California Physics Standard 4a Send comments to: layton@physics.ucla.edu W1

4. Waves have characteristic properties that do not depend on the type of wave.

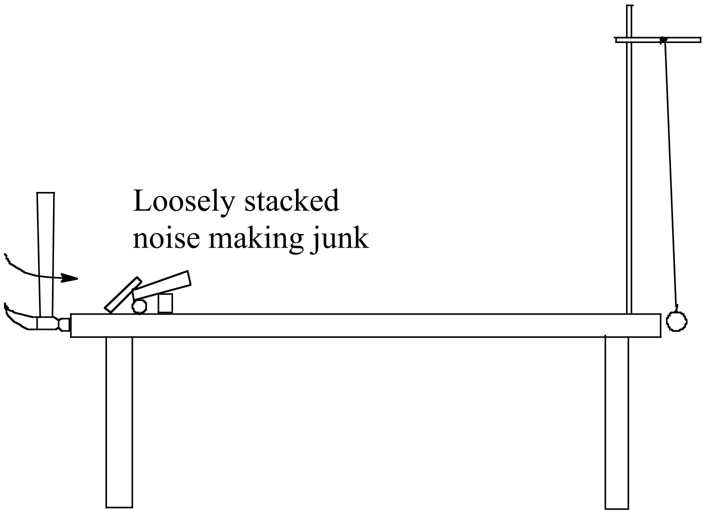
As a basis for understanding this concept:

a. Students know waves carry energy from one place to another.

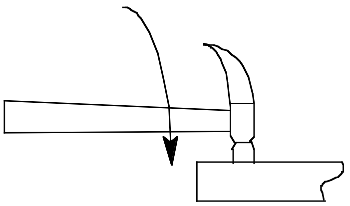
The important idea about waves is that they can transfer energy without any net motion of the medium transporting the energy. In mechanical waves (ocean waves, sound waves, etc.) the medium supporting the wave transports energy without transporting momentum. When Maxwell developed the theory of electromagnetic waves, the idea that an electromagnetic wave could not transport momentum was retained as a general property of the electromagnetic wave. However, when Einstein introduced the idea of the particle nature of light, later to be called the photon, the possibility of electromagnetic waves transporting momentum was advanced. Compton demonstrated experimentally that X-rays could transfer momentum as well as energy. However, when discussing the wave nature of both mechanical and electromagnetic waves, the concept to stress is that waves can transfer energy with no net motion of the substance supporting the wave.

Students are probably familiar with the stunt called “the wave” performed by fans at a football game. The cheerleader directs successive columns of fans to stand up, wave and then to sit down, giving the impression that something is moving across the stadium. Certain types of lights in signs can give the appearance of motion if they are turned off and on in an appropriate sequence. The important thing to stress with these examples is that the motion is only apparent. Nothing really moves in the direction of “wave travel.”

A demonstration to show that energy can be transmitted without any net motion of the medium uses a substantial table with a pendulum suspended so it lightly touches the table, as illustrated on the right. A few pieces of loosely stacked junk that will rattle making a noise is placed on the left end of the table. When the end of the table is struck with a hammer, the pendulum will bounce away from the table but the junk on the left end will make no noise.



If, however, the hammer is struck with a downward blow on the table, the noise producing junk will rattle but the pendulum will not bounce off of the end of the table. This is both a good introduction to the fact that energy is transferred without any net motion of the medium as well as transverse and longitudinal waves.



California Physics Standard 4b Send comments to: layton@physics.ucla.edu **W2**

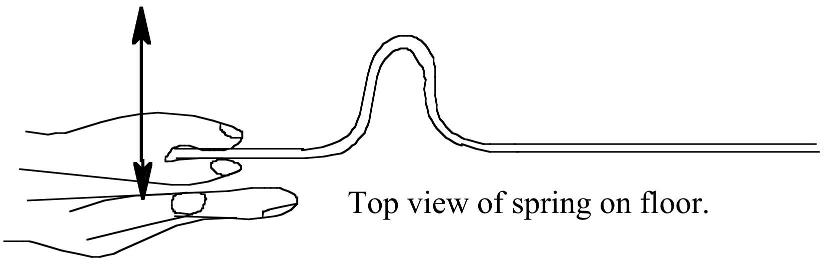
4. Waves have characteristic properties that do not depend on the type of wave.

As a basis for understanding this concept:

b. Students know how to identify transverse and longitudinal waves in mechanical media such as springs, ropes, and the Earth (seismic waves).

