mass} * \text{velocity}^2$$

This equation shows that an increase in velocity increases kinetic energy more than an increase in mass. If mass doubles, kinetic energy doubles as well, but if velocity doubles, kinetic energy increases by a factor of four. That's because velocity is squared in the equation.

Let's consider an example. The Figure below shows Juan running on the beach with his dad. Juan has a mass of 40 kg and is running at a velocity of 1 m/s. How much kinetic energy does he have? Substitute these values for mass and velocity into the equation for kinetic energy:

$$KE = \frac{1}{2} * 40kg * (1\frac{m}{s})^2 = 20kg * \frac{m^2}{s^2} = 20N * m,$$

or **20J**

Notice that the answer is given in joules (J), or N \* m, which is the SI unit for energy. One joule is the amount of energy needed to apply a force of 1 Newton over a distance of 1 meter.



What about Juan's dad? His mass 80 kg, and he's running at the same velocity as Juan (1 m/s). Because his mass is twice as great as Juan's, his kinetic energy is twice as great:  
or **40J**

Q: What is Juan's kinetic energy if he speeds up to 2 m/s from 1 m/s?

$$KE = \frac{1}{2} * 40kg * (2\frac{m}{s})^2 = 40kg * \frac{m^2}{s^2} = 40N * m,$$

## SUMMARY

- Kinetic energy (KE) is the energy of moving matter. Anything that is moving has kinetic energy.
- The amount of kinetic energy in a moving object depends directly on its mass and velocity. It can be calculated with the equation:  $KE = \frac{1}{2}mass * velocity^2$

## VOCABULARY

kinetic energy: Energy of moving matter.

## SUPPLEMENTAL LINKS

Cartoon introduction to kinetic energy and how it is related to work

<http://bit.ly/1fupTjA>

Review kinetic energy

<http://bit.ly/1aNluYx>

## REVIEW

1. What is kinetic energy?
2. The kinetic energy of a moving object depends on its mass and its
  - a) volume.
  - b) velocity.
  - c) distance.
  - d) acceleration.
3. The bowling ball is whizzing down the bowling lane at 4 m/s. If the mass of the bowling ball is 7 kg, what is its kinetic energy?



# CONSERVATION OF ENERGY

Students will learn how to apply energy conservation in a closed system.

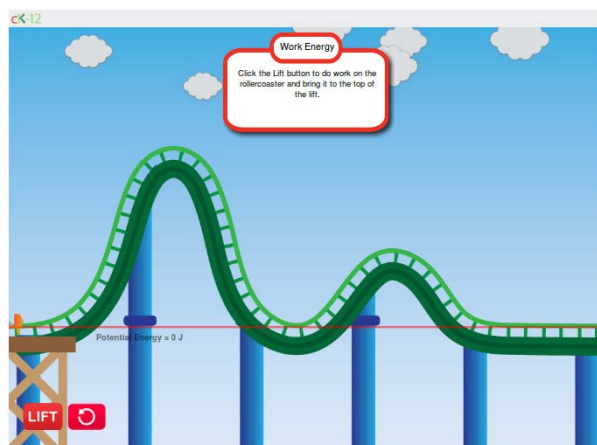
## Key Equations

$\sum E_{\text{initial}} = \sum E_{\text{final}}$  The total energy does not change in closed systems

Energy is conserved in a closed system. That is, if you add up all the energy of an object(s) at one time it will equal all the energy of said object(s) at a later time. A closed system is a system where no energy is transferred in or out. The total energy of the universe is a constant (i.e. it does not change). The problems below do not consider the situation of energy transfer (called work). So friction and other sources where energy leaves the system are not present. Thus, one simply adds up all the potential energy and kinetic energy before and sets it equal to the addition of the total potential energy and kinetic energy after.

## SIMULATION

Watch this Explanation  
Energy Skate Park (PhET Simulation)



<http://simulations.ck12.org/Rollercoaster/>



# **STANDARD 4, OBJECTIVE 3: DESCRIBE COMMON ENERGY TRANSFORMATIONS AND THE EFFECT ON AVAILABILITY OF ENERGY.**

## **ENERGY TRANSFORMATIONS**

### **Changing Energy**

Watching movies, eating hot popcorn, and many other activities depend on electrical energy. Most electrical energy comes from the burning of fossil fuels, which contain stored chemical energy. When fossil fuels are burned, the chemical energy changes to thermal energy and the thermal energy is then used to generate electrical energy. These are all examples of energy conversion. Energy conversion is the process in which one kind of energy changes into another kind. When energy changes in this way, the energy isn't used up or lost. The same amount of energy exists after the conversion as before. Energy conversion obeys the law of conservation of energy, which states that energy cannot be created or destroyed.

### **How Energy Changes Form**

Energy, whether classified as kinetic or potential, can change into any other form of either type. Frequently the energy changes into two or more different forms. For example, the popcorn machine changes electrical energy into thermal energy. The thermal energy in turn changes to both mechanical energy (the corn popping) and into mechanical energy of air molecules moving (sound).



### Energy Conversions in a Popcorn Machine

- 1. The popcorn machine changes electrical energy to thermal energy, which heats the popcorn.*
- 2. The heat causes the popcorn to pop. You can see that the popping corn has mechanical energy (energy of movement). It overflows the pot and falls into the pile of popcorn at the bottom of the machine.*
- 3. The popping corn also has sound energy. That's why it makes popping sounds.*



### Kinetic-Potential Energy Changes

Mechanical energy commonly changes between kinetic and potential energy. Kinetic energy is the energy of moving objects. Potential energy is energy that is stored in objects, typically because of their position or shape. Kinetic energy can be used to change the position or shape of an object, giving it potential energy. Potential energy gives the object the potential to move. If it does, the potential energy changes back to kinetic energy.

That's what happened to Sari. After she and Daniel left the theater, the storm cleared and they went to the pool. That's Sari in the Figure below coming down the water slide. When she was at the top of the slide, she had potential energy. Why? She had the potential to slide into the pool because of the pull of gravity. As she moved down the slide, her potential energy changed to kinetic energy. By the time she reached the pool, all the potential energy had changed to kinetic energy.

Q: How could Sari regain her potential energy?

A roller coaster is another fun example of changes between kinetic and potential energy.

Q: Can you think of other fun examples of energy changing between kinetic and potential energy?



## SUPPLEMENTAL LINKS

You can see other examples of energy changing form at <http://bit.ly/MGcdIb>

Roller Coaster animation (Notice how the roller coaster's total energy (kinetic energy + potential energy) does not change.)

<http://bit.ly/1deHG9z>

<http://bit.ly/1beUvEa>

<http://bit.ly/1emxnoD>

## SUMMARY

- Energy conversion is the process in which energy changes from one form or type to another. Energy is always conserved in energy conversions.
- Different forms of energy—such as electrical, chemical, and thermal energy—often change to other forms of energy.
- Mechanical energy commonly changes back and forth between kinetic and potential energy.

## REVIEW

1. Define energy conversion.
2. Relate energy conversion (from one form of energy to another) to the law of conservation of energy.
3. Describe an original example of energy changing from one form to two other forms.
4. Explain how energy changes back and forth between kinetic and potential energy when you jump on a trampoline. Include a sketch to help explain the energy conversions taking place while you jump.
5. Research and report on the transformation of energy. Describe how your cell phone receives a charge and include how the electricity is formed. Also

○ Vocabulary

○ energy

conversion:

Process in which

energy changes

from one type or

form to another.

describe the process of the battery storing energy and then using it when you make a call.

# WAVES

## CHAPTER 5

Standard 5: Students will understand the properties and applications of waves.

## **STANDARD 5, OBJECTIVE 1: DEMONSTRATE AN UNDERSTANDING OF MECHANICAL WAVES IN TERMS OF GENERAL WAVE PROPERTIES.**

Objective:

- Explain the transfer of energy through a medium by mechanical waves.



No doubt you've seen this happen. Droplets of water fall into a body of water, and concentric circles spread out through the water around the droplets. The concentric circles are waves moving through the water.

## Waves in Matter

The waves in the picture above are examples of mechanical waves. A mechanical wave is a disturbance in matter that transfers energy through the matter. A mechanical wave starts when matter is disturbed. A source of energy is needed to disturb matter and start a mechanical wave.

Q: Where does the energy come from in the water wave pictured above?

A: The energy comes from the falling droplets of water, which have kinetic energy because of their motion.

## The Medium

The energy of a mechanical wave can travel only through matter. The matter through which the wave travels is called the medium (plural, media). The medium in the water wave pictured above is water, a liquid. But the medium of a mechanical wave can be any state of matter, even a solid.

