Lesson 1a) Waves and Wavelike Motion

Waves are everywhere. Whether we recognize it or not, we encounter waves on a daily basis. Sound waves, visible light waves, radio waves, microwaves, water waves, sine waves, cosine waves, stadium waves, earthquake waves, waves on a string, and slinky waves and are just a few of the examples of our daily encounters with waves. In addition to waves, there are a variety of phenomena in our physical world that resemble waves so closely that we can describe such phenomenon as being wavelike. The motion of a pendulum, the motion of a mass suspended by a spring, the motion of a child on a swing, and the "Hello, Good Morning!" wave of the hand can be thought of as wavelike phenomena. Waves (and wavelike phenomena) are everywhere!

We study the physics of waves because it provides a rich glimpse into the physical world that we seek to understand and describe as students of physics. Before beginning a formal discussion of the nature of waves, it is often useful to ponder the various encounters and exposures that we have of waves. Where do we see waves or examples of wavelike motion? What experiences do we already have that will help us in understanding the physics of waves?

For many people, the first thought concerning waves conjures up a picture of a wave moving across the surface of an ocean, lake, pond or other body of water. The waves are created by some form of a disturbance, such as a rock thrown into the water, a duck shaking its tail in the water or a boat moving through the water. The water wave has a crest and a trough and travels from one location to another. One crest is often followed by a second crest that is often followed by a third crest. Every crest is separated by a trough to create an alternating pattern of crests and troughs. A duck or gull at rest on the surface of the water is observed to bob up-and-down at rather regular time intervals as the wave passes by. The waves may appear to be plane waves that travel together as a *front* in a straight-line direction, perhaps towards a sandy shore. Or the waves may be circular waves that originate from the point where the disturbances occur; such circular waves travel across the surface of the water in all directions. These mental pictures of water waves are useful for understanding the nature of a wave and will be revisited later when we begin our formal discussion of the topic.

A rock tossed into the water will create a circular disturbance which travels outwards in all directions.

The thought of waves often brings to mind a recent encounter at the baseball or football stadium when the crowd enthusiastically engaged in *doing the wave*. When performed with reasonably good timing, a noticeable ripple is produced that travels around the circular stadium or back and forth across a section of bleachers. The observable ripple results when a group of enthusiastic fans rise up from their seats, swing their arms up high, and then sit back down. Beginning in Section 1, the first row of fans abruptly rise up to begin the *wave*; as they sit back down, row 2 begins its motion; as row 2 sits back down, row 3 begins its motion. The process continues, as each consecutive row becomes involved by a momentary standing up and sitting back down. The *wave* is passed from row to row as each individual member of the row becomes temporarily displaced out of his or her seat, only to return to it as the *wave* passes by. This mental picture of a *stadium wave* will also provide a useful context for the discussion of the physics of wave motion.

Another picture of waves involves the movement of a slinky or similar set of coils. If a slinky is stretched out from end to end, a wave can be introduced into the slinky by either vibrating the first coil up and down vertically or back and forth horizontally. A wave will subsequently be seen traveling from one end of the slinky to the other. As the wave moves along the slinky, each individual coil is seen to move out of place and then return to its original position. The coils always move in the same direction that the first coil was vibrated. A continued vibration of the first coil results in a continued back and forth motion of the other coils. If looked at closely, one notices that the wave does not stop when it reaches the end of the slinky; rather it seems to bounce off the end and head back from where it started. A

Slinky waves can be made by vibrating the first coil back and forth in either a horizontal or a vertical direction.

slinky wave provides an excellent mental picture of a wave and will be used in discussions and demonstrations throughout this unit.

We likely have memories from childhood of holding a long jump rope with a friend and vibrating an end up and down. The up and down vibration of the end of the rope created a disturbance of the rope that subsequently moved towards the other end. Upon reaching the opposite end, the disturbance often bounced back to return to the end we were holding. A single disturbance could be created by the single vibration of one end of the rope. On the other hand, a repeated disturbance would result in a repeated and regular vibration of the rope. The shape of the pattern formed in the rope was influenced by the frequency at which we vibrated it. If we vibrated the rope rapidly, then a short wave was created. And if we vibrated the rope less frequently (not as often), a long wave was created. While we were likely unaware of it as children, we were entering the world of the physics of waves as we contentedly played with the rope.

Then there is the "Hello, Good Morning!" wave. Whether encountered in the driveway as you begin your trip to school, on the street on the way to school, in the parking lot upon arrival to school, or in the hallway on the way to your first class, the "Hello, Good Morning!" wave provides a simple (yet excellent) example of physics in action. The simple back and forth motion of the hand is called *a wave*. When Mom commands us to "*wave* to Mr. Smith," she is telling us to raise our hand and to temporarily or even repeatedly vibrate it back and forth. The hand is raised, moved to the left, and then back to the far right and finally returns to its original position. Energy is put into the hand and the hand begins its back-and-forth vibrational motion. And we call the process of doing it "waving." Soon we will see how this simple act is representative of the nature of a physical wave.

We also encountered waves in Math class in the form of the sine and cosine function. We often plotted y = B•sine(A•x) on our calculator or by hand and observed that its graphical shape resembled the characteristic shape of a wave. There was a crest and a trough and a repeating pattern. If we changed the constant A in the equation, we noticed that we could change the *length* of the repeating pattern. And if we changed B in the equation, we noticed that we changed the *height* of the pattern. In math class, we encountered the underlying mathematical functions that describe the physical nature of waves.