Producing longitudinal and transverse pulses:

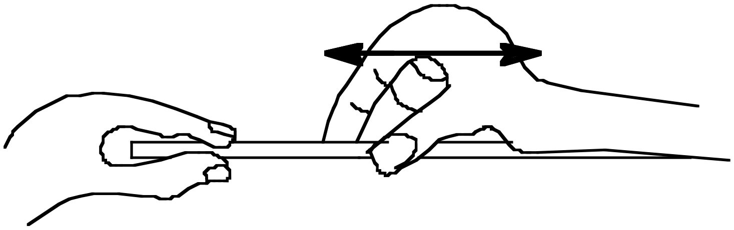
The essential idea to stress is that the particles in a longitudinal wave move back and forth in the same direction as the wave travels and in a transverse wave, the particles move perpendicular (or transverse) to the direction of wave travel. Longitudinal and transverse pulses can be easily demonstrated with a coiled metal spring (often called a snake spring) or, not quite as well, with a slinkey. Place the spring on the floor and use your hand to create a quick transverse pulse. The technique is to move outward and back as rapidly as possible, stopping your hand with your other hand when it returns to the central position. This is illustrated in top view on the right.



Top view of spring on floor.

Using this technique, different sized pulses can be created (both in amplitude and pulse length) and it is easy to demonstrate that no matter the size or shape of the pulse, it always moves at the same speed.

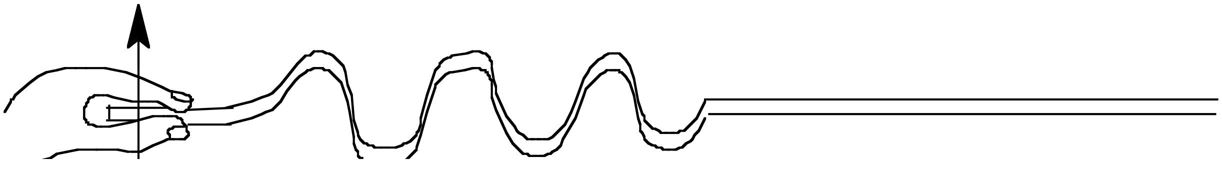
It is also possible to produce a longitudinal pulse in a snake spring by gathering spring coils into a tight compressed bunch along the direction of the spring and quickly releasing this bunch of coils.



One interesting additional demonstration with pulses in a spring is to show that transverse pulses travel slower than longitudinal pulses. It is possible to pull the spring to one side and to compress some spring coils into a single "transverse and longitudinal" bunch. When this bunch is released, a noticeable difference in the arrival time of the pulses at the other end will be observed. This demonstration can be extended to a discussion of the difference in speeds of the P and S earthquake waves.

Producing traveling waves:

Later we will discuss standing waves but it is best to show students how waves travel with a quick burst of three or four wavelengths so they can see them travel down the spring, reflect off of the fixed end at the other end of the spring and return to the starting point. Transverse waves show this best as illustrated below:



Allowing this small transverse wave train to move down to the end of the spring and return will enable the students to see clearly that the waves appear to move, yet if a small piece of string were tied to any point on the spring, it will also be clear that it only moves transverse to the direction of wave travel.

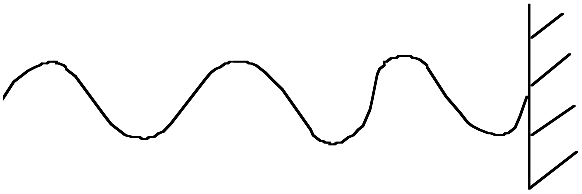
Using a pulse, it is also instructive to show students that the pulse inverts in phase as it reflects from a fixed end. This also happens with the small wave train but it is not so obvious. This exercise will prepare the students for a better understanding of standing waves.

Producing standing waves:

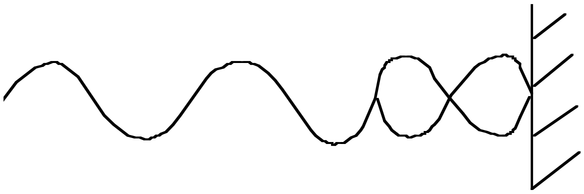
Although the standards do not specifically address standing waves, this would be a good time to show students the basics of standing waves. The basics of standing waves are essential to understanding musical instruments, room acoustics, TV antennas and many other related topics.

The key to producing standing waves is that waves returning from the reflected end begin to form an interference pattern with the waves that are being generated. This will become apparent if a wave train is generated (as in the previous section) followed by a continuously generated set of waves of the same frequency. If done properly, the students will see the initial wave train move down the spring but as the reflected wave begins to return, nodes and antinodes will be produced in succession as the reflected wave returns to the source.

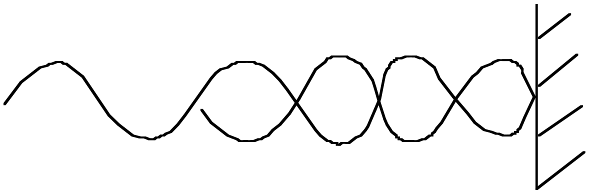
The initial wave train is launched and is seen to travel down the spring until it reaches the fixed end.