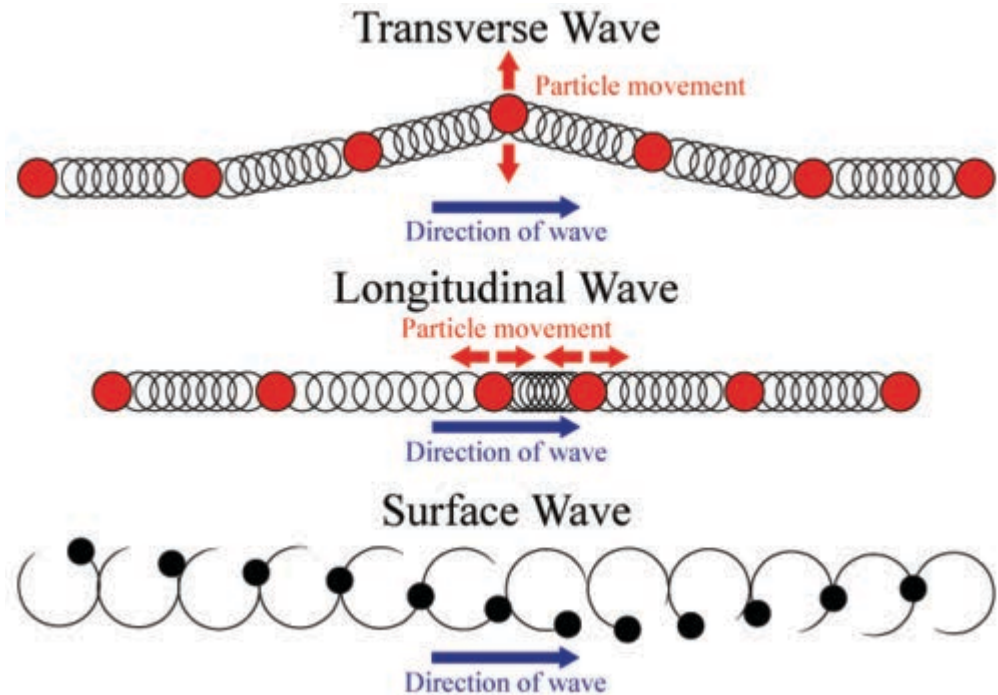
Q: How do the particles of the medium move when a wave passes through them?

A: The particles of the medium just vibrate in place. As they vibrate, they pass the energy of the disturbance to the particles next to them, which pass the energy to the particles next to them, and so on. Particles of the medium don't actually travel along with the wave. Only the energy of the wave travels through the medium.

## Types of Mechanical Waves

There are three types of mechanical waves: transverse, longitudinal, and surface waves. They differ in how particles of the medium move. You can see this in the Figure below and in the animation at the following URL.

**<http://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html>**



- In a transverse wave, particles of the medium vibrate up and down perpendicular to the direction of the wave.
- In a longitudinal wave, particles of the medium vibrate back and forth parallel to the direction of the wave.
- In a surface wave, particles of the medium vibrate both up and down and back and forth, so they end up moving in a circle.

Q: How do you think surface waves are related to transverse and longitudinal waves?

A: A surface wave is combination of a transverse wave and a longitudinal wave.

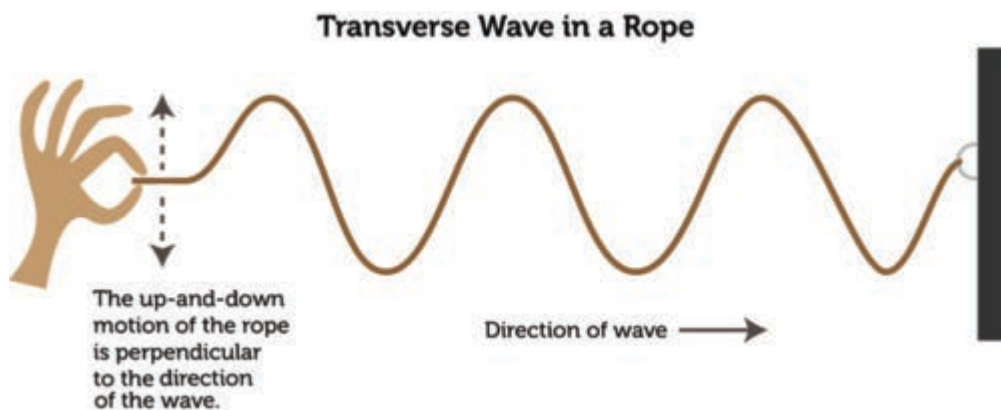
### What Is a Transverse Wave?

A transverse wave is a wave in which particles of the medium vibrate at right angles, or perpendicular, to the direction that the wave travels. Another example of a transverse wave is the wave that passes through a rope with you shake one end of the rope up and down, as in the Figure below. The direction of the wave is down the length of the rope

away from the hand. The rope itself moves up and down as the wave passes through it.

You can watch a video of a transverse wave in a rope at this URL:  
<http://www.youtube.com/watch?v=TZlr9mpERbU&NR=1>

To see a transverse wave in slow motion, go to this URL:



<http://www.youtube.com/watch?v=g49mahYeNgc>

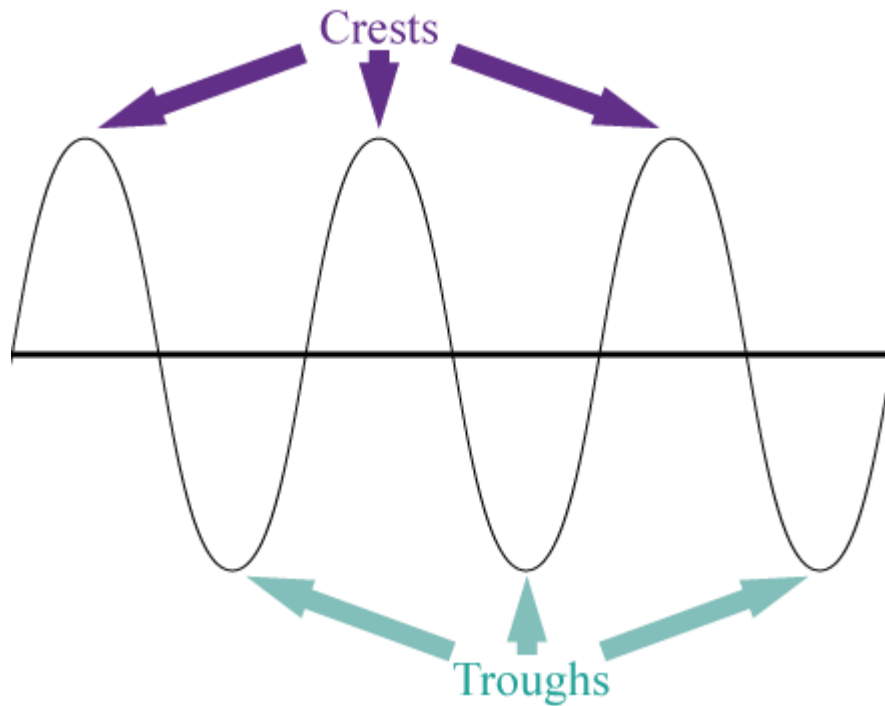
Q: When a guitar string is plucked, in what direction does the wave travel? In what directions does the string vibrate?

A: The wave travels down the string to the end. The string vibrates up and down at right angles to the direction of the wave.



### Crests and Troughs

A transverse wave is characterized by the high and low points reached by particles of the medium as the wave passes through. The high points are called crests, and the low points

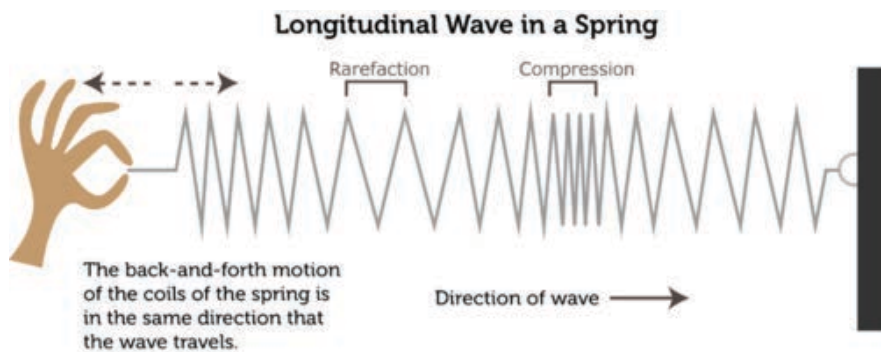


are called troughs. You can see both in the Figure below.

### What Is a Longitudinal Wave?

A longitudinal wave is a type of mechanical wave. A mechanical wave is a wave that travels through matter, called the medium. In a longitudinal wave, particles of the medium vibrate in a direction that is parallel to the direction that the wave travels. You can see this in the Figure below. The person's hand pushes and pulls on one end of the spring. The energy of this disturbance passes through the coils of the spring to the other end. You can see a video of a longitudinal wave in a spring at this URL:

**<http://www.youtube.com/watch?v=ubRlaCCQfDk&feature=related>**



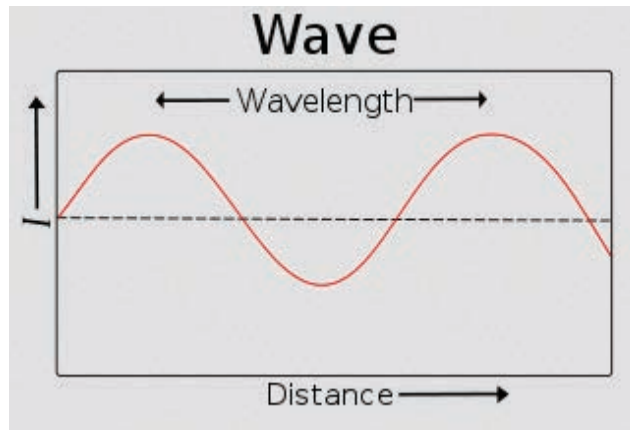
## SUMMARY

- A mechanical wave is a disturbance in matter that transfers energy through the matter.
- The matter through which a mechanical wave travels is called the medium (plural, media).
- There are three types of mechanical waves: transverse, longitudinal, and surface waves. They differ in how particles of the medium move when the energy of the wave passes through.

