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NAME____ **HR**_____

Waves and Wavelike Motion

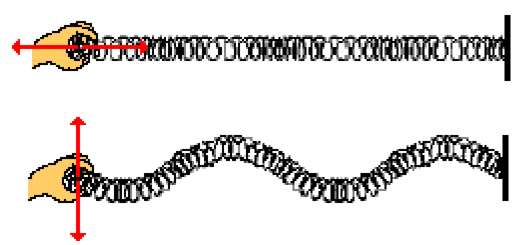
Waves are everywhere. Whether we recognize it or not, we encounter waves on a daily basis. Sound waves, visible light waves, radio waves, microwaves, water waves, stadium waves, earthquake waves, waves on a string, and slinky waves. These are just a few of the examples of our daily encounters with waves.

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

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.

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. 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.

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 (**reflection**) from where it started.



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

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. This is called a **pulse**. On the other hand, a repeated disturbance would result in a repeated and regular vibration of the rope. This can be called a wave or a **wave train**. 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.

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. This is the most important fact to know about waves: ***they transmit energy***. 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.

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**.

What is a Wave?

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.

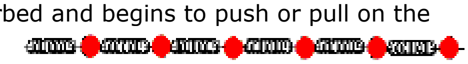
What is a Medium?

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 which 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.

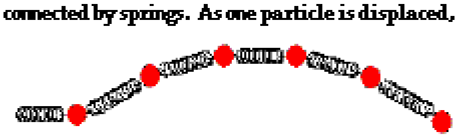
Particle-to-Particle Interaction

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



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.

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.

Animation

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. This energy passes to the second, then third, etc. until it reaches the other person's hand. The energy then slightly moves the second person's hand. Energy transferred from one end to the other, but molecules did not transfer to new locations. 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. 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 position.

Check Your Understanding

TRUE or **FALSE**:

1. In order for John to hear Jill, air molecules must move from the lips of Jill to the ears of John.

2. Curly and Moe are conducting a wave experiment using a slinky. Curly introduces a disturbance into the slinky by giving it a quick back and forth jerk. Moe places his cheek (facial) at the opposite end of the slinky. Using the terminology of this unit, describe what Moe experiences as the pulse reaches the other end of the slinky.

3. Mac and Tosh are experimenting with pulses on a rope. They vibrate an end up and down to create the pulse and observe it moving from end to end. How does the position of a point on the rope, before the pulse comes, compare to the position after the pulse has passed?

4. Minute after minute, hour after hour, day after day, ocean waves continue to splash onto the shore. Explain why the beach is not completely submerged and why the middle of the ocean has not yet been depleted of its water supply.

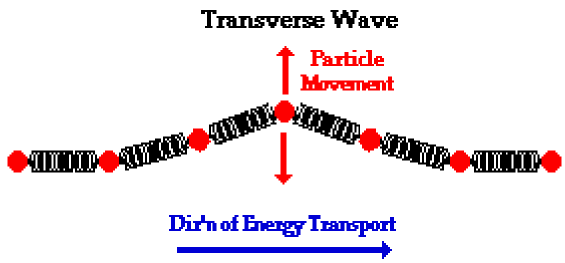
5. A medium is able to transport a wave from one location to another because the particles of the medium are ____.
a. frictionless
b. isolated from one another
c. able to interact
d. very light

Categories of Waves

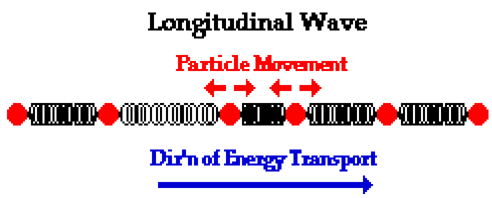
Waves come in many shapes and forms. While all waves share some basic characteristic properties and behaviors, some waves can be distinguished from others based on some observable (and some non-observable) characteristics. It is common to categorize waves based on these distinguishing characteristics.

Longitudinal versus Transverse Waves versus Surface Waves

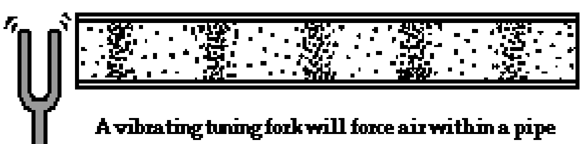
A **transverse wave** is a wave in which particles of the medium move in a direction perpendicular to the direction that the wave moves. Imagine a jump rope wave. If you jerk the rope up, the molecules of the rope go up then back down. This pattern continues along the rope—molecules up, then down. But the wave itself is travelling sideways toward the other kid. Transverse waves have particles moving perpendicular to the actual wave.



