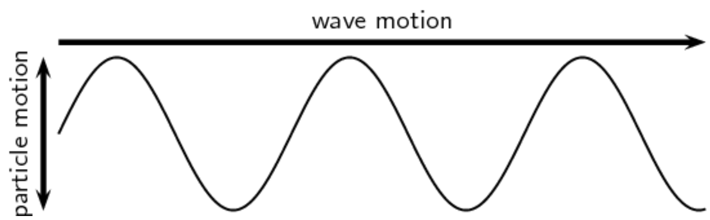
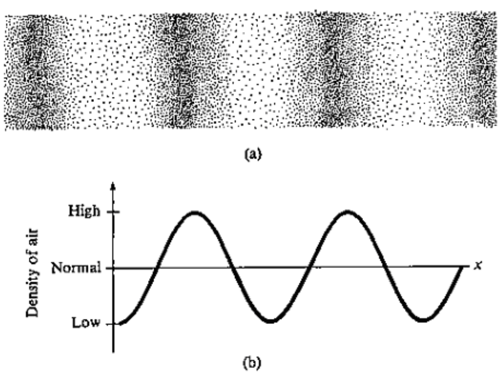
Single or repeated vibrations

A single vibration or disturbance is called a **pulse**. A continuous vibration is **wave**. Pulses and waves propagate and transfer energy. Sound, light, water, and earthquakes are all examples of waves that transfer energy across space, without having to transfer matter/particles.

Classifying waves as direction of vibrations

A **transverse** wave is when the particle motion is perpendicular to the direction of wave propagation. These waves have high (positive) displacements called **crests** or **peaks** and low (negative) displacements called **troughs**. Electromagnetic waves, light, is a prime example of a transverse wave.





Sound waves, on the other hand, are vibrations in some **medium** (matter – solid, liquid, or gas) where particles are vibrating back and forth in the same direction, or parallel, as the wave propagation. This is called a **longitudinal wave.** Longitudinal waves have areas of high pressure which are called **compressions** and low pressure called **rarefactions**. This can also be demonstrated by the compressing and stretching of a long spring.

For the sake of description we can plot the pressure vs. distance of a wave which will produce a sinusoidal[1] wave.

Mechanical waves vs. Electromagnetic waves

Some examples of mechanical waves are seen as earthquakes, ripples in water or a vibrating tuning fork. **These waves requires a medium in order to transfer energy.** Each particle vibrates and

[1] Sinusoidal – of, relating to, shaped like, or varying according to a sine curve or sine wave. Note that a sine wave is 90 degrees shifted from a cosine wave.

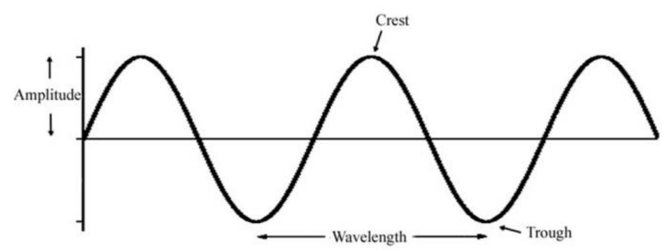
forces the nearby particles to also vibrate thus transferring energy over long distances. Light was once thought to require a medium called "luminiferous aether" but we now know that such a thing does not exist. Instead, light and other electromagnetic waves (radiowaves, x-rays, UV rays, etc) do not require a medium to transfer energy. Thus, astronauts in space communicate to ground control via radio waves.

Wave anatomy (parts of a wave)

The wave is described with six measurements.

1. **wavelength** (λ) – the distance (in meters) a wave covers in one full cycle. This can be measured from one crest to the next or one trough to the next. One crest and one trough forms one full cycle as well. It is abbreviated with the greek letter "lambda".

2. **period** (T) – the time (in seconds) it takes for one cycle to leave the source. Inverse of a wave's frequency ($f = 1/T$).