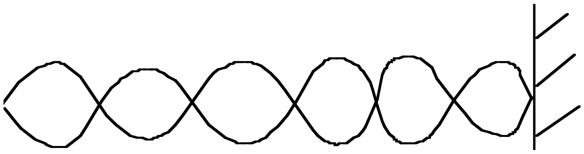
As the reflections, inverted in phase, begin to return, the first nodes are seen to develop.



As the reflected wave continues back to the source and the source continues generating new waves, the standing wave pattern becomes more apparent.



Continued generation of the same frequency waves sets up a “permanent” standing wave.



With a little practice, you can learn to feel the returning waves and adjust your generating frequency to form standing waves of different frequencies. Any college physics text will illustrate the appearance of the first few standing waves produced in this way. Stress that the nodes always do not move, and the antinodes move with the maximum possible amplitude.

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4. Waves have characteristic properties that do not depend on the type of wave.

As a basis for understanding this concept:

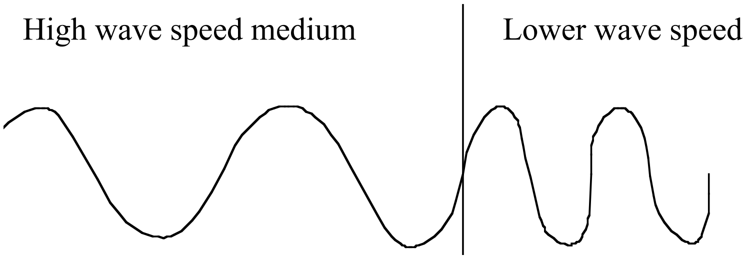
c. Students know how to solve problems involving wavelength, frequency, and wave speed.

This standard seems largely to focus on having the student use a formula. However, do make sure your students understand that in a uniform medium, waves travel at a speed that is independent of amplitude, wavelength and frequency. Also, take some time to make sure they understand the meaning of amplitude, wavelength (λ) and frequency (f).

The relationship $v = f\lambda$ can be used to solve such problems. Notice that amplitude does not influence wave speed. Frequency, f, is measured in hertz, which is another name for sec^{-1} or, cycles per second. When the wavelength, λ, is measured in meters and the frequency in hertz, the wave speed will be in meter/sec. (Some teachers call the above relationship "the wave equation". Actually the wave equation is quit a different "animal" and is usually not encountered until college courses in physics.)

It is interesting to consider what happens when a wave suddenly encounters a medium with a different wave velocity. This frequently happens when light passes from air into water or even when an ocean wave passes over a reef. Illustrated below is a representation of a transverse wave (perhaps light) that suddenly encounters a medium in which the wave speed is less.

It is important to appreciate that the frequency does not change. If the wave speed in the new medium is less, the wavelength will be correspondingly smaller. In the illustration, as the velocity slows, the wavelength decreases.



What the illustration does not show is that there will always be a reflection when a wave suddenly encounters a different substance. When light passes from air to glass, we always see a reflection at the surface.

Example Problem: Assume sounds travels in air at about 1100 ft/sec. and about 4 times faster in water. A very loud siren produces a frequency of 660 Hz near a swimming pool.

Although most of the sound energy will be reflected at the surface of the water, find the following:
a. What is the wavelength of the sound in air?
b. What is the frequency of the sound under the water?
c. What is the wavelength of sound in the water?
d. Discuss any experience you may have had listening to a sound in air and then listening to the same sound under water.

This simple problem gives the student an opportunity to use v = f λ and should help to point out that although wavelength changes when a wave moves into a medium with a different velocity, the frequency will remain the same.

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4. Waves have characteristic properties that do not depend on the type of wave.

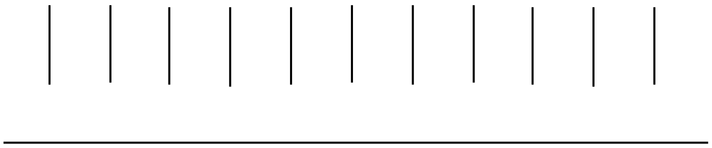
As a basis for understanding this concept

d. Students understand sound is a longitudinal wave whose speed depends on the properties of the medium in which it propagates.

To help students to appreciate that all different sizes and shapes of sound waves travel the same speed in a uniform medium, remind them that when they hear a band playing at a great distance, all the notes from all the different instruments arrive in the proper sequence. Loud, soft, high or low pitch, when the sound arrives after traveling a great distance, the music is still appropriately in the proper synchronization.

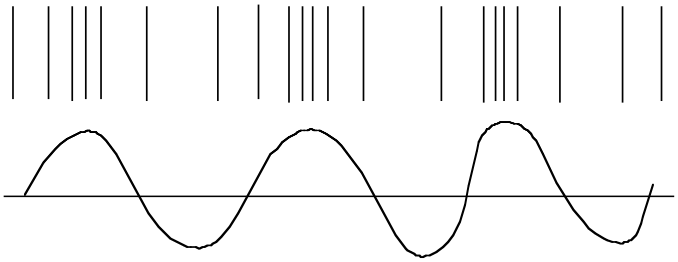
The method of illustrating sound waves with a transverse representation is often confusing to students. Since it is easier to draw transverse waves, texts often use only transverse representations of sound waves leading students to think that sound is transverse. Carefully illustrating this at the outset might help.