Finally, we are familiar with microwaves and visible light waves. While we have never seen them, we believe that they exist because we have witnessed how they carry energy from one location to another. And similarly, we are familiar with radio waves and sound waves. Like microwaves, we have never seen them. Yet we believe they exist because we have witnessed the signals that they carry from one location to another and we have even learned how to tune into those signals through use of our ears or a tuner on a television or radio. Waves, as we will learn, carry energy from one location to another. And if the frequency of those waves can be changed, then we can also carry a complex signal that is capable of transmitting an idea or thought from one location to another. Perhaps this is one of the most important aspects of waves and will become a focus of our study in later units.

Waves are everywhere in nature. Our understanding of the physical world is not complete until we understand the nature, properties and behaviors of waves. The goal of this unit is to develop mental models of waves and ultimately apply those models to an understanding of the two most common types of waves - sound waves and light waves.

Lesson 1b) What is a Wave?

So waves are everywhere. But what makes a wave *a wave*? What characteristics, properties, or behaviors are shared by the phenomena that we typically characterize as being a wave? How can waves be described in a manner that allows us to understand their basic nature and qualities?

A wave can be described as a disturbance that travels through a medium from one location to another location. Consider a slinky wave as an example of a wave. When the slinky is stretched from end to end and is held at rest, it assumes a natural position known as the **equilibrium or rest position**. The coils of the slinky naturally assume this position, spaced equally far apart. To introduce a wave into the slinky, the first particle is displaced or moved from its equilibrium or rest position. The particle might be moved upwards or downwards, forwards or backwards; but once moved, it is returned to its original equilibrium or rest position. The act of moving the first coil of the slinky in a given direction and then returning it to its equilibrium position creates a **disturbance** in the slinky. We can then observe this disturbance moving through the slinky from one end to the other. If the first coil of the slinky is given a single back-and-forth vibration, then we call the observed motion of the disturbance through the slinky a *slinky pulse*. A **pulse** is a single disturbance moving through a medium from one location to another location. However, if the first coil of the slinky is continuously and periodically vibrated in a back-and-forth manner, we would observe a repeating disturbance moving within the slinky that endures over some prolonged period of time. The repeating and periodic disturbance that moves through a medium from one location to another is referred to as a **wave**.

When a slinky is stretched, the individual coils assume an equilibrium or rest position.

When the first coil of the slinky is repeatedly vibrated back and forth, a disturbance is created which travels through the slinky from one end to the other.

What is a Medium?

But what is meant by the word *medium*? A **medium** is a substance or material that carries the wave. You have perhaps heard of the phrase *news media*. The news media refers to the various institutions (newspaper offices, television stations, radio stations, etc.) within our society that carry the news from one location to another. The news *moves through* the media. The media doesn't make the news and the media isn't the same as the news. The news media is merely the *thing* that carries the news from its source to various locations. In a similar manner, a wave medium is the substance that carries a wave (or disturbance) from one location to another. The wave medium is not the wave and it doesn't make the wave; it merely carries or transports the wave from its source to other locations. In the case of our slinky wave, the medium through that the wave travels is the slinky coils. In the case of a water wave in the ocean, the medium through which the wave travels is the ocean water. In the case of a sound wave moving from the church choir to the pews, the medium through which the sound wave travels is the air in the room. And in the case of the stadium wave, the medium through which the stadium wave travels is the fans that are in the stadium.

Particle-to-Particle Interaction

To fully understand the nature of a wave, it is important to consider the medium as a collection of interacting *particles*. In other words, the medium is composed of parts that are capable of interacting with each other. The interactions of one particle of the medium with the next adjacent particle allow the disturbance to travel through the medium. In the case of the slinky wave, the *particles* or interacting parts of the medium are the individual coils of the slinky. In the case of a sound wave in air, the *particles* or interacting parts of the medium are the individual molecules of air. And in the case of a stadium wave, the *particles* or interacting parts of the medium are the fans in the stadium.

Consider the presence of a wave in a slinky. The first coil becomes disturbed and begins to push or pull on the second coil; this push or pull on the second coil will displace the second coil from its equilibrium position. As the second coil becomes displaced, it begins to push or pull on the third coil; the push or pull on the third coil displaces it from its equilibrium position. As the third coil becomes displaced, it begins to push or pull on the fourth coil. This process continues in consecutive fashion, with each individual *particle* acting to displace the adjacent particle. Subsequently, the disturbance travels through the medium. The medium can be pictured as a series of particles connected by springs. As one particle moves, the spring connecting it to the next particle begins to stretch and apply a force to its adjacent neighbor. As this neighbor begins to move, the spring attaching this neighbor to its neighbor begins to stretch and apply a force on its adjacent neighbor.

A medium can be modeled by a series of particles connected by springs. As one particle is displaced, ...

... the spring attaching it to the next is stretched and begins to exert a force on its neighbor, thus displacing the neighbor from its rest position.

A Wave Transports Energy and Not Matter

When a wave is present in a medium (that is, when there is a disturbance moving through a medium), the individual particles of the medium are only temporarily displaced from their rest position. There is always a force acting upon the particles that restores them to their original position. In a slinky wave, each coil of the slinky ultimately returns to its original position. In a water wave, each molecule of the water ultimately returns to its original position. And in a stadium wave, each fan in the bleacher ultimately returns to its original position. It is for this reason, that a wave is said to involve the movement of a disturbance without the movement of matter. The particles of the medium (water molecules, slinky coils, stadium fans) simply vibrate about a fixed position as the pattern of the disturbance moves from one location to another location.

Waves are said to be an **energy transport phenomenon**. As a disturbance moves through a medium from one particle to its adjacent particle, energy is being transported from one end of the medium to the other. In a slinky wave, a person imparts energy to the first coil by doing work upon it. The first coil receives a large amount of energy that it subsequently transfers to the second coil. When the first coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. The first coil transferred its energy to the second coil. The second coil then has a large amount of energy that it subsequently transfers to the third coil. When the second coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. The third coil has received the energy of the second coil. This process of energy transfer continues as each coil interacts with its neighbor. In this manner, energy is transported from one end of the slinky to the other, from its source to another location.