## PRACTICE PROBLEMS

6. Explain the difference between a transverse wave and a longitudinal wave.
7. List at least 2 real-world examples of transverse and longitudinal waves.
8. The highest point on a transverse wave is the \_\_\_\_\_ while the lowest part is the \_\_\_\_\_.
9. Differentiate between period, frequency, wavelength, and amplitude of waves.
10. Wavelength is one way of measuring the size of waves. It is the distance between two corresponding points on adjacent waves, and it is usually measured in meters. How it is measured is a little different for transverse and longitudinal waves.

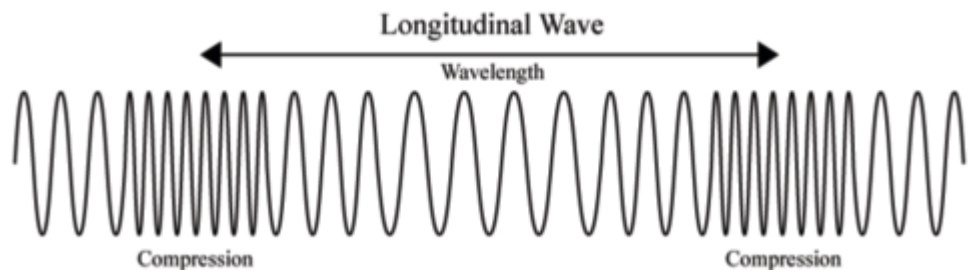
In a transverse wave, particles of the medium vibrate up and down at right angles to the direction that the wave travels. The wavelength of a transverse wave can be measured as the distance between two adjacent crests, or high points, as shown in the diagram below.



<http://eileen2126.wikispaces.com/file/view/320px-Wavelength.svg.png/72898929/320px-Wavelength.svg.png>

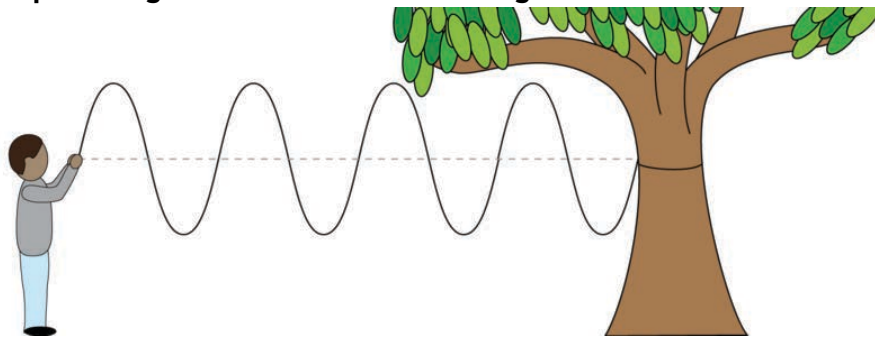
In a longitudinal wave, particles of matter vibrate back and forth in the same direction that the wave travels. The wavelength of a longitudinal wave can be measured as the distance between two adjacent compressions, as shown in the diagram below.

Compressions are the places where particles of the medium crowd close together as the energy of the wave passes through.

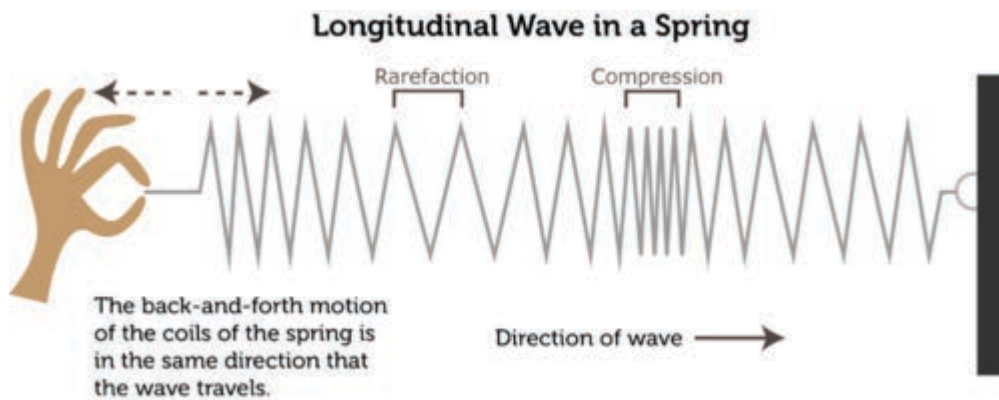


At the following URL, watch the animation to see examples of wavelength. Also, get a feel for wavelength by playing with the wave generator.

<http://earthguide.ucsd.edu/wav/wavelength.html>



Imagine making transverse waves in a rope, like the person in the sketch above. You tie one end of the rope to a tree or other fixed point, and then you shake the other end of the rope up and down with your hand. You can move the rope up and down slowly or quickly. How quickly you move the rope determines the frequency of the waves.



You can make a longitudinal wave by moving a slinky back and forth in the same direction as illustrated in the picture above.

### What is the Period of a Wave?

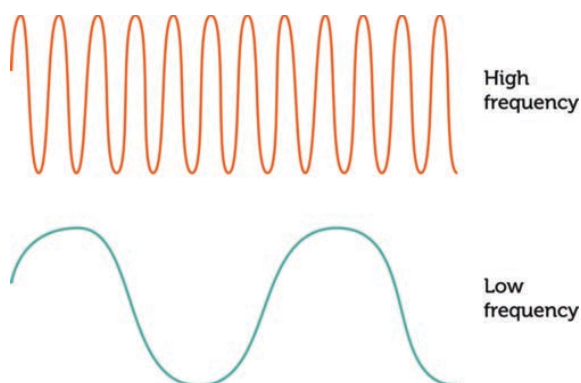
The period,  $T$ , is the amount of time for the harmonic motion to repeat itself, or for the object to go one full cycle. In SHM (simple harmonic motion),  $T$  is the time it takes the object to return to its exact starting point and starting direction. The period of a wave depends on the period of oscillation of the object creating the wave.

### What Is Frequency?

The number of waves that pass a fixed point in a given amount of time is wave frequency. Wave frequency can be measured by counting the number of wavelengths of waves that pass the fixed point in 1 second or some other time period. The higher the number is, the greater the frequency of the waves. The SI unit for wave frequency is the hertz (Hz), where 1 hertz equals 1 wave passing a fixed point in 1 second. The Figure below shows high-frequency and low-frequency transverse waves. You can simulate transverse waves with different frequencies at these URLs:

<http://phet.colorado.edu/en/simulation/wave-on-a-string> and

<http://zonalandeducation.com/mstm/physics/waves/partsOfAWave/waveParts.htm>



Q: The wavelength of a wave is the distance between corresponding points on adjacent waves. For example, it is the distance between two adjacent crests in the transverse waves in the diagram. Infer how wave frequency is related to wavelength.

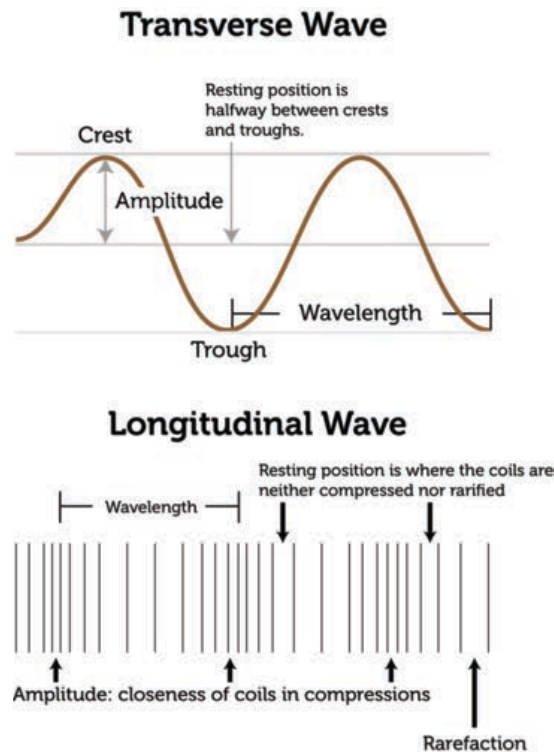
A: Waves with a higher frequency have crests that are closer together, so higher frequency waves have shorter wavelengths.

### What Is Amplitude?

Wave amplitude is the maximum distance the particles of the medium move from their equilibrium position when a wave passes through. The resting position of a particle of the medium is where the particle would be in the absence of a wave. The Figure below show the amplitudes of two different types of waves: transverse and longitudinal waves.

In a transverse wave, particles of the medium move at right angles to the direction of the wave. Wave amplitude of a transverse wave is the difference in height between the crest and the resting position. The trough is the lowest point particles of the medium reach. The crest is the highest point particles of the medium reach. The higher the crests are, the greater the amplitude of the wave.

In a longitudinal wave, particles of the medium move back and forth in the same direction as the wave. Wave amplitude of a longitudinal wave is [related to](#) the distance between particles of the medium where it is compressed by the wave. The closer together the particles are, the greater the amplitude of the wave.



Q: What do you think determines a wave's amplitude?

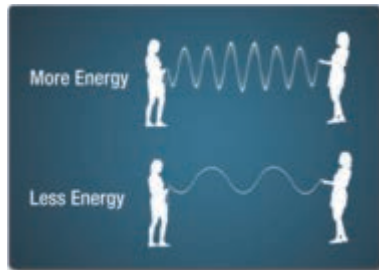
A: Wave amplitude is determined by the energy of the disturbance that causes the wave.