Begin with an illustration of evenly spaced lines that represent the undisturbed air. Directly below this is a straight line representing a plot of atmospheric pressure.

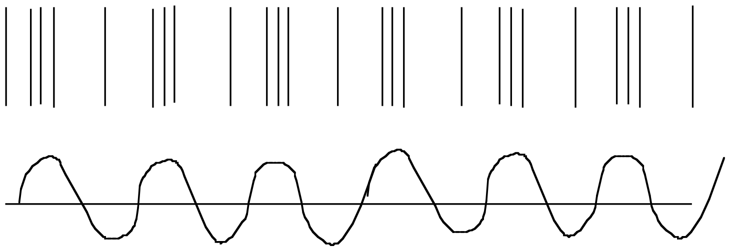


These illustrations will take a little time to produce but encourage your students to carefully copy your efforts so they will come to understand what the representations mean.

Now make a careful drawing of a sine wave and above it space the lines close together where there is a pressure maximum and far apart where there is a minimum. Have the line spacing correspond to the sine wave you have drawn.



The students should come to appreciate that the sine wave is really a plot of air pressure above and below atmospheric pressure. When the lines are close together the pressure is higher than atmospheric, etc.

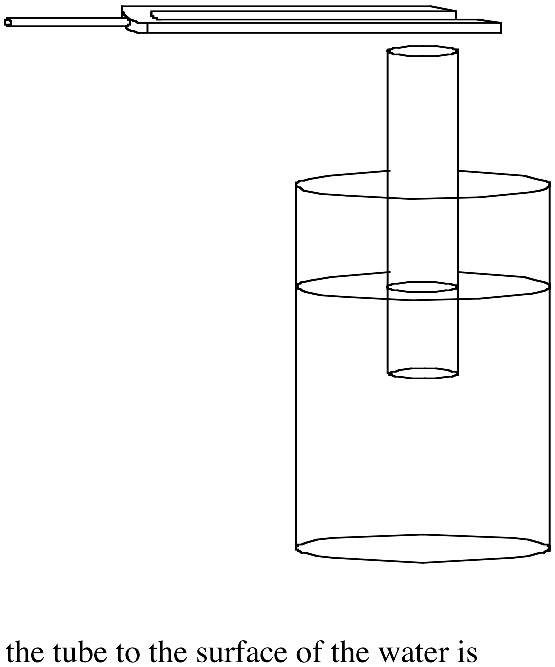


Repeat the illustration with a higher frequency. Perhaps again with a louder or softer sound. The idea is to have the students appreciate that the transverse wave representation of the sound wave is simply a plot of air pressure along the direction of the wave. After this idea is understood, you will be able to use these transverse wave representations of sound waves confidently, yet your students should understand that sound is a longitudinal wave.

It might be appropriate to point out that transverse waves usually only transmit through substances that can support sheer, such as solids. Sound is usually associated with waves in air, a fluid, hence it could not be a transverse wave. (Naturally, waves on the surface of water appear to be transverse and are actually both transverse and longitudinal. The waves on the surface of liquids are more complex than simply longitudinal or transverse.)

Measuring the velocity of sound, resonance method.

A simple but quite accurate experiment is to measure the velocity of sound using a resonant method. A metal or glass tube has one end immersed into a container of water. The distance from the top of the tube to the surface of the water is adjusted to produce resonance with a tuning fork.



For best results the fork should be held as illustrated very close to the top of the tube. The tube is adjusted until the volume of air inside the tube between the top of the water and the top of the tube loudly resonates with the fork. It can be argued (see below) that the distance from the top of the tube to the surface of the water (L) is one-fourth the wavelength of the sound produced. With the frequency of the fork (f) the velocity of sound can be calculated from $v = f\lambda$. That is, $v = 4fL$. There is a slight correction for the diameter of the tube but if the tube is long compared to its diameter, the correction will be small.

One way to argue that the distance from the top of the tube to the surface of the water is one-fourth the wavelength is to point out that a standing wave has been established inside of the tube with a node at closed end formed by the water and an antinode at the open end near the turning fork. The distance between a node in a standing wave and the next antinode is one-fourth of a wavelength.

Another argument that might appeal to some students is to carefully bounce a ball and point out that your hand goes through one half cycle from the time the ball leaves your hand to when the ball returns to your hand. This is a form of resonance. When you allow your hand to go through one half cycle, the ball moves from you hand, to the floor and back again, just when your hand is at the top of its swing ready to push the ball back down. But the total distance the ball has moved in this half cycle is down to the floor (a distance L) and back to your hand, (a total distance 2L) In half a cycle (f/2) the ball moves a distance 2L. Therefore, in a full cycle, the ball will move a total distance 4L.