A **longitudinal or compression wave** is a wave in which particles of the medium move in the same direction that the wave moves. This can be seen by pulling back a few slinky coils and letting them snap toward the other person. This type of wave is a longitudinal wave. Longitudinal waves have particle motion that is parallel to wave motion.



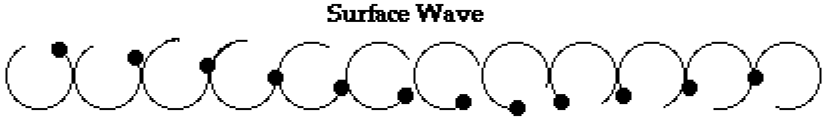
A sound wave traveling through air is a longitudinal wave. As a sound wave moves from the lips of a speaker to the ear of a listener, particles of air vibrate back and forth in the same direction and the opposite direction of energy transport. Each individual particle pushes on its neighboring particle so as to push it forward. After colliding, the original particle bounces back to its original spot, like a basketball bouncing off a backboard. This back and forth motion of particles creates areas where the particles are pressed together and other areas where the particles are spread apart. This process continues along the *chain* of particles until the sound wave reaches the ear of the listener.



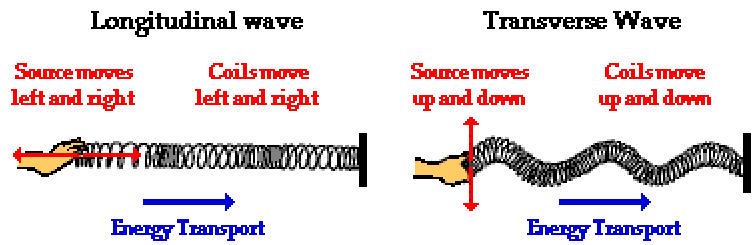
A vibrating tuning fork will force air within a pipe to begin vibrating back and forth in a direction parallel to the energy transport; sound is a longitudinal wave.

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.

Surface Wave



A surface wave is sometimes referred to as a circular wave since particles of the medium undergo a motion in a complete circle.



The subsequent direction of motion of individual particles of a medium is the same as the direction of vibration of the source of the disturbance.

Animation

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 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.

Animation

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.

Check Your Understanding

1. A transverse wave is transporting energy from east to west. The particles of the medium will move_____.
   a. east to west only
   b. both eastward and westward
   c. north to south only
   d. both northward and southward

2. A wave is transporting energy from left to right. The particles of the medium are moving back and forth in a leftward and rightward direction. This type of wave is known as a _____.
   a. mechanical
   b. electromagnetic
   c. transverse
   d. longitudinal

3. Describe how the fans in a stadium must move in order to produce a longitudinal stadium wave.

4. A sound wave is a mechanical wave, not an electromagnetic wave. This means that
   a. particles of the medium move perpendicular to the direction of energy transport.
   b. a sound wave transports its energy through a vacuum.
   c. particles of the medium regularly and repeatedly oscillate about their rest position.
   d. a medium is required in order for sound waves to transport energy.

5. A science fiction film depicts inhabitants of one spaceship (in outer space) hearing the sound of a nearby spaceship as it zooms past at high speeds. Critique the physics of this film.

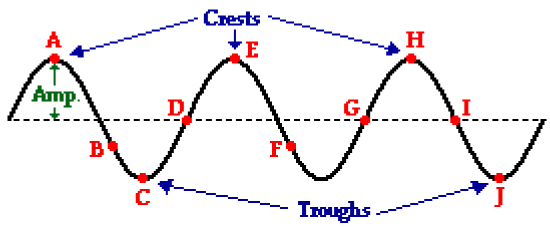
6. Which of the following is not a characteristic of mechanical waves?

a. They consist of disturbances or oscillations of a medium.
b. They transport energy.
c. They travel in a direction that is at right angles to the direction of the particles of the medium.
d. They are created by a vibrating source.

7. The sonar device on a fishing boat uses underwater sound to locate fish. Would you expect sonar to be a longitudinal or a transverse wave?

The Anatomy of a Wave

If a snapshot of 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.