You can simulate waves with different amplitudes in the animation at this URL:

**<http://sci-culture.com/advancedpoll/GCSE/sine%20wave%20simulator.html>**

### Wave Frequency and Energy

The frequency of a wave is the same as the frequency of the vibrations that caused the wave. For example, to generate a higher-frequency wave in a rope, you must move the rope up and down more quickly. This takes more energy, so a higher-frequency wave has more energy than a lower-frequency wave with the same amplitude. You can see examples of different frequencies in the Figure below (Amplitude is the distance that particles of the medium move when the energy of a wave passes through them .)



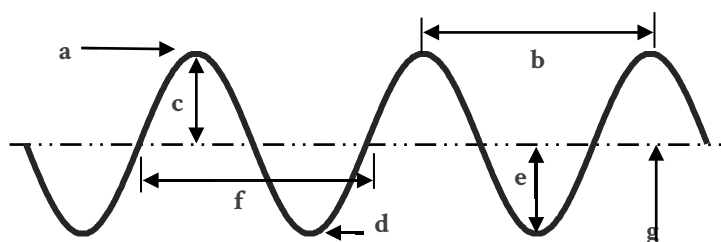
## SUMMARY

- Wave frequency is the number of waves that pass a fixed point in a given amount of time.
- The SI unit for wave frequency is the hertz (Hz), where 1 hertz equals 1 wave passing a fixed point in 1 second.
- A higher frequency electromagnetic wave has more energy than a lower frequency electromagnetic wave.

## PRACTICE PROBLEMS

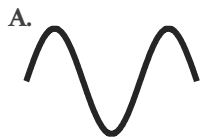
1. The illustration below shows a series of transverse waves. Label each part in the space provided.

- 
- 
- 
- 
- 
- 
- 



Fill in the blanks:

- Waves carry \_\_\_\_\_ from one place to another.
- The \_\_\_\_\_ is the height of the wave.
- The distance from one crest to the next is the \_\_\_\_\_.
- Below are a number of series of waves. Underneath each diagram write the numbers of waves in the series.



\_\_\_\_\_



\_\_\_\_\_



\_\_\_\_\_



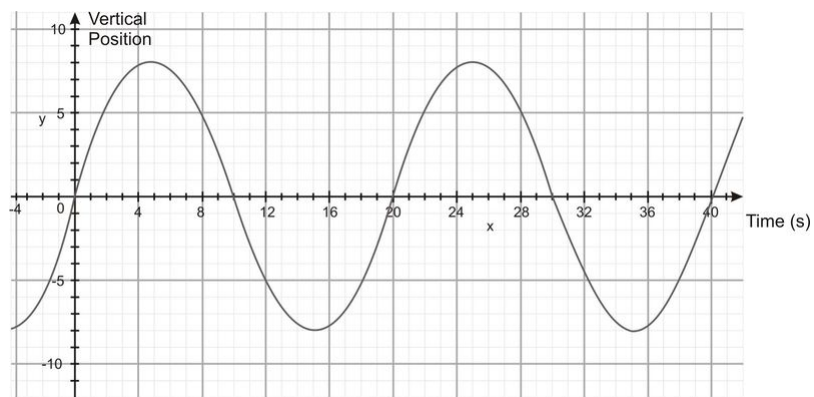
\_\_\_\_\_



Reread the difference between transverse and longitudinal waves. For each of the following types of waves, tell what type it is and why. (Include a sketch for each.)

- sound waves
- water waves in the wake of a boat
- a vibrating string on a guitar
- a swinging jump rope
- the vibrating surface of a drum
- the “wave” done by spectators at a sports event
- slowly moving traffic jams

A mass is oscillating up and down on a spring. Below is a graph of its vertical position as a function of time.



Determine the

- amplitude,
- period and
- frequency.

11. What is the amplitude at  $t = 32$ seconds?

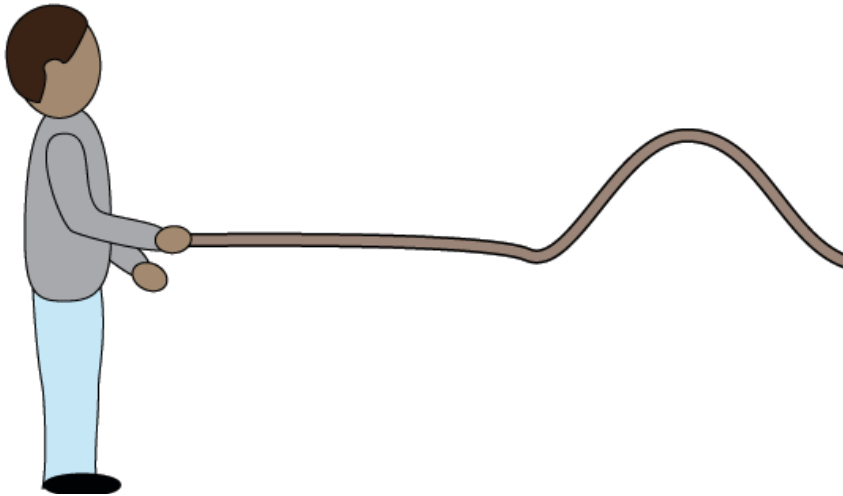
12. At what times is the mass momentarily at rest? How do you know?

13. Velocity is defined as change in position over time. Can you see that would be the slope of this graph? (slope = rise over run and in this case the ‘rise’ is position and the ‘run’ is time). Find the instantaneous speed at  $t = 20$ sec.

## Answers

a. 8 m; 20 s ; 0.05 Hz; b. - 4 m c.  $\approx 2.3$  m/s

Identify the relationship between the speed, wavelength, and frequency of a wave.



Assume that you move one end of a rope up and down just once to generate a wave in the rope. How long will take the wave to travel down the rope to the other end? It depends on the speed of the wave.

### The Speed of a Wave

Wave speed is the distance a wave travels in a given amount of time, such as the number of meters it travels per second. Wave speed (and speed in general) can be represented by the equation:

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} = \frac{\lambda}{T}$$

### Wave Speed, Wavelength, and Wave Frequency

Sometimes it is more useful to write the equation in terms of frequency instead of period, using the relationship  $T = 1/f$ . Wave speed is related to both wavelength and wave frequency. Wavelength is the distance between two corresponding points on adjacent

waves. Wave frequency is the number of waves that pass a fixed point in a given amount of time. This equation shows how the three factors are related:

$$\text{Speed} = \text{Wavelength} \times \text{Wave Frequency}, v = \lambda f$$

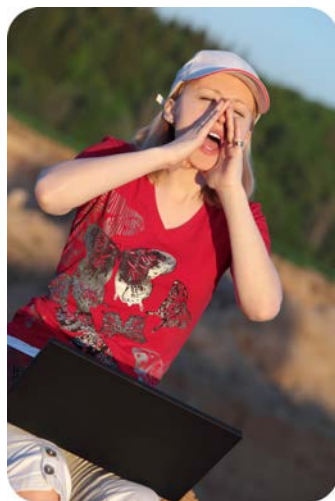
In this equation, wavelength is measured in meters and frequency is measured in hertz (Hz), or number of waves per second. Therefore, wave speed is given in meters per second, which is the SI unit for speed.

Q: If you increase the wavelength of a wave, does the speed of the wave increase as well?

A: Increasing the wavelength of a wave doesn't change its speed. That's because when wavelength increases, wave frequency decreases. As a result, the product of wavelength and wave frequency is still the same speed. The speed is dependent on the wave medium.

At the following URL, you can see what happens to the wavelength when the frequency of a wave increases.

**[http://www.youtube.com/watch?v=7lv4GmyXsCQ&feature=player\\_embedded](http://www.youtube.com/watch?v=7lv4GmyXsCQ&feature=player_embedded)**



*Investigate and compare reflection, refraction, and differentiation of waves.*

Did you ever hear an echo of your own voice? An echo occurs when sound waves bounce back from a surface that they can't pass through. The girl pictured here is trying to create an echo by shouting toward a large building. When the sound waves strike the wall of the building, most of them bounce back toward the girl, and she hears an echo of her voice. An echo is just one example of how waves interact with matter.