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4. Waves have characteristic properties that do not depend on the type of wave.
As a basis for understanding this concept:
e. Students know radio waves, light and X-rays are different wavelength bands in the spectrum of electromagnetic waves whose speed in vacuum is approximately $3\text{x}10^8$ m/s (186,000 miles/second).

Students should have been introduced to the electromagnetic spectrum in Grade Seven with standard 6a. This revisiting the EM spectrum should give more emphasis to the wave nature of all electromagnetic waves. (We will discuss the nature of electromagnetic waves again following the next unit on electricity and magnetism.)

The discussion of the electromagnetic spectrum almost requires a large chart to refer to during the lesson. Several scientific supply houses do have such charts available. There are numerous web pages that present the EM spectrum in different levels of detail. The URLs for two of them are listed here:

http:;//www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

http://imagine.gsfc.nasa.gov/docs/science/know_11/emspectrum.html

Several points about electromagnetic waves should be stressed:

1. Unlike mechanical waves such as waves in springs or sound, EM waves travel through a vacuum.

2. All different kinds of EM waves are transverse and travel at $3 \text{ x } 10^8$ m/sec in a vacuum.

3. When electromagnetic waves travel through matter, they always travel at a slower speed that when in a vacuum. The ratio of the speed of an electromagnetic wave in a

vacuum to its speed in a substance is called the index of refraction of the substance. For example, the index of refraction of water for visible light is about 1.33. This means the speed of light in water is about ¾ the speed of light in a vacuum.

The relationship $v = f\lambda$ can be used for electromagnetic waves but the velocity v is usually replaced with a "c" which is the universal symbol for the speed of electromagnetic waves in a vacuum. (Also, often frequency is represented with the Greek letter ν rather than f.)

Finally students usually find it interesting to compute the wavelength of their favorite radio station and perhaps the wavelength of their cell phone transmissions.

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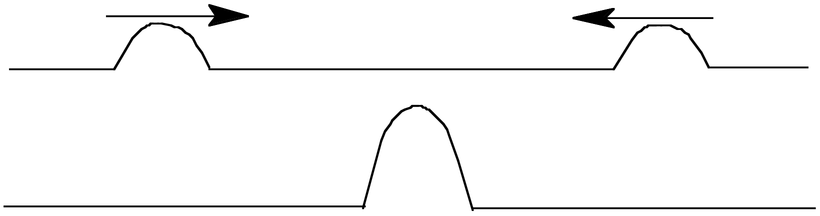
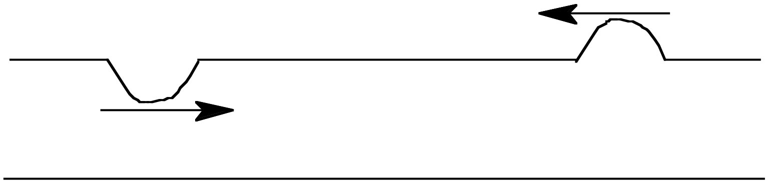
4. Waves have characteristic properties that do not depend on the type of wave.
As a basis for understanding this concept:
f. Students know how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.

When waves from different sources come together in the same place, they combine to form a single wave. This combination can lead to a momentary reinforcement, called constructive interference or perhaps a momentary cancellation called destructive interference. This effect can be easily demonstrated using pulses on a snake spring. With a student at the other end of the spring, carefully instruct them on how to generate quick transverse pulses. (See the illustration and discussion in **Waves** 4b.)

Coordinate launch times so you and the student start the pulses at the same time. If the pulses are in phase, they will double in amplitude when they cross in the center of the spring.



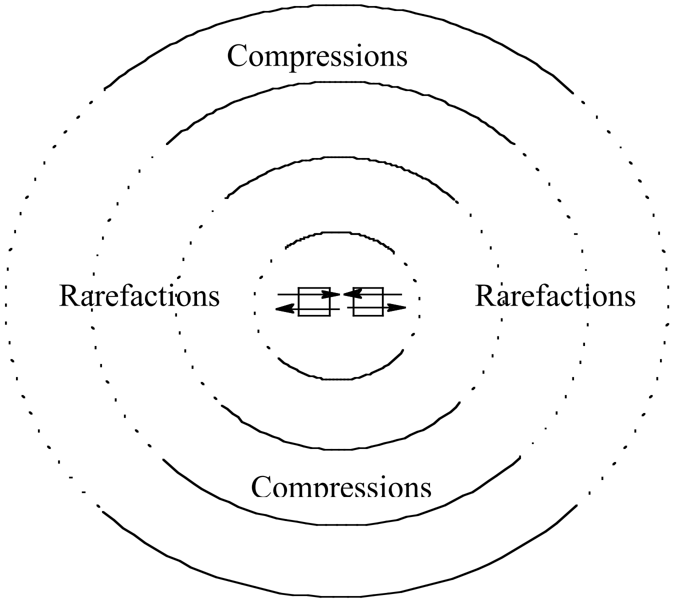
Now have the student continue to launch the same pulse as before only you reverse the phase of your pulse. This time the combined pulse will give no displacement.