3. **frequency** (f) – the number of waves that pass a point in one second. The S.I. unit is the **Hertz** (Hz). Hence, 100 Hz means that 100 waves pass by in one second. Frequency is also the inverse of a wave's period ($T=1/f$).

4. **velocity** (v) [2] – how fast the wave travels in a medium. This is mostly affected by the density of the material. For instance, the speed of sound is slower at higher altitudes and colder temperatures[3].

5. **amplitude** (A) – the displacement (in meters) from equilibrium

6. **phase** – the measure of how much a wave has passed or a measure of how similar/dissimilar two waves may be. Since a full wave is 360 degrees (one full cycle), half of a wave is 180 degrees and a quarter of the wave is 90 degrees. Two waves that are 360 degrees apart are said to be in-phase. Any wave that is not 360 degrees is a certain amount of degrees out-of-phase.

The wave equation

The **wave equation**, which holds for <u>all types of waves</u> (electromagnetic and mechanical), shows three of these measurements to be related:

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[2] Wave speed/velocity is determined by determined by the characteristics of a medium

[3] Temperature is measured by the kinetic energy of molecules. Thus molecules vibrate slower at colder temperatures. High altitudes have low densities of air molecules.

$$v = \lambda f \text{ (eq. 1)}$$

Period and frequency are inversely related as show in eq. 2.

$$T = 1/f \text{ (eq.2)}$$

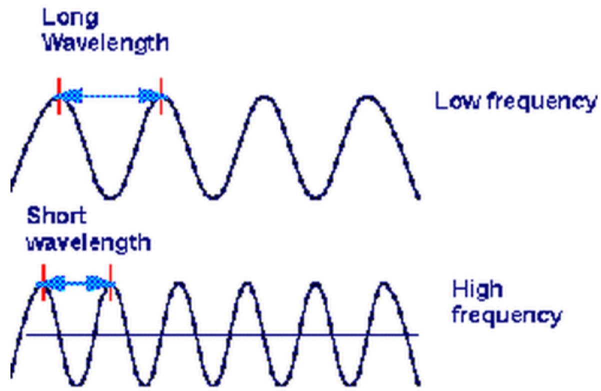
Thus we can combine them to form the following equation

$$v = \lambda f = \lambda/T$$

The velocity of a wave is constant as long as it stays in a uniform medium. This means that as the frequency of a wave source increases, the wavelength decreases.

Sound waves

When you listen to a sound wave, you perceive two distinct things about it. First is the pitch, how "high" or 'low" it seems, and corresponds to different musical notes. **Pitch is the musical term for a wave's frequency**; a high-pitched sound has a high frequency, and is created by something vibrating very fast. Pitch is also related to the size of a vibrating object – small things vibrate faster than large things, so small vibrating objects produce higher pitched sounds than big vibrating objects.



On a guitar, the long strings on a guitar produce the low notes, and the short strings produce the high notes. If you increase the pitch by one **octave**, you double the note's frequency, and get a higher pitch which sounds oddly the same as the original.

The second distinct perception of a sound is the **loudness** (or volume) of a sound. **Louder sounds correspond to higher amplitude wave**, or greater pressure change in the air. This is caused by a source vibrating farther back and forth. Banging on a table harder makes a louder sound because the surface vibrates farther back and forth thus moving more air.

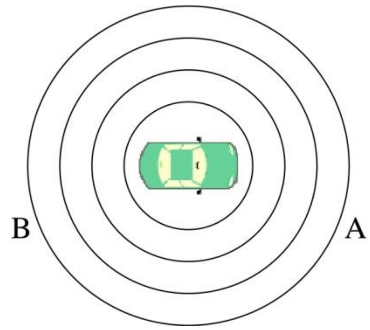
Musical instruments

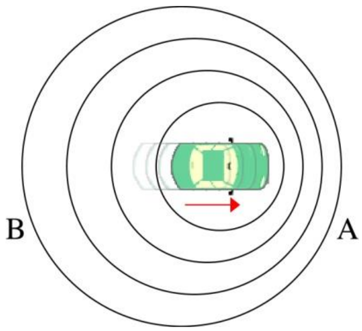
Musical instruments, violins, trumpets, pianos, don't produce "pure" sine or cosine waves, because they vibrate in very complex ways. Even when you play one note (or frequency) on a piano, the vibrating string produces lots of multiples of that frequency, called **harmonics**[4], which make the sound richer. The particular combination of harmonics produced by a musical instrument gives it its characteristic sound, called the instrument's **timbre**.