This characteristic of a wave as an energy transport phenomenon distinguishes waves from other types of phenomenon. Consider a common phenomenon observed at a softball game - the collision of a bat with a ball. A batter is able to transport energy from her to the softball by means of a bat. The batter applies a force to the bat, thus imparting energy to the bat in the form of kinetic energy. The bat then carries this energy to the softball and transports the energy to the softball upon collision. In this example, a bat is used to transport energy from the player to the softball. However, unlike wave phenomena, this phenomenon involves the transport of matter. The bat must move from its starting location to the contact location in order to transport energy. In a wave phenomenon, energy can move from one location to another, yet the particles of matter in the medium return to their fixed position. A wave transports its energy without transporting matter.

Waves are seen to move through an ocean or lake; yet the water always returns to its rest position. Energy is transported through the medium, yet the water molecules are not transported. Proof of this is the fact that there is still water in the middle of the ocean. The water has not moved from the middle of the ocean to the shore. If we were to observe a gull or duck at rest on the water, it would merely bob up-and-down in a somewhat circular fashion as the disturbance moves through the water. The gull or duck always returns to its original position. The gull or duck is not transported to the shore because the water on which it rests is not transported to the shore. In a water wave, energy is transported without the transport of water.

The same thing can be said about a stadium wave. In a stadium wave, the fans do not get out of their seats and walk around the stadium. We all recognize that it would be silly (and embarrassing) for any fan to even contemplate such a thought. In a stadium wave, each fan rises up and returns to the original seat. The disturbance moves through the stadium, yet the fans are not transported. Waves involve the transport of energy without the transport of matter.

In conclusion, a wave can be described as a disturbance that travels through a medium, transporting energy from one location (its source) to another location without transporting matter. Each individual particle of the medium is temporarily displaced and then returns to its original equilibrium positioned.

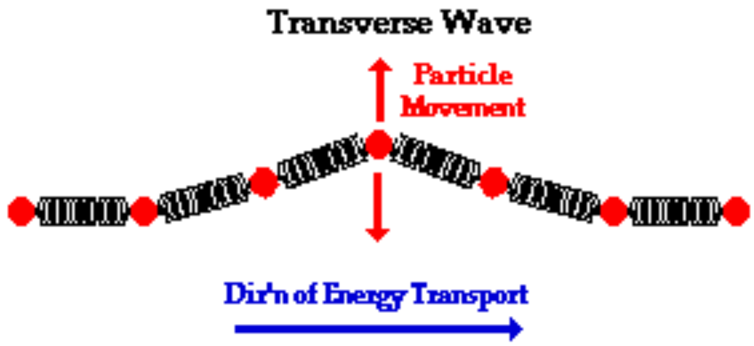
Lesson 1c) Categories of Waves

Waves come in many shapes and forms. While all waves share some basic characteristic properties and behaviors, some waves can be distinguished from others based on some observable (and some non-observable) characteristics. It is common to categorize waves based on these distinguishing characteristics.

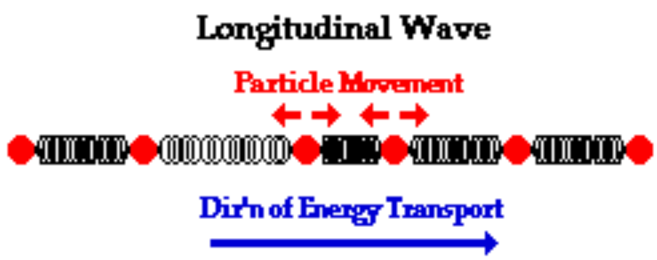
Longitudinal versus Transverse Waves versus Surface Waves

One way to categorize waves is on the basis of the direction of movement of the individual particles of the medium relative to the direction that the waves travel. Categorizing waves on this basis leads to three notable categories: transverse waves, longitudinal waves, and surface waves.

A **transverse wave** is a wave in which particles of the medium move in a direction perpendicular to the direction that the wave moves. Suppose that a slinky is stretched out in a horizontal direction across the classroom and that a pulse is introduced into the slinky on the left end by vibrating the first coil up and down. Energy will begin to be transported through the slinky from left to right. As the energy is transported from left to right, the individual coils of the medium will be displaced upwards and downwards. In this case, the particles of the medium move perpendicular to the direction that the pulse moves. This type of wave is a transverse wave. Transverse waves are always characterized by particle motion being perpendicular to wave motion.



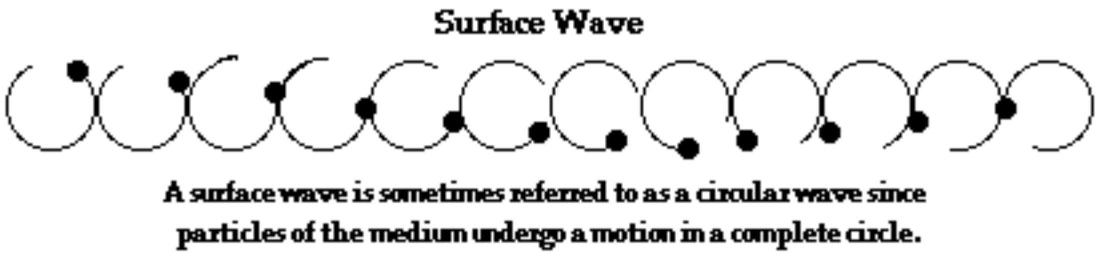
A **longitudinal wave** is a wave in which particles of the medium move in a direction parallel to the direction that the wave moves. Suppose that a slinky is stretched out in a horizontal direction across the classroom and that a pulse is introduced into the slinky on the left end by vibrating the first coil left and right. Energy will begin to be transported through the slinky from left to right. As the energy is transported from left to right, the individual coils of the medium will be displaced leftwards and rightwards. In this case, the particles of the medium move parallel to the direction that the pulse moves. This type of wave is a longitudinal wave. Longitudinal waves are always characterized by particle motion being parallel to wave motion.