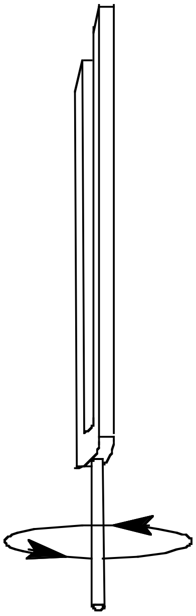


After the pulses cross over in the center of the spring, point out that they spring back into life and retain the same phase as they had before they interfered. When waves interfere, they will return to their original condition after they cross over one another.

An important question that will be addressed in some detail at the end of this section is: What happened to the energy of the two out of phase pulses as they seemed to destroy themselves when they crossed over one another in the center of the spring?

Another simple demonstration to show the interference of sound waves is to have a student slowly rotate a tuning fork near her ear and note there are directions in which the sound will be loud but other directions where the sound will be soft. A careful note of where the sound is loud and where the sound is soft will reveal that each time the fork is rotated 45° the sound will go from loud to soft. The explanation for this is illustrated on the right. From top view the fork tines vibrate in and out in the same plane. At an instant when compressions are produced in one direction, at the same instant, rarefactions are produced in a direction at right angles. These compressions and rarefactions interfere at the places where they cross over, as shown.





This same interference of sound waves from a tuning fork can be shown to the entire class by striking the fork, holding it in a vertical position and rotating it fairly rapidly about its vertical axis, as illustrated on the left. Students should hear a rapid increase and decrease of the loudness of the fork as you rotate it. Slower rotation will show that whenever the fork is at an angle where the compressions in one direction overlap the rarefactions generated, the loudness will decrease. (In the illustration on the previous page, these nodes will be at 45°, 135°, 225°, and 315°).

If you have access to two loudspeakers and an audio oscillator, excellent demonstrations of interference can be presented by placing the speakers about two meters apart, driving the speakers with a signal of approximately 200 Hz, and allowing the students to move around the room and listen to the interference produced. If a higher frequency is used, the interference nodes and antinodes will be heard to be closer together. It is suggested that the students place a finger in one of their ears to better hear the effect. (An individual's two ears may be far enough apart so at least one would be out of the center of the node hence the large decrease in sound intensity would not be noticed.) (Audio oscillator programs are available on the web.)

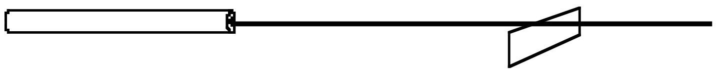
Beats occur when two sound sources of about the same loudness but of slightly different frequency are sounded together. Since the frequencies of the two sources are different, at times they will be in phase and reinforce each other but slightly later they will be out of phase and will cancel each other. With a little practice, it is possible to have a speaker and audio oscillator produce a given frequency and a musically inclined student could sing the same frequency and then sing it slightly out of tune producing beats. It is difficult to have two musically inclined students produce this effect but it is possible.

Musical instruments might be employed in this demonstration. Finally, if you have several tuning forks of the "same" frequency, it is almost certain that they will not be the same frequency. Select two that are the most different, sound them together and very slow beats should be heard. It is fairly easy to show that the number of beats produced per second when two different frequencies are sounded together will be the difference between the two frequencies.

Diffraction occurs when waves pass by a barrier. The waves will bend around the barrier and if the frequency is high enough, an interference pattern will be observed. The lower the frequency of the waves, the more easily they will bend around the barrier. A simple demonstration of this is to hold your hand in front of your mouth while you sing a note. The students will observe that the sound is hardly changed in loudness even though they can't see your mouth. Sound waves are of such a low frequency that they easily diffract around your hand but light waves are of such a high frequency, they are completely blocked by your hand.

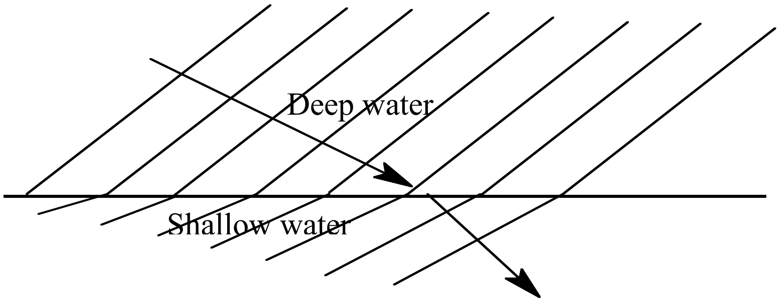
Laser Demonstrations of Diffraction

A small laser in a darkened room can be used to demonstrate very interesting diffraction effects. Direct the laser beam just over the top of a sharp edge, such as a razor blade. Study carefully the result as the beam strikes a screen. The shadow will not be sharp but will show a pattern of dark and light bars as the light fades into the dark shadow of the razor blade. This diffraction pattern was first observed by Grimaldi in 1665 (long before the invention of the laser) and is used today as a clear proof of the wave nature of light. More interesting diffraction patterns can be demonstrated using single and double slit wave plates. Such plates are available from scientific supply houses or can be made by carefully scratching a painted microscope slide with a razor blade (for a single slit) or two razor blades held tightly together (for a double slit.)