[4] See standing waves

Moving observers or wave sources

When an ambulance rushes past you, its siren seems to change pitch as it passes by. As it comes towards you it sounds higher pitched than when it is moving away.
This is the **Doppler effect,** an apparent change in a wave's frequency when the wave source is moving relative to you. In the diagram below left, a car is at rest, while the sound of its engine fans out. Observers at points A and B will both measure the same wavelength and frequency for the sound waves.

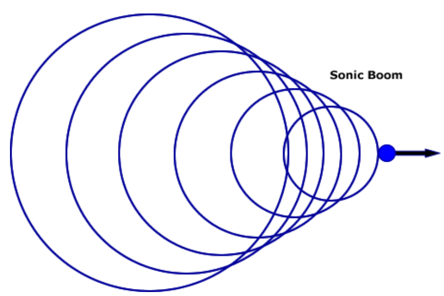




If instead the car drives to the right, then you get the picture to the left. The car drives into the waves in front of it, so the waves "pile up" and the crests are closer together. So an observer in front of the car at A would hear a shorter wavelength and a higher frequency sound. But behind the car the waves seem stretched out, so an observer at B would hear a longer wavelength and a lower frequency sound.

It doesn't have to be the car moving - if you move towards the car, the engine will sound higher pitched, as if the car were moving towards you.

If the car was supersonic, it would move faster than its own sound waves, producing a picture like that below right. The sound waves it leaves behind would overlap, causing constructive interference in a cone behind it, creating a really loud shock wave – a **sonic boom**.



A **boundary** is consider when a wave encounters a change in medium. Any time waves hit a boundary, like the surface of a lake, three behaviors can be observed.

- The wave is **partly reflected** back. Echoes are when sound waves bounce back after a certain delay. Normally we don't observe echoes because other objects dissipate the energy. You can easily observe in empty hallways, long tunnels or large canyons when objects won't interfere as much.

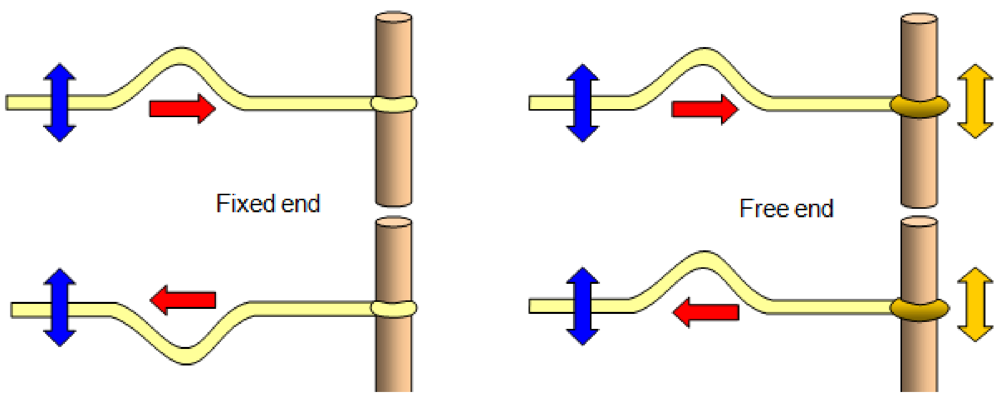
- The wave is **partly absorbed** by the surface as internal energy. This can be affected the type of material, the thickness or the shape of the material. This is useful in sound-proofing a room or creating a recording studio so as to eliminate ambient sound.
- The wave is **transmitted** across the boundary. This is when you can hear your loud neighbors from the next apartment or house over or your sibling's annoying music from the next room.