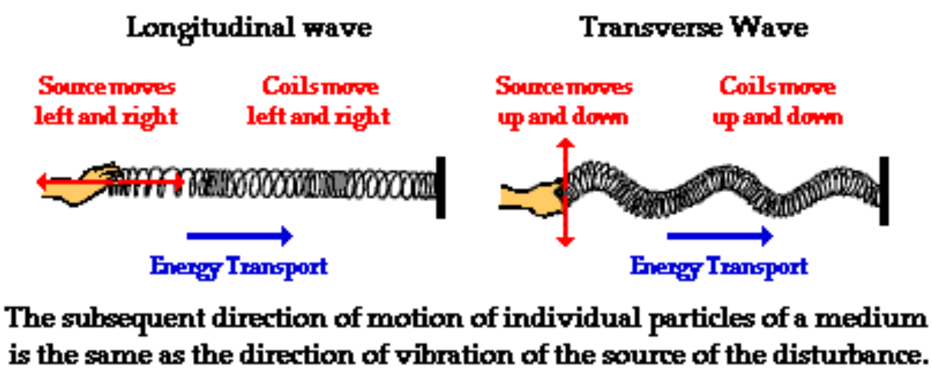
A sound wave traveling through air is a classic example of a longitudinal wave. As a sound wave moves from the lips of a speaker to the ear of a listener, particles of air vibrate back and forth in the same direction and the opposite direction of energy transport. Each individual particle pushes on its neighboring particle so as to push it forward. The *collision* of particle #1 with its neighbor serves to restore particle #1 to its original position and displace particle #2 in a forward direction. This back and forth motion of particles in the direction of energy transport creates regions within the medium where the particles are pressed together and other regions where the particles are spread apart. Longitudinal waves can always be quickly identified by the presence of such regions. This process continues along the *chain* of particles until the sound wave reaches the ear of the listener. A detailed discussion of sound is presented in another unit of The Physics Classroom Tutorial.

Waves traveling through a solid medium can be either transverse waves or longitudinal waves. Yet waves traveling through the bulk of a fluid (such as a liquid or a gas) are always longitudinal waves. Transverse waves require a relatively rigid medium in order to transmit their energy. As one particle begins to move it must be able to exert a pull on its nearest neighbor. If the medium is not rigid as is the case with fluids, the particles will slide past each other. This sliding action that is characteristic of liquids and gases prevents one particle from displacing its neighbor in a direction perpendicular to the energy transport. It is for this reason that only longitudinal waves are observed moving through the bulk of liquids such as our oceans. Earthquakes are capable of producing both transverse and longitudinal waves that travel through the solid structures of the Earth. When seismologists began to study earthquake waves they noticed that only longitudinal waves were capable of traveling through the core of the Earth. For this reason, geologists believe that the Earth's core consists of a liquid - most likely molten iron.

While waves that travel within the depths of the ocean are longitudinal waves, the waves that travel along the surface of the oceans are referred to as surface waves. A **surface wave** is a wave in which particles of the medium undergo a circular motion. Surface waves are neither longitudinal nor transverse. In longitudinal and transverse waves, all the particles in the entire bulk of the medium move in a parallel and a perpendicular direction (respectively) relative to the direction of energy transport. In a surface wave, it is only the particles at the surface of the medium that undergo the circular motion. The motion of particles tends to decrease as one proceeds further from the surface.



Any wave moving through a medium has a source. Somewhere along the medium, there was an initial displacement of one of the particles. For a slinky wave, it is usually the first coil that becomes displaced by the hand of a person. For a sound wave, it is usually the vibration of the vocal chords or a guitar string that sets the first particle of air in vibrational motion. At the location where the wave is introduced into the medium, the particles that are displaced from their equilibrium position always moves in the same direction as the source of the vibration. So if you wish to create a transverse wave in a slinky, then the first coil of the slinky must be displaced in a direction perpendicular to the entire slinky. Similarly, if you wish to create a longitudinal wave in a slinky, then the first coil of the slinky must be displaced in a direction parallel to the entire slinky.



Electromagnetic versus Mechanical Waves

Another way to categorize waves is on the basis of their ability or inability to transmit energy through a vacuum (i.e., empty space). Categorizing waves on this basis leads to two notable categories: electromagnetic waves and mechanical waves.

An **electromagnetic wave** is a wave that is capable of transmitting its energy through a vacuum (i.e., empty space). Electromagnetic waves are produced by the vibration of charged particles. Electromagnetic waves that are produced on the sun subsequently travel to Earth through the vacuum of outer space. Were it not for the ability of electromagnetic waves to travel to through a vacuum, there would undoubtedly be no life on Earth. All light waves are examples of electromagnetic waves. Light waves are the topic of another unit at The Physics Classroom Tutorial. While the basic properties and behaviors of light will be discussed, the detailed nature of an electromagnetic wave is quite complicated and beyond the scope of The Physics Classroom Tutorial.