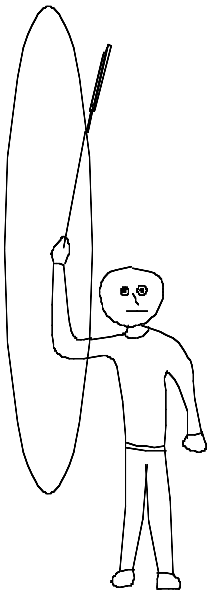
Refraction is usually associated with the behavior of light when it passes through transparent materials, but refraction is a general property of all waves.

If waves on the surface of water were moving in relatively deep water and were suddenly to encounter shallow water, the waves would slow down. Since the waves slow down, should they strike the shallow water at an angle, the entire wave front will change direction as illustrated on the right. This change in speed of the wave and corresponding change in direction is called refraction.



The term index of refraction, usually associated with light, also applies to waves and is the ratio of the velocity of waves in one substance to the velocity of the waves in another substance. In the case of light, index of refraction is, by definition, the velocity of light in a vacuum over the velocity of light in a particular substance. The index of refraction of a substance for light (such as glass) will always be greater than one. If the velocity of the waves gradually change rather than change abruptly as in the above illustration, the waves will bend slowly in the slower moving direction. This can explain why ocean waves that can originate from almost any direction at sea almost always approach the shore straight on. As the waves in deep water begin to approach the shallow waters near the shore, the waves will turn and eventually roll into the shore straight on. With light, this can be use to explain why the sun seems to flatten out as it sets and why the sun actually sets later than it would if there were no atmosphere.

Doppler effect in sound is the apparent change in pitch of a sound source due to the relative motion of the source and the observer. This is often observed when a car honking its horn passes you traveling in the opposite direction at a high speed. The pitch of the horn is high as it approaches and drops to a lower pitch as it passes you. It is important to appreciate that the actual frequency of the horn does not change. When the car approaches the wavelengths are shorter and when it recedes they are longer, causing the observer to hear first a higher pitch then a lower pitch. It's important that students understand that the Doppler effect deals with pitch and not loudness. A very simple demonstration to illustrate the Doppler effect is shown on the right. Firmly tie a tuning fork to a strong string. Strike the fork and swing it in a circle as shown. The class should be able to hear the rise and fall in the pitch of the fork as it approaches and recedes from them.



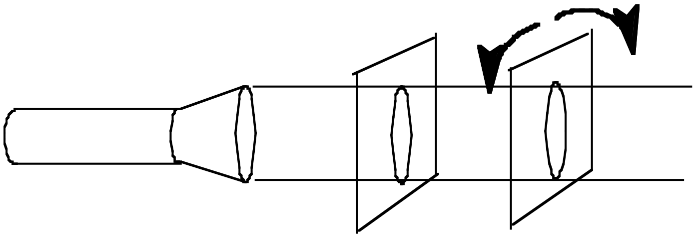
The Doppler effect is also observed with light. An approaching light source would have the light shifted to the blue and a receding light source would produce light shifted to the red. The fact that galaxies at greater distance from us have their light increasingly shifted to the red has led to the understanding that the universe is expanding.
An interactive program that shows how the motion of a wave producing source produces shorter and longer wavelengths can be found at:
http://ephysics.physics.ucla.edu/physlets/edoppler_shift.htm

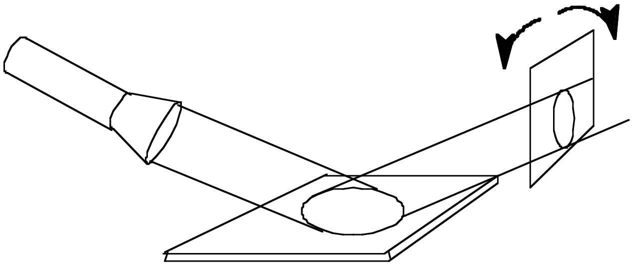
Polarization only occurs with transverse waves. If a transverse wave is linearly polarized, then the transverse vibrations in the wave are all in the same direction. Light is frequently used as an example of polarization. The light that is emitted by an incandescent light bulb is not polarized since the electromagnetic waves produced will be vibrating in random directions. However, using certain crystals, or by using a special plastic polarizing films, the transverse vibrations of a light source can be made to all vibrate in the same direction. (The fact that light can be polarized was the first proof that it was a transverse wave.) Radio, TV and even cell phone transmissions are produced by accelerating charges in a particular direction. For this reason, these electromagnetic waves are polarized. Light coming directly from the sun is not polarized, however, when the light interacts with the earth's atmosphere, the light coming from the sky at right angles with the sun is highly polarized. (Photographers make use of this when photographing the sky to enhance the appearance of clouds.) When light reflects at an angle from a substance like water, it becomes polarized. This is why polarized sunglasses are so effective in reducing glare from horizontal surfaces.