Fixed end vs. Loose end

When a wave or pulse approaches a **fixed end,** the internal restoring forces which allow the wave to propagate exert an upward force on the end of the string. Since the end is clamped, it cannot move. According to Newton's third law, the wall must be exerting an equal downward force on the end of the string. This new force creates a wave pulse that propagates from right to left, with the same speed and amplitude as the incident wave, but with opposite polarity (upside down).

At a fixed boundary, the wave or pulse is **reflected and inverted** (changes its polarity).

When a wave or pulse approaches a **free end,** the last particle is able to move with the displacement of the wave and so the wave **is reflected but maintains its orientation**.
(if you search "fixed vs free end animation" you should be able to find some nice demonstrations of what's happening.)



Superposition and Interference

When you are listening to conversation in a room, you aren't just hearing the sound waves coming directly from someone speaking, you are also hearing the sound waves reflecting off the walls and other surfaces in the room. At any given point in space, many waves are overlapping, or **interfering**. Depending on where you are in the room, this may make the sound seem louder or softer. The **principle of superposition** states that when waves overlap at a point, they form a single wave whose amplitude is the sum of the amplitudes of all the individual waves.

In the first picture on the left above, two waves whose crests and troughs line up (the waves are "in phase")

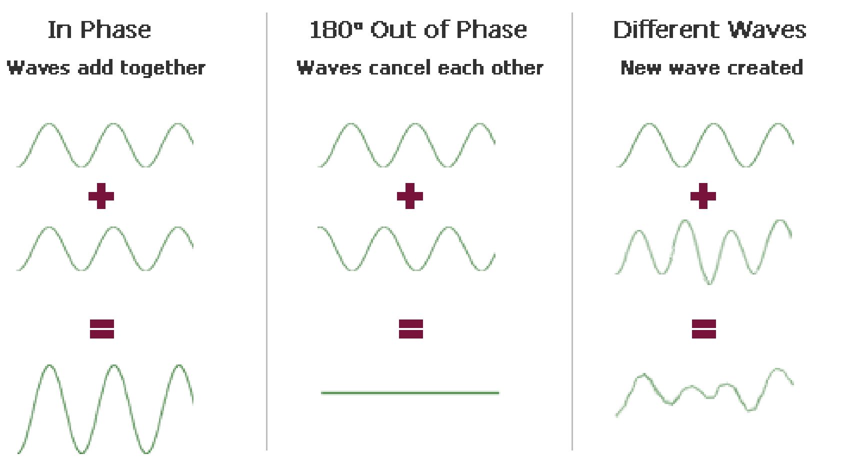
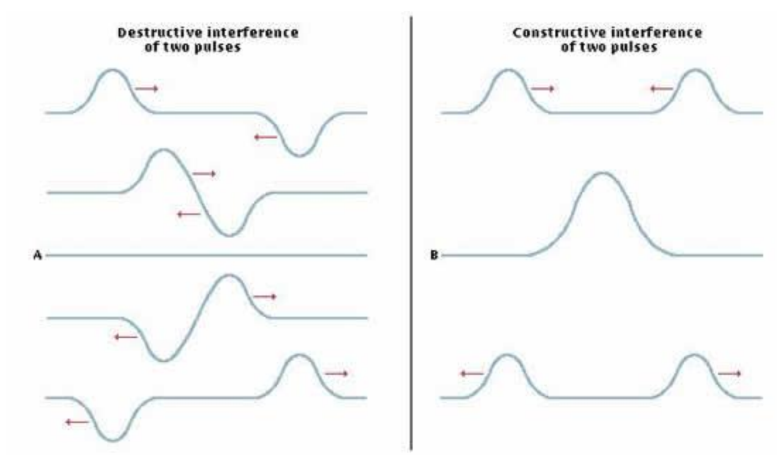
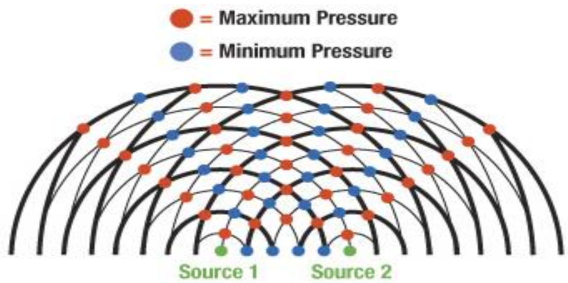