## How Waves Interact with Matter

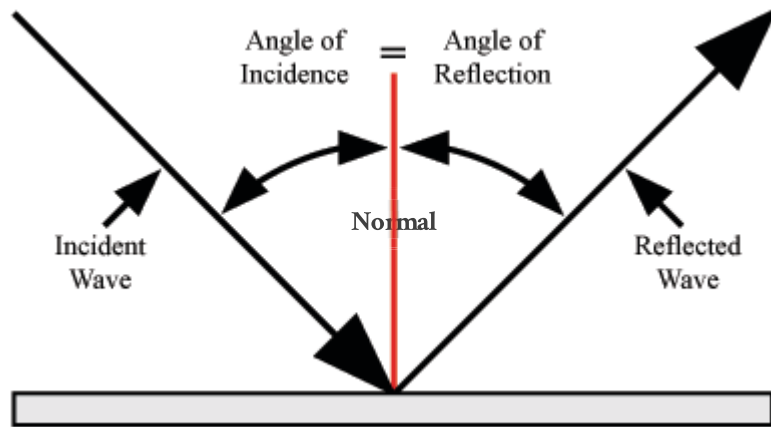
Waves interact with matter in several ways. The interactions occur when waves pass from one medium to another. The types of interactions are reflection, refraction, and diffraction. Each type of interaction is described in detail below. You can see animations of the three types at this URL:

**<http://www.acoustics.salford.ac.uk/schools/teacher/lesson3/flash/whiteboardcomplete.swf>**

### Reflection

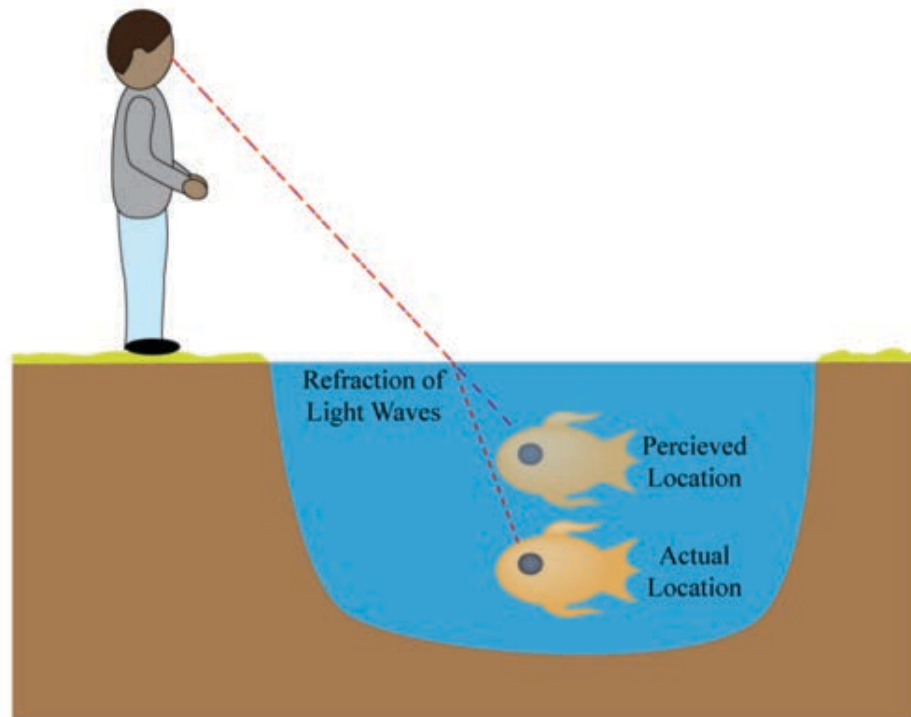
An echo is an example of wave reflection. Reflection occurs when waves bounce back from a boundary that separates two different mediums. Reflection can happen with any type of waves, not just sound waves. For example, light waves can also be reflected. In fact, that's how we see most objects. Light from a light source, such as the sun or a light bulb, shines on the object and some of the light is reflected. When the reflected light enters our eyes, we can see the object.

Reflected waves have the same speed and frequency as the original waves before they were reflected because they do not change the medium. However, the direction of the reflected waves is different. When waves strike an obstacle head on, the reflected waves bounce straight back in the direction they came from. When waves strike an obstacle at any other angle, they bounce back at the same angle but in a different direction. This is illustrated in diagram below. In this diagram, waves strike a wall at an angle, called the angle of incidence. The waves are reflected at the same angle, called the angle of reflection, but in a different direction. Notice that both angles are measured relative to a line that is perpendicular to the wall. This line is called the normal line.



### Refraction

Refraction is another way that waves interact with matter. Refraction occurs when waves bend as they enter a new medium at an angle. You can see an example of refraction in the picture below. Light bends when it passes from air to water or from water to air. The bending of the light traveling from the fish to the man's eyes causes the fish to appear to be in a different place from where it actually is.



Waves bend as they enter a new medium because they start traveling at a different speed in the new medium. For example, light travels more slowly in water than in air. This causes it to refract when it passes from air to water or from water to air.

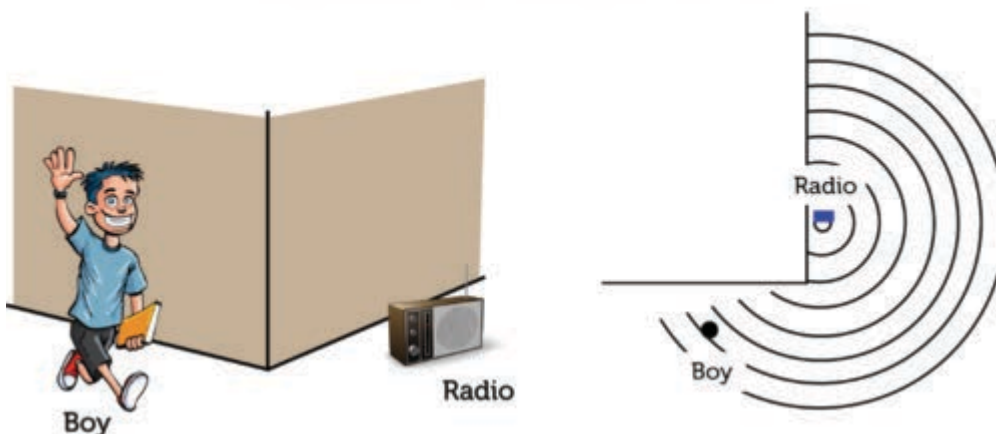
Q: Where would the fish appear to be if the man looked down at it from straight above its actual location?

A: The fish would appear to be where it actually is because refraction occurs only when waves (in this case light waves from the fish) enter a new medium at an angle other than to the normal.

### Diffraction

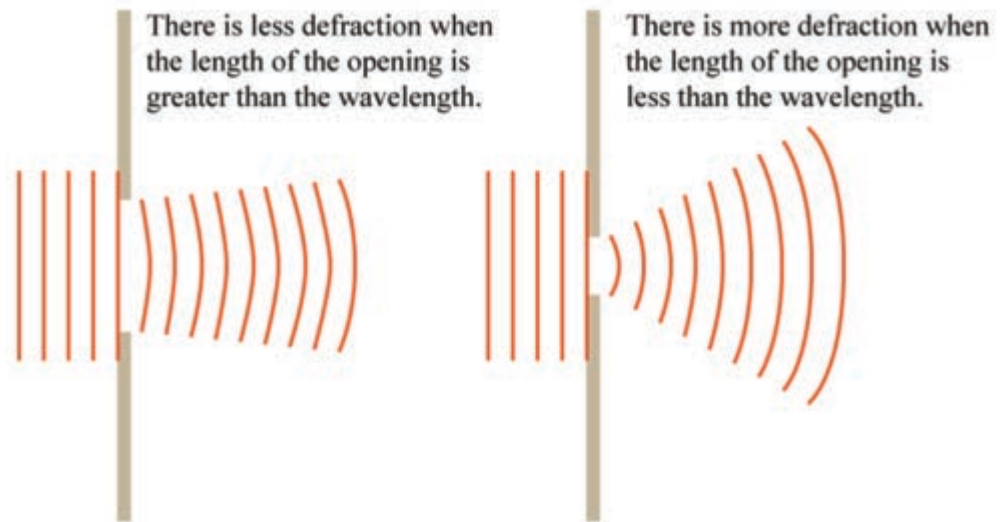
Did you ever notice that you can hear sounds around the corners of buildings even though you can't see around them? The Figure below shows why this happens. As you can see from the figure, sound waves spread out and travel around obstacles. This is called diffraction. It also occurs when waves pass through an opening in an obstacle. All waves may be diffracted, but it is more pronounced in some types of waves than others. For example, sound waves bend around corners much more than light does. That's why you can hear but not see around corners.

### Diffraction of Sound Waves



For a given type of waves, such as sound waves, how much the waves diffract depends on the size of the obstacle (or opening in the obstacle) and the wavelength of the waves. The

Figure below shows how the amount of diffraction is affected by the size of the opening in a barrier. Note that the wavelength of the wave is the distance between the vertical lines.



For an interactive animation of a diagram like the one below, go to the following URL:  
<http://phet.colorado.edu/en/simulation/wave-interference>

## SUMMARY

- Three ways that waves may interact with matter are reflection, refraction, and diffraction.
- Reflection occurs when waves bounce back from a surface boundary that separates two different mediums.
- Refraction occurs when waves bend as they enter a new medium at an angle and start traveling at a different speed.
- Diffraction occurs when waves spread out as they travel around obstacles or through openings in obstacles in the same medium.

### Vocabulary

- diffraction: Bending of a wave around an obstacle or through an opening in an obstacle.
- reflection: Bouncing back of waves from a barrier they cannot pass through.
- refraction: Bending of waves as they enter a new medium at an angle and change speed.