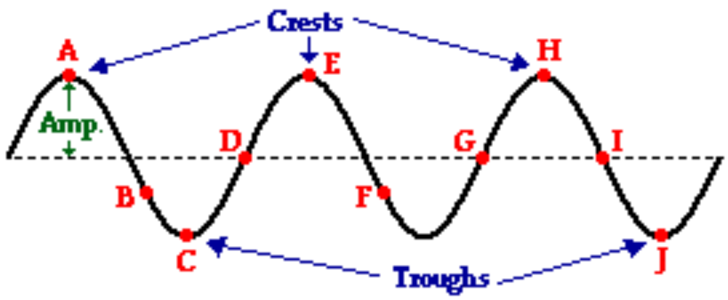
A **mechanical wave** is a wave that is not capable of transmitting its energy through a vacuum. Mechanical waves require a medium in order to transport their energy from one location to another. A sound wave is an example of a mechanical wave. Sound waves are incapable of traveling through a vacuum. Slinky waves, water waves, stadium waves, and jump rope waves are other examples of mechanical waves; each requires some medium in order to exist. A slinky wave requires the coils of the slinky; a water wave requires water; a stadium wave requires fans in a stadium; and a jump rope wave requires a jump rope.

The above categories represent just a few of the ways in which physicists categorize waves in order to compare and contrast their behaviors and characteristic properties. This listing of categories is not exhaustive; there are other categories as well. The five categories of waves listed here will be used periodically throughout this unit on waves as well as the units on sound and light

Waves - Lesson 2

Lesson 2a) The Anatomy of a Wave

A transverse wave is a wave in which the particles of the medium are displaced in a direction perpendicular to the direction of energy transport. A transverse wave can be created in a rope if the rope is stretched out horizontally and the end is vibrated back-and-forth in a vertical direction. If a snapshot of such a transverse wave could be taken so as to *freeze* the shape of the rope in time, then it would look like the following diagram.

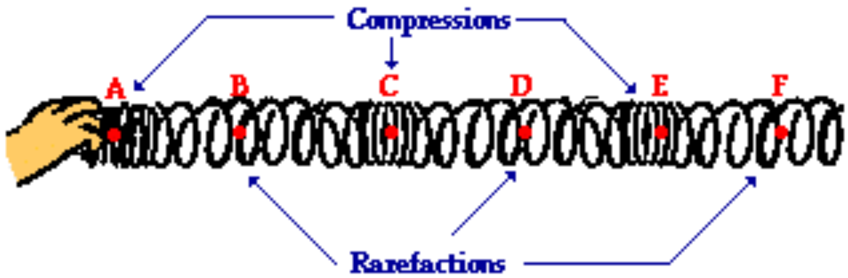


The dashed line drawn through the center of the diagram represents the equilibrium or rest position of the string. This is the position that the string would assume if there were no disturbance moving through it. Once a disturbance is introduced into the string, the particles of the string begin to vibrate upwards and downwards. At any given moment in time, a particle on the medium could be above or below the rest position. Points A, E and H on the diagram represent the crests of this wave. The **crest** of a wave is the point on the medium that exhibits the maximum amount of positive or upward displacement from the rest position. Points C and J on the diagram represent the troughs of this wave. The **trough** of a wave is the point on the medium that exhibits the maximum amount of negative or downward displacement from the rest position.

The wave shown above can be described by a variety of properties. One such property is amplitude. The **amplitude** of a wave refers to the maximum amount of displacement of a particle on the medium from its rest position. In a sense, the amplitude is the distance *from rest to crest*. Similarly, the amplitude can be measured from the rest position to the trough position. In the diagram above, the amplitude could be measured as the distance of a line segment that is perpendicular to the rest position and extends vertically upward from the rest position to point A.

The wavelength is another property of a wave that is portrayed in the diagram above. The **wavelength** of a wave is simply the length of one complete wave cycle. If you were to trace your finger across the wave in the diagram above, you would notice that your finger repeats its path. A wave is a repeating pattern. It repeats itself in a periodic and regular fashion over both time and space. And the length of one such spatial repetition (known as a *wave cycle*) is the wavelength. The wavelength can be measured as the distance from crest to crest or from trough to trough. In fact, the wavelength of a wave can be measured as the distance from a point on a wave to the corresponding point on the next cycle of the wave. In the diagram above, the wavelength is the horizontal distance from A to E, or the horizontal distance from B to F, or the horizontal distance from D to G, or the horizontal distance from E to H. Any one of these distance measurements would suffice in determining the wavelength of this wave.

A longitudinal wave is a wave in which the particles of the medium are displaced in a direction parallel to the direction of energy transport. A longitudinal wave can be created in a slinky if the slinky is stretched out horizontally and the end coil is vibrated back-and-forth in a horizontal direction. If a snapshot of such a longitudinal wave could be taken so as to *freeze* the shape of the slinky in time, then it would look like the following diagram.



Because the coils of the slinky are vibrating longitudinally, there are regions where they become pressed together and other regions where they are spread apart. A region where the coils are pressed together in a small amount of space is known as a compression. A **compression** is a point on a medium through which a longitudinal wave is traveling that has the maximum density. A region where the coils are spread apart, thus maximizing the distance between coils, is known as a rarefaction. A **rarefaction** is a point on a medium through which a longitudinal wave is traveling that has the minimum density. Points A, C and E on the diagram above represent compressions and points B, D, and F represent rarefactions. While a transverse wave has an alternating pattern of crests and troughs, a longitudinal wave has an alternating pattern of compressions and rarefactions.

As discussed above, the wavelength of a wave is the length of one complete cycle of a wave. For a transverse wave, the wavelength is determined by measuring from crest to crest. A longitudinal wave does not have crest; so how can its wavelength be determined? The wavelength can always be determined by measuring the distance between any two corresponding points on adjacent waves. In the case of a longitudinal wave, a wavelength measurement is made by measuring the distance from a compression to the next compression or from a rarefaction to the next rarefaction. On the diagram above, the distance from point A to point C or from point B to point D would be representative of the wavelength.

Lesson 2b) Frequency and Period of a Wave

The nature of a wave was discussed in Lesson 1 of this unit. In that lesson, it was mentioned that a wave is created in a slinky by the periodic and repeating vibration of the first coil of the slinky. This vibration creates a disturbance that moves through the slinky and transports energy from the first coil to the last coil. A single back-and-forth vibration of the first coil of a slinky introduces a pulse into the slinky. But the act of continually vibrating the first coil with a back-and-forth motion in periodic fashion introduces a wave into the slinky.