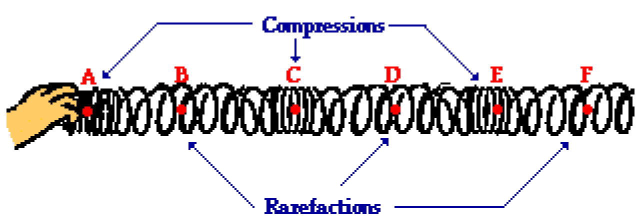


The dashed line drawn through the center of the diagram represents the **equilibrium or rest position** of the string. This is the position that the string would assume if there were no disturbance moving through it. Once a disturbance is introduced into the string, the particles of the string begin 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 greatest distance a particle moves 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.

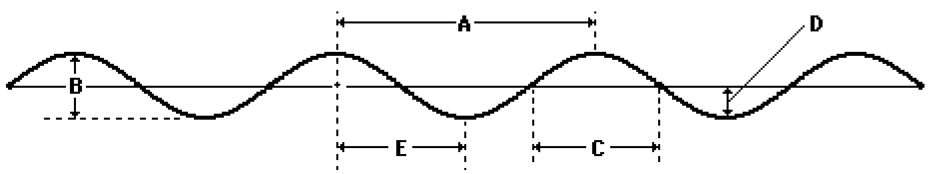


Because the coils of the slinky are vibrating longitudinally, there are regions where they become pressed together and other regions where they are spread apart. A region where the coils are pressed together in a small amount of space is known as a compression. A **compression** is a point on a medium 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. 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.

Check Your Understanding

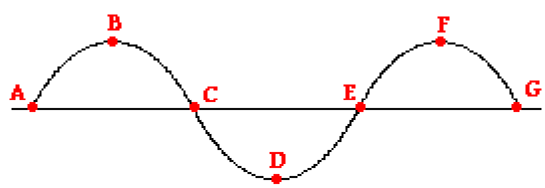
Consider the diagram below in order to answer questions #1-2.



1. The wavelength of the wave in the diagram above is given by letter _______.

2. The amplitude of the wave in the diagram above is given by letter ______.

3. Indicate the interval that represents one full wavelength.



a. A to C
b. B to D
c. A to G
d. C to G

Frequency and Period of a 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 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 wavelength/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 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.

Check Your Understanding

Throughout this unit, internalize the meaning of terms such as period, frequency, and wavelength. Utilize the meaning of these terms to answer conceptual questions; avoid a *formula fixation*.

2. Frieda the fly flaps its wings back and forth 121 times each second. The frequency of the wing flapping is ____________ per second.

3. A tennis coach paces back and forth along the sideline 10 times in 2 minutes. The frequency of her pacing is _________ Hz.

a. 5.0 b. 0.20 c. 0.12 d. 0.083

4. Non-digital clocks (which are becoming more rare) have a second hand that rotates around in a regular and repeating fashion. The frequency of rotation of a second hand on a clock is ________ Hz.

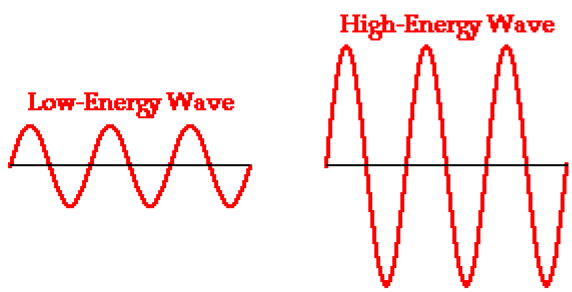
a. 1/60 b. 1/12 c. ½ d. 1 e. 60

5. Olive Udadi accompanies her father to the park for an afternoon of fun. While there, she hops on the swing and begins a motion characterized by a complete back-and-forth cycle every 2 seconds. The frequency of swing is __________.

a. 0.5 Hz b. 1 Hz c. 2 Hz

Energy Transport and the Amplitude of a Wave

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. A high amplitude ocean wave can do considerable damage to the rocks and piers along the shoreline when it crashes upon it, compared to a low one. The energy is imparted by high amplitude waves give it greater kinetic energy.



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

Check Your Understanding

1. Mac and Tosh stand 8 meters apart and demonstrate the motion of a transverse wave on a snakey. The wave e can be described as having a vertical distance of 32 cm from a trough to a crest, a frequency of 2.4 Hz, and a horizontal distance of 48 cm from a crest to the nearest trough. Determine the amplitude, period, and wavelength of such a wave.

2. An ocean wave has an amplitude of 2.5 m. Weather conditions suddenly change such that the wave has an amplitude of 5.0 m. The amount of energy transported by the wave is ___________.

a. greater
b. less
c. remains the same