*Explain the observed change in frequency of a mechanical wave coming from a moving object as it approaches and moves away.*



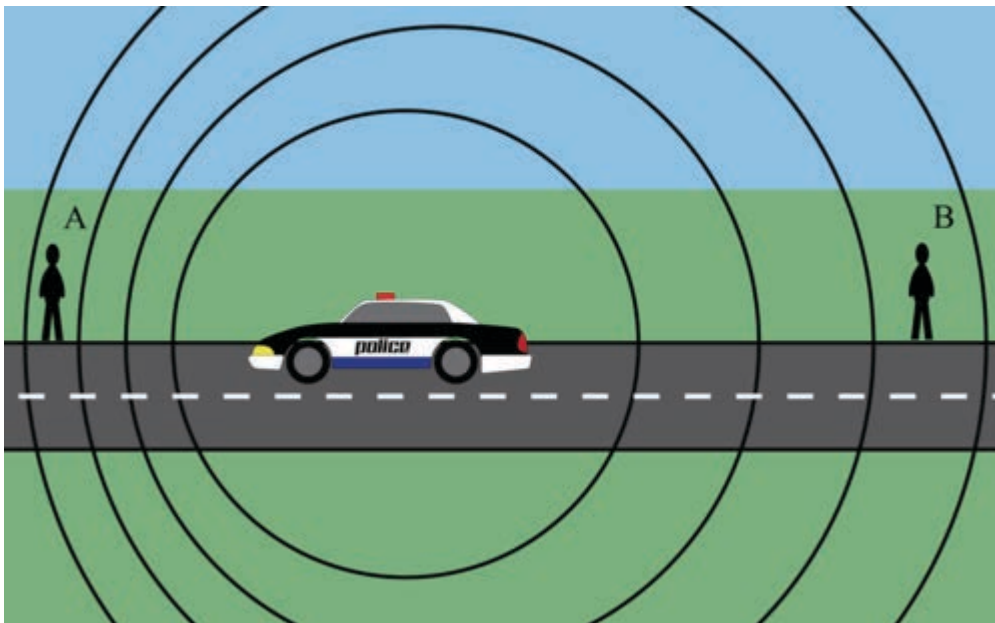
Has this ever happened to you? You hear a siren from a few blocks away. The source is a police car that is racing in your direction. As the car approaches, zooms past you, and then speeds off into the distance, the sound of its siren keeps changing in pitch. First the siren gets higher in pitch, and then it suddenly gets lower. Do you know why this happens? The answer is the Doppler effect.

### **What Is the Doppler Effect?**

The Doppler effect is a change in the frequency of sound waves that occurs when the source of the sound waves is moving relative to a stationary listener. (It can also occur when the sound source is stationary and the listener is moving.) The diagram below shows how the Doppler effect occurs. The sound waves from the police car siren travel outward in all directions. Because the car is racing forward (to the left), the sound waves get bunched up in front of the car and spread out behind it. As they propagate outward they retain their circular shape. Sound waves that are closer together have a higher frequency, and sound waves that are farther apart have a lower frequency. The frequency

of sound waves, in turn, determines the pitch of the sound. Sound waves with a higher frequency produce sound with a higher pitch, and sound waves with a lower frequency produce sound with a lower pitch. For an interactive animation of a diagram like the one below, go to the following URL:

**<http://www.colorado.edu/physics/2000/applets/doppler.html>**



### Experiencing the Doppler Effect

As the car approaches listener A, the sound waves [appear](#) closer together, increasing their frequency. This listener hears the pitch of the siren get higher. As the car speeds away from listener B, the sound waves get farther apart, decreasing their frequency. This listener hears the pitch of the siren get lower. You can experience the Doppler effect with a moving siren in the following animation:

**<http://www.epicphysics.com/physics-animations/doppler-effect-animation/>**

## Vocabulary

- **Doppler effect:**  
Change in the frequency and pitch of sound that occurs when the source of the sound is moving relative to the listener.

Q: What will the siren sound like to listener A after the police car passes him?

A: The siren will suddenly get lower in pitch because the sound waves will be much more spread out and have a lower frequency.

## SUMMARY

- The Doppler effect is a change in the frequency of sound waves that occurs when the source of the sound waves is moving relative to a stationary listener.
- As the source of sound waves approaches a listener, the sound waves get closer together, increasing their frequency and the pitch of the sound. The opposite happens when the source of sound waves moves away from the listener.

## PRACTICE

At the following URL, observe the Doppler effect in the animation and then answer the question. Check your answer by reading the “Discussion” section of the Web page.

<http://www.ndt->

[ed.org/EducationResources/HighSchool/Sound/dopplereffect.htm](http://www.ndt-ed.org/EducationResources/HighSchool/Sound/dopplereffect.htm)

14. Define the Doppler effect.
15. Explain why the Doppler effect occurs.
16. Does the siren of a moving police car seem to change pitch to the police officers inside the car? Why or why not?

## **STANDARD 5, OBJECTIVE 2: DESCRIBE THE NATURE OF ELECTROMAGNETIC RADIATION AND VISIBLE LIGHT.**



Did you ever wonder how a microwave works? It directs invisible waves of radiation toward the food placed inside of it. The radiation transfers energy to the food, causing it to get warmer. The radiation is in the form of microwaves, which are a type of electromagnetic waves.

### **What Are Electromagnetic Waves?**

Electromagnetic waves are waves that consist of vibrating electric and magnetic fields. Like other waves, electromagnetic waves transfer energy from one place to another. The transfer of energy by electromagnetic waves is called electromagnetic radiation.

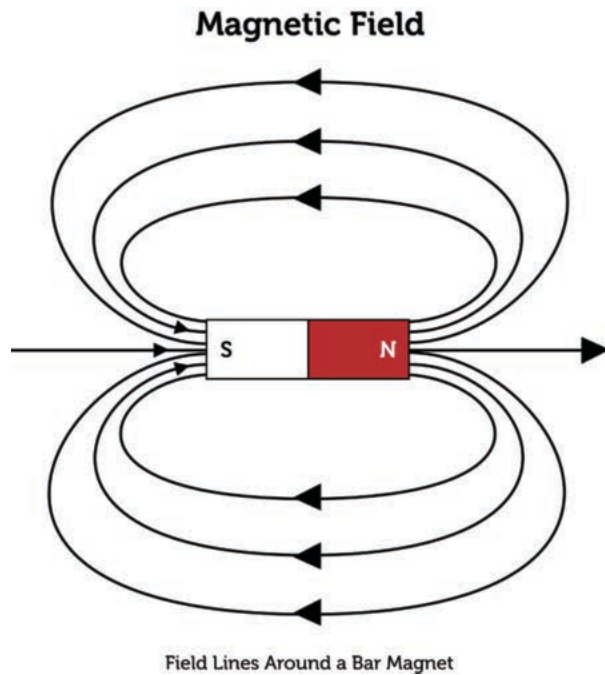
Electromagnetic waves can transfer energy through matter or across empty space. For an excellent video introduction to electromagnetic waves, go to this URL:  
<http://www.youtube.com/watch?v=cfXzwh3KadE>

Q: How do microwaves transfer energy inside a microwave oven?

A: They transfer energy through the air inside the oven to the food.

### May the Force Be with You

A familiar example may help you understand the vibrating electric and magnetic fields that make up electromagnetic waves. Consider a bar magnet, like the one in the Figure below. The magnet exerts magnetic force over an area all around it. This area is called a magnetic field. The field lines in the diagram represent the direction and location of the magnetic force. Because of the field surrounding a magnet, it can exert force on objects without touching them. They just have to be within its magnetic field.

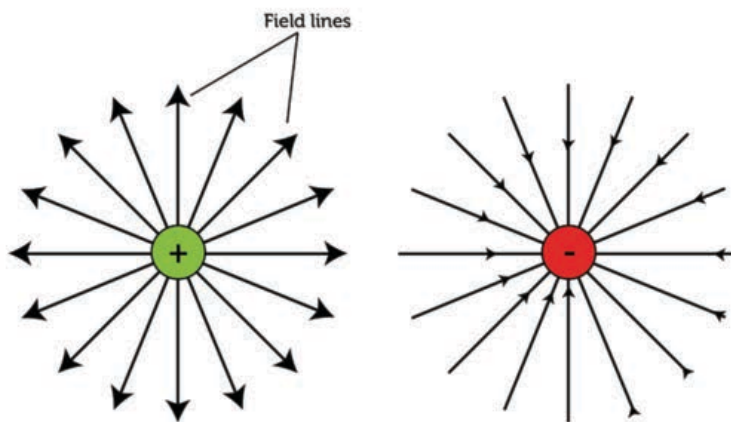


Q: How could you demonstrate that a magnet can exert force on objects without touching them?

A: You could put small objects containing iron, such as paper clips, near a magnet and show that they move toward the magnet.

An electric field is similar to a magnetic field. It is an area of electrical force surrounding a positively or negatively charged particle. You can see electric fields in the following Figure below. Like a magnetic field, an electric field can exert force on objects over a distance without actually touching them.