Suppose that a hand holding the first coil of a slinky is moved back-and-forth two complete cycles in one second. The rate of the hand's motion would be 2 cycles/second. The first coil, being attached to the hand, in turn would vibrate at a rate of 2 cycles/second. The second coil, being attached to the first coil, would vibrate at a rate of 2 cycles/second. The third coil, being attached to the second coil, would vibrate at a rate of 2 cycles/second. In fact, every coil of the slinky would vibrate at this rate of 2 cycles/second. This rate of 2 cycles/second is referred to as the frequency of the wave. The **frequency** of a wave refers to how often the particles of the medium vibrate when a wave passes through the medium. Frequency is a part of our common, everyday language. For example, it is not uncommon to hear a question like "How *frequently* do you mow the lawn during the summer months?" Of course the question is an inquiry about *how often* the lawn is mowed and the answer is usually given in the form of "1 time per week." In mathematical terms, the frequency is the number of complete vibrational cycles of a medium per a given amount of time. Given this definition, it is reasonable that the quantity *frequency* would have units of cycles/second, waves/second, vibrations/second, or something/second. Another unit for frequency is the **Hertz** (abbreviated Hz) where 1 Hz is equivalent to 1 cycle/second. If a coil of slinky makes 2 vibrational cycles in one second, then the frequency is 2 Hz. If a coil of slinky makes 3 vibrational cycles in one second, then the frequency is 3 Hz. And if a coil makes 8 vibrational cycles in 4 seconds, then the frequency is 2 Hz (8 cycles/4 s = 2 cycles/s).

The quantity frequency is often confused with the quantity period. Period refers to the time that it takes to do something. When an event occurs repeatedly, then we say that the event is **periodic** and refer to the time for the event to repeat itself as the period. The **period** of a wave is the time for a particle on a medium to make one complete vibrational cycle. Period, being a time, is measured in units of time such as seconds, hours, days or years. The period of orbit for the Earth around the Sun is approximately 365 days; it takes 365 days for the Earth to complete a cycle. The period of a typical class at a high school might be 55 minutes; every 55 minutes a class cycle begins (50 minutes for class and 5 minutes for passing time means that a class begins every 55 minutes). The period for the minute hand on a clock is 3600 seconds (60 minutes); it takes the minute hand 3600 seconds to complete one cycle around the clock.

Frequency and period are distinctly different, yet related, quantities. Frequency refers to how often something happens. Period refers to the time it takes something to happen. Frequency is a rate quantity. Period is a time quantity. Frequency is the cycles/second. Period is the seconds/cycle. As an example of the distinction and the relatedness of frequency and period, consider a woodpecker that drums upon a tree at a periodic rate. If the woodpecker drums upon a tree 2 times in one second, then the frequency is 2 Hz. Each drum must endure for one-half a second, so the period is 0.5 s. If the woodpecker drums upon a tree 4 times in one second, then the frequency is 4 Hz; each drum must endure for one-fourth a second, so the period is 0.25 s. If the woodpecker drums upon a tree 5 times in one second, then the frequency is 5 Hz; each drum must endure for one-fifth a second, so the period is 0.2 s. Do you observe the relationship? Mathematically, the period is the reciprocal of the frequency and vice versa. In equation form, this is expressed as follows.

$$\text{period} = \frac{1}{\text{frequency}} \qquad \text{frequency} = \frac{1}{\text{period}}$$

Since the symbol **f** is used for frequency and the symbol **T** is used for period, these equations are also expressed as:

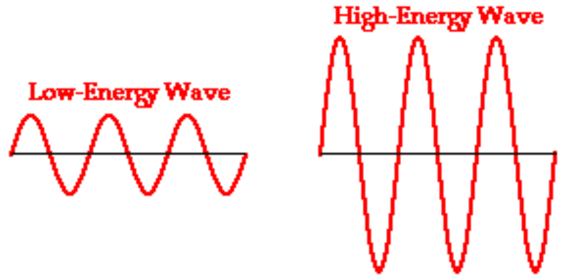
$$T = \frac{1}{f} \qquad f = \frac{1}{T}$$

The quantity frequency is also confused with the quantity speed. The speed of an object refers to how fast an object is moving and is usually expressed as the distance traveled per time of travel. For a wave, the speed is the distance traveled by a given point on the wave (such as a crest) in a given period of time. So while wave frequency refers to the number of cycles occurring per second, wave speed refers to the meters traveled per second. A wave can vibrate back and forth very frequently, yet have a small speed; and a wave can vibrate back and forth with a low frequency, yet have a high speed. Frequency and speed are distinctly different quantities. Wave speed will be discussed in more detail later in this lesson.

Lesson 2c) Energy Transport and the Amplitude of a Wave

As mentioned earlier, a wave is an energy transport phenomenon that transports energy along a medium without transporting matter. A pulse or a wave is introduced into a slinky when a person holds the first coil and gives it a back-and-forth motion. This creates a disturbance within the medium; this disturbance subsequently travels from coil to coil, transporting energy as it moves. The energy is imparted to the medium by the person as he/she does work upon the first coil to give it kinetic energy. This energy is transferred from coil to coil until it arrives at the end of the slinky. If you were holding the opposite end of the slinky, then you would feel the energy as it reaches your end. In fact, a high energy pulse would likely do some rather noticeable work upon your hand upon reaching the end of the medium; the last coil of the medium would displace you hand in the same direction of motion of the coil. For the same reasons, a high energy ocean wave can do considerable damage to the rocks and piers along the shoreline when it crashes upon it.