Image courtesy of www.mediacollege.com

interfere to produce a wave with a bigger amplitude, so it sounds louder - this is called **constructive interference**. In the middle case above, the crests overlap troughs and cancel out (the waves are "out of phase) so the result sounds quieter - a situation called total **destructive interference**. In the third example, a combination of constructive and destructive interference occur at different points along the wave.

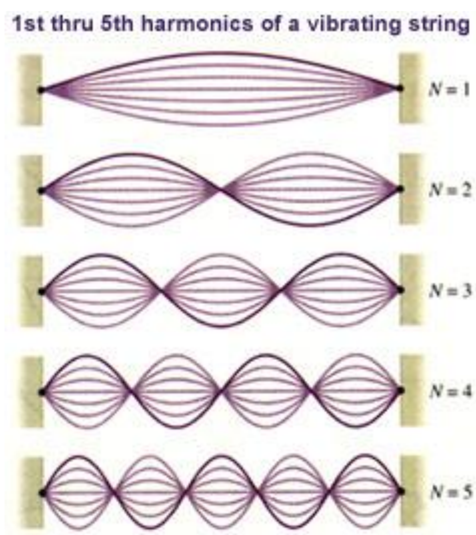
<u>Interference doesn't change the original waves.</u> If you send individual pulses along a rope towards each other, you see that the change in amplitude only occurs when they overlap, but then the pulses continue on their way unchanged.





Since sound waves fan out from a sound source all around it, we can draw the waves by showing the crests as concentric circles leaving the source - this is called a **wavefront diagram**. The picture at right shows crests as bold lines, and for clarity shows troughs also, as light lines. If we draw identical sound waves coming from two speakers as shown above, there are places where crests overlap crests, and troughs overlap troughs. At these points of constructive interference, the sound will be louder. Notice these points form lines, so if you were to walk across this room from right to left, the sound would slightly fade in and out, getting louder and softer as you heard different kinds of interference. It would seem loudest along the line down the middle of the room right between the two speakers, where there is always constructive interference.

Standing waves



In a musical instrument like a guitar where a vibrating string makes the sound, the vibration in the string is a wave itself, which reflects back from both ends. The string vibrates at a specific **natural frequency**, which depends on the length and tension in the string.

The vibration travels down the string and reflects back from both ends, <u>setting up a situation where the vibration interferes with itself,</u> creating a **standing wave**. A standing wave is so named because you can't see the wave move (oscillate) along the string.

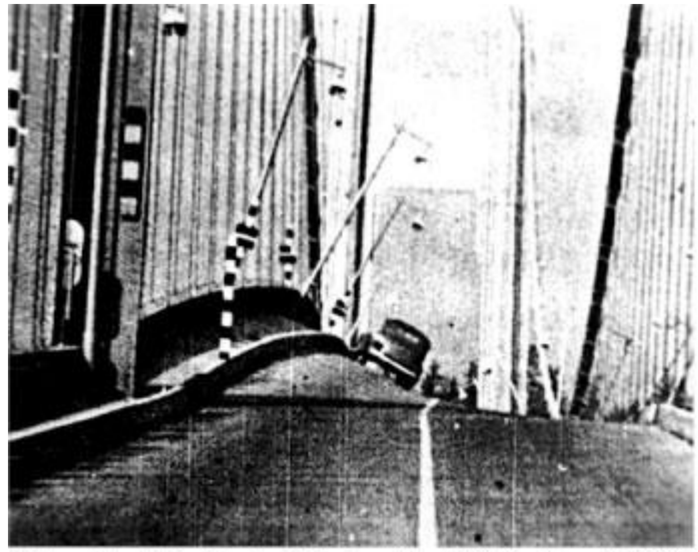
There are places where the string vibrates up and down a lot (**antinodes**, where constructive interference constantly happens) and places where the string seems at rest (**nodes**, where destructive interference constantly happens). A good way to remember that nodes are places where there is NO DisplacEment and <u>a</u>ntinodes are places with <u>a</u>mplitude.