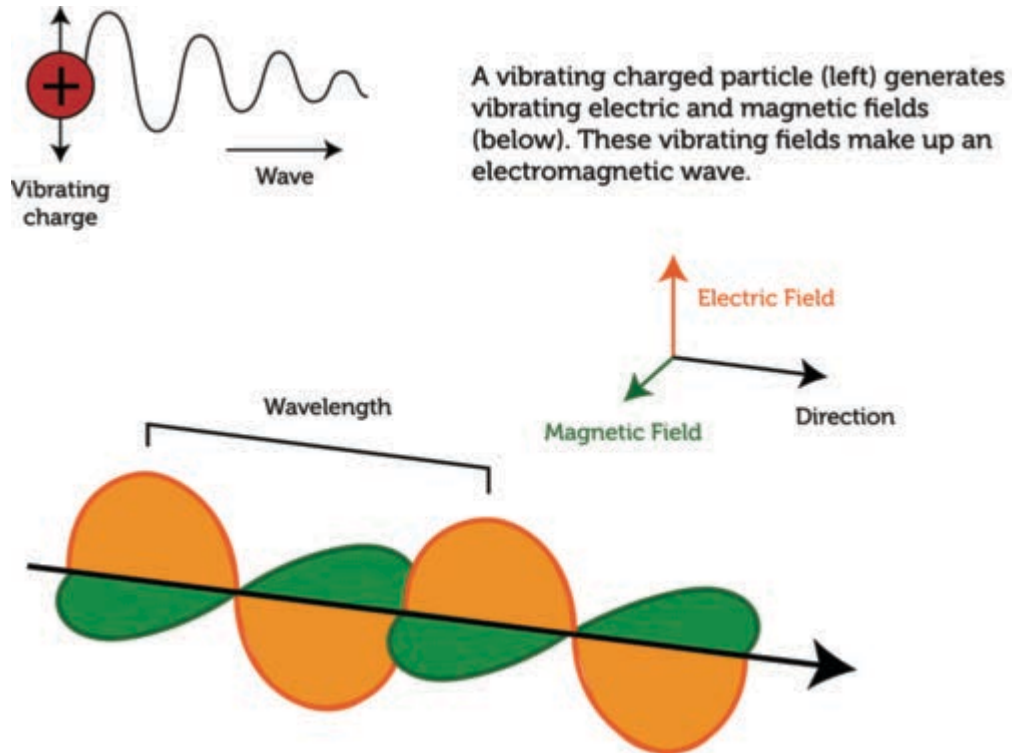
### Electric Field



### How an Electromagnetic Wave Begins

An electromagnetic wave begins when an electrically charged particle vibrates. The Figure below shows how this happens. A vibrating charged particle causes the electric field surrounding it to vibrate as well. A vibrating electric field, in turn, creates a vibrating magnetic field. The two types of vibrating fields combine to create an electromagnetic wave. You can see animations of electromagnetic waves at these URLs:

<http://www.youtube.com/watch?v=Qju7QnbrOhM&feature=related>  
<http://www.phys.hawaii.edu/~teb/java/ntnujava/emWave/emWave.html>



Video on <http://www.youtube.com/watch?v=Gf33ueRXMzQ>

### How an Electromagnetic Wave Travels

As you can see in the diagram above, the electric and magnetic fields that make up an electromagnetic wave are perpendicular (at right angles) to each other. Both fields are also perpendicular to the direction that the wave travels. Therefore, an electromagnetic wave is a transverse wave. However, unlike a mechanical transverse wave, which can only travel through matter, an electromagnetic transverse wave can travel through empty space. When waves travel through matter, they lose some energy to the matter as they pass through it. But when electromagnetic waves travel through space, no energy is lost. Therefore, electromagnetic waves don't get weaker as they travel. However, the energy is

“diluted” as it travels farther from its source because it spreads out over an ever-larger area.

### **Electromagnetic Wave Interactions**

When electromagnetic waves strike matter, they may interact with it in the same ways that mechanical waves interact with matter. Electromagnetic waves may:

- reflect, or bounce back from a surface;
- refract, or bend when entering a new medium;
- diffract, or spread out around obstacles.

Electromagnetic waves may also be absorbed by matter and converted to other forms of energy. Microwaves are a familiar example. When microwaves strike food in a microwave oven, they are absorbed and converted to thermal energy, which heats the food.

### **Sources of Electromagnetic Waves**

- **The most important source of electromagnetic waves on Earth is the sun.**
- **Electromagnetic waves travel from the sun to Earth across space and provide virtually all the energy that supports life on our planet. Many other sources of electromagnetic waves depend on technology. Radio waves, microwaves, and X rays are examples. We use these electromagnetic waves for communications, cooking, medicine, and many other purposes.**



## Vocabulary

- electromagnetic radiation: Transfer of energy by electromagnetic waves across space or through matter.
- electromagnetic wave: Transverse wave consisting of vibrating electric and magnetic fields that can travel across space.

## SUMMARY

- Electromagnetic waves are waves that consist of vibrating electric and magnetic fields. They transfer energy through matter or across space. The transfer of energy by electromagnetic waves is called electromagnetic radiation.
- The electric and magnetic fields of an electromagnetic wave are areas of electric or magnetic force. The fields can exert force over objects at a distance.
- An electromagnetic wave begins when an electrically charged particle vibrates. This causes a vibrating electric field, which in turn creates a vibrating magnetic field. The two vibrating fields together form an electromagnetic wave.
- An electromagnetic wave is a transverse wave that can travel across space as well as through matter. When it travels through space, it doesn't lose energy to a medium as a mechanical wave does.
- When electromagnetic waves strike matter, they may be reflected, refracted, or diffracted. Or they may be absorbed by matter and converted to other forms of energy.
- The most important source of electromagnetic waves on Earth is the sun. Many other sources of electromagnetic waves depend on technology.

## PRACTICE

Watch the electromagnetic wave animation at the following URL, and then answer the questions below. <http://www.youtube.com/watch?v=4CtnUETLIFs>

17. Identify the vibrating electric and magnetic fields of the wave.
18. Describe the direction in which the wave is traveling.

## REVIEW

19. What is an electromagnetic wave?
20. Define electromagnetic radiation.
21. Describe the electric and magnetic fields of an electromagnetic wave.
22. How does an electromagnetic wave begin? How does it travel?
23. Compare and contrast electromagnetic and mechanical transverse waves.
24. List three sources of electromagnetic waves on Earth.



What do these two photos have in common? They both represent electromagnetic waves. These are waves that consist of vibrating electric and magnetic fields. They transmit energy through matter or across space. Some electromagnetic waves are generally harmless. The light we use to see is a good example. Other electromagnetic waves can be very harmful and care must be taken to avoid too much exposure to them. X rays are a familiar example. Why do electromagnetic waves vary in these ways? It depends on their properties. Like other waves, electromagnetic waves have properties of speed, wavelength, and frequency.

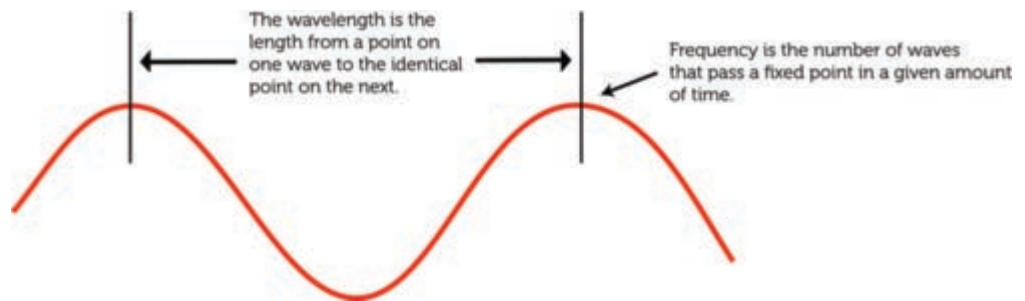
### Speed of Electromagnetic Waves

All electromagnetic waves travel at the same speed through empty space. That speed, called the speed of light, is about 300 million meters per second ( $3.0 \times 10^8$  m/s). Nothing else in the universe is known to travel this fast. The sun is about 150 million kilometers (93 million miles) from Earth, but it takes electromagnetic radiation only 8 minutes to reach Earth from the sun. If you could move that fast, you would be able to travel around Earth 7.5 times in just 1 second! You can learn more about the speed of light at this URL: <http://videos.howstuffworks.com/discovery/29407-assignment-discovery-speed-of-light-video.htm>

### Wavelength and Frequency of Electromagnetic Waves

Although all electromagnetic waves travel at the same speed across space, they may differ in their wavelengths, frequencies, and energy levels.

- Wavelength is the distance between corresponding points of adjacent waves (see the Figure below). Wavelengths of electromagnetic waves range from longer than a soccer field to shorter than the diameter of an atom.
- Wave frequency is the number of waves that pass a fixed point in a given amount of time. Frequencies of electromagnetic waves range from thousands of waves per second to trillions of waves per second.
- The energy of electromagnetic waves depends on their frequency. Low-frequency waves have little energy and are normally harmless. High-frequency waves have a lot of energy and are potentially very harmful.



Q: Which electromagnetic waves do you think have higher frequencies: visible light or X rays?

A: X rays are harmful but visible light is harmless, so you can infer that X rays have higher frequencies than visible light.

### Speed, Wavelength, and Frequency

The speed of a wave is a product of its wavelength and frequency. Because all electromagnetic waves travel at the same speed through space, a wave with a shorter wavelength must have a higher frequency, and vice versa. This relationship is represented by the equation:

$$\text{Speed} = \text{Wavelength} \times \text{Frequency}$$

The equation for wave speed can be rewritten as:

$$\text{Frequency} = \frac{\text{Speed}}{\text{Wavelength}} \quad \text{or} \quad \text{Wavelength} = \frac{\text{Speed}}{\text{Frequency}}$$

Therefore, if either wavelength or frequency is known, the missing value can be calculated. Consider an electromagnetic wave that has a wavelength of 3 meters. Its speed, like the speed of all electromagnetic waves, is  $3.0 \times 10^8$  meters per second. Its frequency can be found by substituting these values into the frequency equation:

$$\text{Frequency} = \frac{3.0 \times 10^8 \text{ m/s}}{3.0 \text{ m}} = 1.0 \times 10^8 \text{ waves/s, or } 1.0 \times 10^8 \text{ Hz}$$

Q: What is the wavelength of an electromagnetic wave that has a frequency of  $3.0 \times 10^8$  hertz?