The amount of energy carried by a wave is related to the amplitude of the wave. A high energy wave is characterized by a high amplitude; a low energy wave is characterized by a low amplitude. As discussed earlier in Lesson 2, the amplitude of a wave refers to the maximum amount of displacement of a particle on the medium from its rest position. The logic underlying the energy-amplitude relationship is as follows: If a slinky is stretched out in a horizontal direction and a transverse pulse is introduced into the slinky, the first coil is given an initial amount of displacement. The displacement is due to the force applied by the person upon the coil to displace it a given amount from rest. The more energy that the person puts into the pulse, the more work that he/she will do upon the first coil. The more work that is done upon the first coil, the more displacement that is given to it. The more displacement that is given to the first coil, the more amplitude that it will have. So in the end, the amplitude of a transverse pulse is related to the energy which that pulse transports through the medium. Putting a lot of energy into a transverse pulse will not affect the wavelength, the frequency or the speed of the pulse. The energy imparted to a pulse will only affect the amplitude of that pulse.



The amplitude of a wave is related to the energy which it transports.

Consider two identical slinkies into which a pulse is introduced. If the same amount of energy is introduced into each slinky, then each pulse will have the same amplitude. But what if the slinkies are different? What if one is made of zinc and the other is made of copper? Will the amplitudes now be the same or different? If a pulse is introduced into two different slinkies by imparting the same amount of energy, then the amplitudes of the pulses will not necessarily be the same. In a situation such as this, the actual amplitude assumed by the pulse is dependent upon two types of factors: an inertial factor and an elastic factor. Two different materials have different mass densities. The imparting of energy to the first coil of a slinky is done by the application of a force to this coil. More massive slinkies have a greater inertia and thus tend to resist the force; this increased resistance by the greater mass tends to cause a reduction in the amplitude of the pulse. Different materials also have differing degrees of *springiness* or elasticity. A more elastic medium will tend to offer less resistance to the force and allow a greater amplitude pulse to travel through it; being less rigid (and therefore more elastic), the same force causes a greater amplitude.

The energy transported by a wave is directly proportional to the square of the amplitude of the wave. This energy-amplitude relationship is sometimes expressed in the following manner.

$$E \propto A^2$$

This means that a doubling of the amplitude of a wave is indicative of a quadrupling of the energy transported by the wave. A tripling of the amplitude of a wave is indicative of a nine-fold increase in the amount of energy transported by the wave. And a quadrupling of the amplitude of a wave is indicative of a 16-fold increase in the amount of energy transported by the wave. The table at the right further expresses this energy-amplitude relationship. Observe that whenever the amplitude increased by a given factor, the energy value is increased by the same factor squared. For example, changing the amplitude from 1 unit to 2 units represents a 2-fold increase in the amplitude and is accompanied by a 4-fold (2^2) increase in the energy; thus 2 units of energy becomes 4 times bigger - 8 units. As another example, changing the amplitude from 1 unit to 4 units represents a 4-fold increase in the amplitude and is accompanied by a 16-fold (4^2) increase in the energy; thus 2 units of energy becomes 16 times bigger - 32 units.

Amp.	Energy
1 unit	2 units
2 units	8 units
3 units	18 units
4 units	32 units
5 units	50 units

Lesson 2d) The Speed of a Wave

A wave is a disturbance that moves along a medium from one end to the other. If one watches an ocean wave moving along the medium (the ocean water), one can observe that the crest of the wave is moving from one location to another over a given interval of time. The crest is observed to *cover* distance. The speed of an object refers to how fast an object is moving and is usually expressed as the distance traveled per time of travel. In the case of a wave, the speed is the distance traveled by a given point on the wave (such as a crest) in a given interval of time. In equation form,

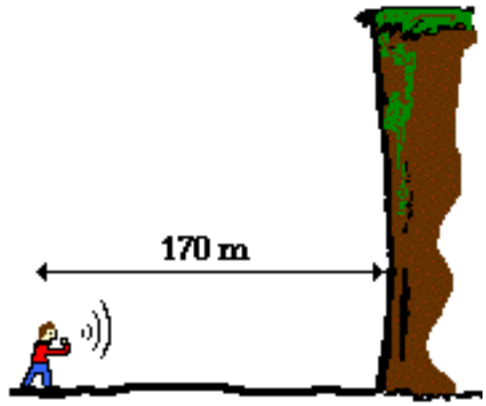
$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

If the crest of an ocean wave moves a distance of 20 meters in 10 seconds, then the speed of the ocean wave is 2 m/s. On the other hand, if the crest of an ocean wave moves a distance of 25 meters in 10 seconds (the same amount of time), then the speed of this ocean wave is 2.5 m/s. The faster wave travels a greater distance in the same amount of time.

Sometimes a wave encounters the end of a medium and the presence of a different medium. For example, a wave introduced by a person into one end of a slinky will travel through the slinky and eventually reach the end of the slinky and the presence of the hand of a second person. One behavior that waves undergo at the end of a medium is reflection. The wave will reflect or bounce off the person's hand. When a wave undergoes reflection, it remains within the medium and merely reverses its direction of travel. In the case of a slinky wave, the disturbance can be seen traveling back to the original end. A slinky wave that travels to the end of a slinky and back has *doubled its distance*. That is, by reflecting back to the original location, the wave has traveled a distance that is equal to twice the length of the slinky.

Reflection phenomena are commonly observed with sound waves. When you *let out a holler* within a canyon, you often hear the echo of the holler. The sound wave travels through the medium (air in this case), reflects off the canyon wall and returns to its origin (you). The result is that you hear the echo (the reflected sound wave) of your holler. A classic physics problem goes like this:

Noah stands 170 meters away from a steep canyon wall. He shouts and hears the echo of his voice one second later. What is the speed of the wave?