Experiments with polarized light.

Plastic polarizing films can be obtain from scientific supply houses. (Cynmar 094-07136 or Sargent Welch WLS-70944, etc.) Several simple experiments can be done with these films to show the effects of polarization.

Pass light from a directed source through a single polarizing filter and rotate it. No appreciable difference will be noticed, however, when a second polarizing filter is placed in the beam of the first and rotated, a large difference in brightness will be observed.





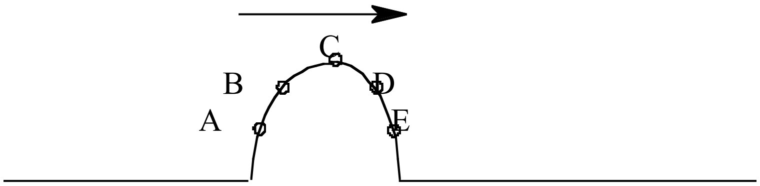
Bounce a light beam off of a flat piece of glass. Rotate a polarizing film held in the reflected beam. A particular orientation of the film will produce a minimum brightness. If the light beam is directed at different angles, a particular angle will produce the maximum decrease in the reflected brightness. This is the Brewster angle.

Go outside in bright sunlight on a clear day. Look at the sky at right angles with respect to the sun with a polarizing filter. Rotate the filter and there will be an orientation that produces a maximum decrease in brightness. Look at the sky at angles different from 90° with respect to the sun, a lesser decrease in brightness will be observed. (The scattering of light by the atmosphere produces a maximum polarization at right angles from the sun. However, clouds do not polarize the light that reflects from them. This can be used to great advantage when photographing the sky.)

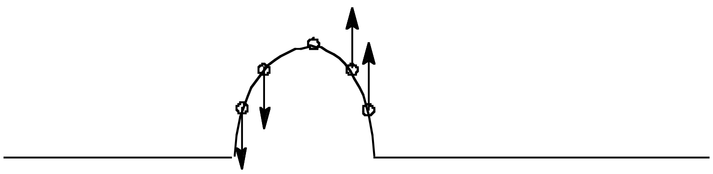
What happens to the energy when two out of phase pulses interfere?

This question was asked earlier with the demonstration of interfering pulses on a spring. The key to understanding this "paradox" is that we were using the principle of superposition only to explain displacement vectors. As the pulse moves along the spring, certain portions of the spring have a velocity as well as a displacement. To see this, consider the following:

As the transverse pulse illustrated moves to the right, ask you class: What must be the directions of the velocities of the spring particles at each of the lettered points indicated?

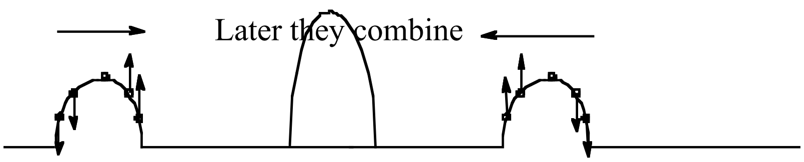


It takes a little thought to appreciate that in order for the pulse to move to the right, the vectors shown in the illustration on the right represent the correct velocity directions.



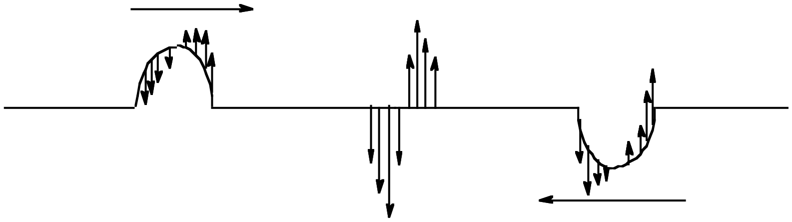
Now consider two in phase pulses moving in the opposite direction. When they combine both the displacement vectors and the velocity vectors must be combined.

If the pulses are symmetrical, at the instant they combine all the displacement vectors will add but the velocity vectors will cancel. Only potential energy exists.



Now consider what happens when two pulses of opposite phase moving in the opposite direction superpose:

If the pulses are symmetrical, at the instant they combine although the displacement vectors cancel, the velocity vectors double and now all the energy is kinetic energy.



A careful consideration of spring potential energy (PE = $1/2kx^2$) and particle kinetic energy (KE = $\frac{1}{2} mv^2$) can show that energy is conserved, always.