A: Use the wavelength equation:

$$\text{Wavelength} = \frac{3.0 \times 10^8 \text{ m/s}}{3.0 \times 10^8 \text{ waves/s}} = 1.0 \text{ m}$$

You can learn more about calculating the frequency and wavelength of electromagnetic waves at these URLs:

**<http://www.youtube.com/watch?v=GwZvtfZRNKk>**  
and **<http://www.youtube.com/watch?v=wjPk108Ua8k&feature=related>**

## Vocabulary

- speed of light:  
Speed at which all electromagnetic waves travel through space, which is  $3.0 \times 10^8$  m/s.

## SUMMARY

- All electromagnetic waves travel across space at the speed of light, which is about 300 million meters per second ( $3.0 \times 10^8$  m/s).
- Electromagnetic waves vary in wavelength and frequency. Longer wavelength electromagnetic waves have lower frequencies, and shorter wavelength waves have higher frequencies. Higher frequency waves have more energy.
- The speed of a wave is a product of its wavelength and frequency. Because the speed of electromagnetic waves through space is constant, the wavelength or frequency of an electromagnetic wave can be calculated if the other value is known.

## PRACTICE

25. Use the calculator at the following URL to find the frequency and energy of electromagnetic waves with different wavelengths. Use at least eight values for wavelength. Record and make a table of the results.

<http://www.1728.org/freqwave.htm>

## REVIEW

26. What is the speed of light across space?
27. Describe the range of wavelengths and frequencies of electromagnetic waves.
28. How is the energy of an electromagnetic wave related to its frequency?
29. If the frequency of an electromagnetic wave is  $6.0 \times 10^8$  Hz, what is its wavelength?
30. Students will learn what an electromagnetic wave is, gain a feel for the main parts of the spectrum and work problems involving basic properties of electromagnetic waves.

Key Equations

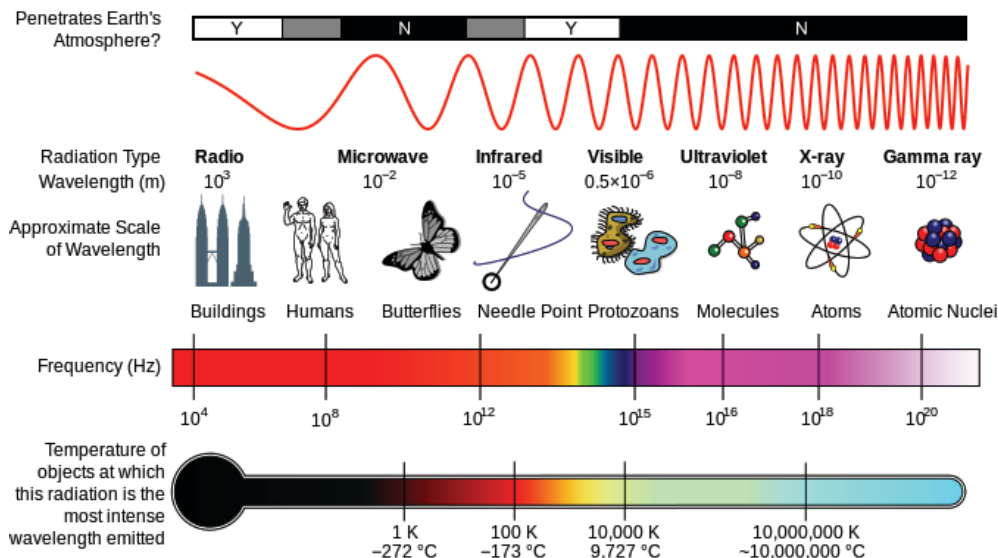
$$c = f\lambda \quad \text{Wave equation for light}$$

$$c = 3 \times 10^8 \text{ m/s}$$

### Guidance

- When charged particles accelerate, changing electric and magnetic fields radiate outward. The traveling electric and magnetic fields of an accelerating (often oscillating) charged particle are known as electromagnetic radiation or light.
- When using the wave equation for light keep in mind that light always travels at the speed of light. So plug in  $c$  for  $v$  in the wave equation.
- The color of light that we observe is a measure of the wavelength of the light: the longer the wavelength, the redder the light.

The spectrum of electromagnetic radiation can be roughly broken into the following ranges:



[http://en.wikipedia.org/wiki/File:EM\\_Spectrum\\_Properties\\_edit.svg](http://en.wikipedia.org/wiki/File:EM_Spectrum_Properties_edit.svg)

The lighter side of ROYGBIV, a song by They Might Be Giants:  
<http://www.youtube.com/watch?v=Gf33ueRXMzQ>

EM wave	Wavelength range	Comparison size
gamma-ray ( $\gamma$ - ray)	$10^{-11}$ m and shorter	atomic nucleus
x-ray	$10^{-11}$ m – $10^{-8}$ m	hydrogen atom
ultraviolet (UV)	$10^{-8}$ m – $10^{-7}$ m	small molecule
violet (visible)	$\sim 4 \times 10^{-7}$ m (400 nm)*	typical molecule
blue (visible)	$\sim 450$ nm	typical molecule
green (visible)	$\sim 500$ nm	typical molecule
red (visible)	$\sim 650$ nm	typical molecule
infrared (IR)	$10^{-6}$ m – 1 mm	human hair
microwave	1 mm – 10 cm	human finger
radio	Larger than 10 cm	car antenna

### Example 1

Which has a higher frequency, green light or microwaves?

Answer

Green light has a higher frequency than microwaves. It is possible to calculate it, but since the speed of an electromagnetic wave is constant we know that waves with higher wavelengths must have a lower frequency based on the wave equation.

A blueshift is any decrease in wavelength (increase in frequency); the opposite effect is referred to as redshift. In visible light, this shifts the color from the red end of the spectrum to the blue end. The term also applies when photons outside the visible spectrum (e.g. x-rays and radio waves) are shifted toward shorter wavelengths. In a contracting universe, cosmological blueshift would be observed; the expanding universe gives a cosmological redshift, and the expansion is observed to be accelerating. In physics (especially astrophysics), redshift happens when light seen coming from an object that is moving away is proportionally increased in wavelength, or shifted to the red end of the spectrum.

<http://en.wikipedia.org/wiki/Blueshift>

# GLOSSARY



## **GLOSSARY**

**Acceleration:** A change in velocity, divided by change in time.

**average velocity:** average displacement divided by time in which the displacement occurred

**compression:** a high concentration of particles.

**Crest:** is the high points the particles reach in a wave.

**diffraction:** bending of a wave around an obstacle or through an opening in an obstacle.

**Displacement:** the difference between final and initial positions

**Distance:** a scalar quantity giving the positive length between two points frame of reference

**doppler effect:** change in the frequency and pitch of sound that occurs when the source of the sound is moving relative to the listener.

**electric charge:** physical property of particles or objects that causes them to attract or repel each other without touching; may be positive or negative.

**electric force:** attractive or repulsive interaction between any two charged objects

**electromagnetic radiation:** transfer of energy by electromagnetic waves across space or through matter.

**electromagnetic wave:** transverse wave consisting of vibrating electric and magnetic fields that can travel across space.

**energy conversion:** process in which energy changes from one type or form to another.

**force:** a push or pull; an interaction between two objects

**friction:** the rubbing of one body against another; while it often opposes motion, that is not always the case

**gravitational force:** the force of attraction between all masses in the universe

**instantaneous velocity:** the velocity at a specific time

**kinetic energy:** energy of moving matter

**law of conservation of charge:** law stating that charges are not destroyed when they are transferred between two materials or within a material, so the total charge remains the same.

**law of universal gravitation:** law stating that gravity is a force of attraction between all objects in the universe and that the strength of gravity is greater when masses of objects are greater or distances between objects are shorter.

**longitudinal wave:** is a type of mechanical wave. In a longitudinal wave, particles of the medium vibrate in a direction that is parallel to the direction that the wave travels.

**mass:** amount of matter in an object

**medium:** the matter through which the wave travels

**net force:** the overall force on an object when all the individual forces acting on the object are added together

**normal force:** support force exerted upon an object that is in contact with another stable object

**position:** location of an object, usually relative to where movement started or ended.

**potential energy:** stored energy an object has because of its position or shape.

**rarefaction:** area of low concentration of particles

**reflection:** bouncing back of waves from a barrier they cannot pass through.

**refraction:** bending of waves as they enter a new medium at an angle and change speed.

**Scalar:** a description of motion referring only to magnitude (e.g. distance, speed)

**Speed:** Total distance traveled divided by total travel time

**speed of light:** speed at which all electromagnetic waves travel through space, which is  $3.0 \times 10^8$  m/s.

**static discharge:** sudden flow of electrons from an object that has a buildup of charges.

**static electricity:** buildup of charges on an object that occurs through induction.  
the number of waves that pass a fixed point in a given amount of time is wave frequency.

**Time:** measurement of a period in which something occurred, is occurring, or will occur

**Trough:** the low points the particles reach in a wave.

**Vector:** a description of motion referring to both magnitude and direction (e.g. displacement, velocity) a quantity that has a direction and a magnitude

**vector diagram:** (also sometimes called a force diagram or free-body diagram) a sketch showing all of the forces acting on an object; used by physicists and engineers to analyze the forces acting on a body

**velocity:** Change in position divided by change in time

**wave amplitude:** is the maximum distance the particles of the medium move from their resting positions when a wave passes through.

**wave frequency:** the number of waves that pass a fixed point in a given amount of time.

**Wavelength:** is one way of measuring the size of waves. it is the distance between two corresponding points on adjacent waves, and it is usually measured in meters.

**weight:** another name for the force of gravity