In this instance, the sound wave travels 340 meters in 1 second, so the speed of the wave is 340 m/s. Remember, when there is a reflection, the wave *doubles its distance*. In other words, the distance traveled by the sound wave in 1 second is equivalent to the 170 meters down to the canyon wall plus the 170 meters back from the canyon wall.

Variables Affecting Wave Speed

What variables affect the speed at which a wave travels through a medium? Does the frequency or wavelength of the wave affect its speed? Does the amplitude of the wave affect its speed? Or are other variables such as the mass density of the medium or the elasticity of the medium responsible for affecting the speed of the wave? These questions are often investigated in the form of a lab in a physics classroom.

Suppose a wave generator is used to produce several waves within a rope of a measurable tension. The wavelength, frequency and speed are determined. Then the frequency of vibration of the generator is changed to investigate the affect of frequency upon wave speed. Finally, the tension of the rope is altered to investigate the affect of tension upon wave speed. Sample data for the experiment are shown below.

Speed of a Wave Lab - Sample Data

Trial	Tension (N)	Frequency (Hz)	Wavelength (m)	Speed (m/s)
1	2.0	4.05	4.00	16.2
2	2.0	8.03	2.00	16.1
3	2.0	12.30	1.33	16.4
4	2.0	16.2	1.00	16.2
5	2.0	20.2	0.800	16.2
6	5.0	12.8	2.00	25.6
7	5.0	19.3	1.33	25.7
8	5.0	25.5	1.00	25.5

In the first five trials, the tension of the rope was held constant and the frequency was systematically changed. The data in rows 1-5 of the table above demonstrate that a change in the frequency of a wave does not affect the speed of the wave. The speed remained a near constant value of approximately 16.2 m/s. The small variations in the values for the speed were the result of experimental error, rather than a demonstration of some physical law. The data convincingly show that wave frequency does not affect wave speed. An increase in wave frequency caused a decrease in wavelength while the wave speed remained constant.

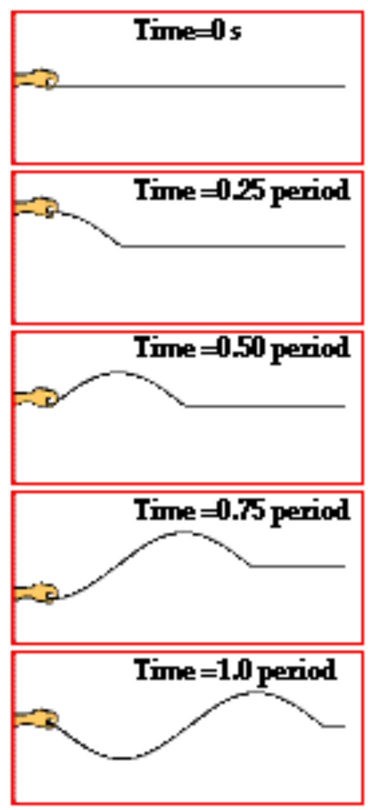
The last three trials involved the same procedure with a different rope tension. Observe that the speed of the waves in rows 6-8 is distinctly different than the speed of the wave in rows 1-5. The obvious cause of this difference is the alteration of the tension of the rope. The speed of the waves was significantly higher at higher tensions. Waves travel through tighter ropes at higher speeds. So while the frequency did not affect the speed of the wave, the tension in the medium (the rope) did. In fact, the speed of a wave is not dependent upon (causally affected by) properties of the wave itself. Rather, the speed of the wave is dependent upon the properties of the medium such as the tension of the rope.

One theme of this unit has been that "a wave is a disturbance moving through a medium." There are two distinct objects in this phrase - the "wave" and the "medium." The medium could be water, air, or a slinky. These media are distinguished by their properties - the material they are made of and the physical properties of that material such as the density, the temperature, the elasticity, etc. Such physical properties describe the material itself, not the wave. On the other hand, waves are distinguished from each other by their properties - amplitude, wavelength, frequency, etc. These properties describe the wave, not the material through which the wave is moving. The lesson of the lab activity described above is that wave speed depends upon the medium through which the wave is moving. Only an alteration in the properties of the medium will cause a change in the speed.

Lesson 2e) The Wave Equation

As was discussed in Lesson 1, a wave is produced when a vibrating source periodically disturbs the first particle of a medium. This creates a wave pattern that begins to travel along the medium from particle to particle. The frequency at which each individual particle vibrates is equal to the frequency at which the source vibrates. Similarly, the period of vibration of each individual particle in the medium is equal to the period of vibration of the source. In one period, the source is able to displace the first particle upwards from rest, back to rest, downwards from rest, and finally back to rest. This complete back-and-forth movement constitutes one complete wave cycle.

The diagrams at the right show several "snapshots" of the production of a wave within a rope. The motion of the disturbance along the medium after every one-fourth of a period is depicted. Observe that in the time it takes from the first to the last snapshot, the hand has made one complete back-and-forth motion. A period has elapsed. Observe that during this same amount of time, the leading edge of the disturbance has moved a distance equal to one complete wavelength. So in a time of one period, the wave has moved a distance of one wavelength. Combining this information with the equation for speed (speed = distance/time), it can be said that the speed of a wave is also the wavelength/period.



$$\text{Speed} = \frac{\text{Wavelength}}{\text{Period}}$$

Since the period is the reciprocal of the frequency, the expression 1/f can be substituted into the above equation for period. Rearranging the equation yields a new equation of the form:

Speed = Wavelength • Frequency

The above equation is known as the wave equation. It states the mathematical relationship between the speed (**v**) of a wave and its wavelength (**λ**) and frequency (**f**). Using the symbols **v**, **λ**, and **f**, the equation can be rewritten as

The equation shown below is known as the general wave equation:

$$v = f \cdot \lambda$$