At the natural frequency, also called the first harmonic, there are two nodes (one at each end of the string) and one antinode in the middle. If you pluck the string harder, you can set up a more complicated vibration with more nodes and antinodes, called **harmonics**. Harmonics are multiples of the natural frequency - how many there are and how loud they are determine the instrument's **timbre**, or distinctive sound. This is also why a piano doesn't sound like a guitar.

Resonance

If you have two strings tuned to the same natural frequency, the sound waves from one string will make the second one start vibrating. This is called **resonance**, where one vibrating causes another object also vibrate. Guitars and violins have wooden boxes behind the strings which resonate when you play, making the sound louder and richer, adding more harmonics to the sound. Blowing across a glass bottle or running a finger over the lip of a wine glass will make the objects resonate at their natural frequency.

In one catastrophic incident, a constant wind caused the Tacoma Narrows Bridge to resonate at one of its harmonics thus causing it to eventually collapse.



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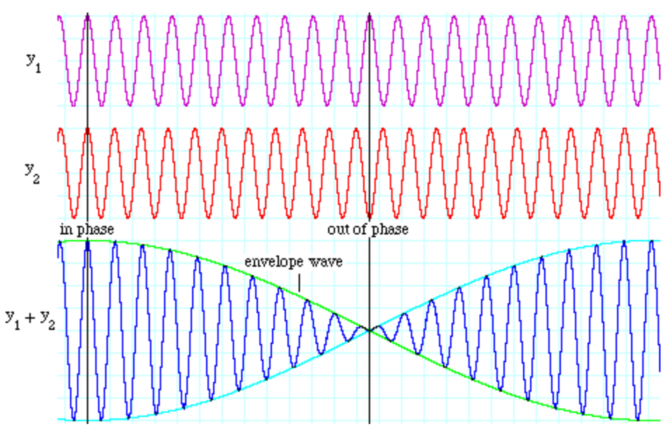
Interference and beat frequencies



If two wave of slightly similar frequencies interfere, their resultant wave may produce a beat frequency, a regular pattern of amplitude and no amplitude.

When the two waves are totally in phase and produce total constructive interference. At other times, the two waves are totally out of phase which produces total destructive interference. (see figure)

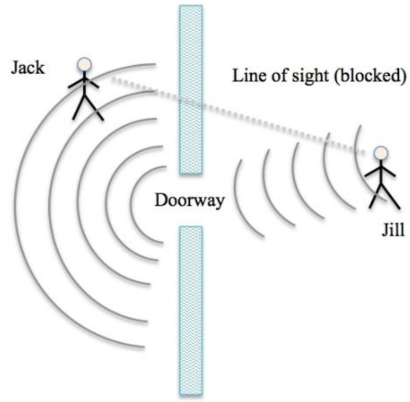
Interactive simulation found here:

https://academo.org/demos/wave-interference-beat-frequency/

Wave Diffraction

When you hear a noise from a room with an open door even when your ears aren't in direct line from the sound source you're experiencing diffraction. The sound waves are bending around the door opening and encountering your ears.

Diffraction is the bending or spreading out of waves around obstacles, or the spreading of waves as they pass through an opening, most apparent when looking at obstacles or wavelengths having a size of the similar to the wavelength. In the diagram, Jack can't see Jill but he can hear her talking to him.



Typically, the smaller the obstacle and wavelength, the greater the diffraction.