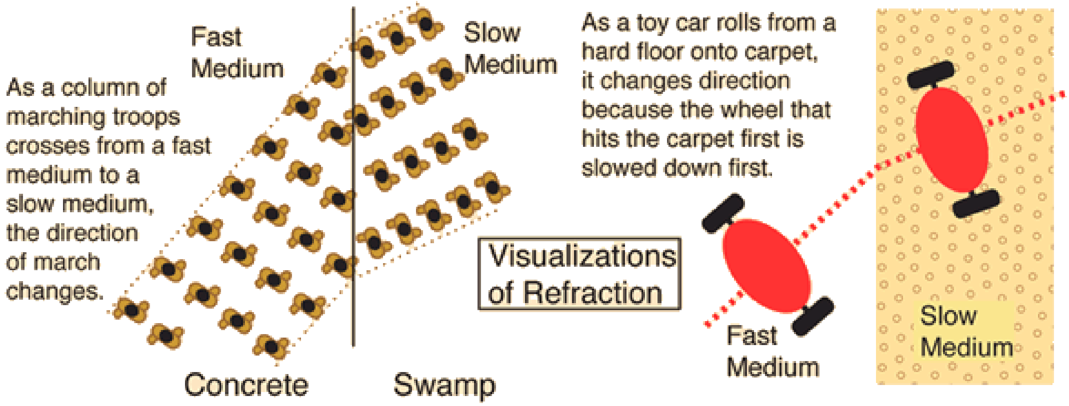
Refraction of Sound

Refraction is the bending of waves when they enter a medium where their speed is different.

Refraction is not so important a phenomenon with sound as it is with light where it is responsible for image formation by lenses, the eye, cameras, etc. But bending of sound waves does occur and is an interesting phenomena in sound



These visualizations may help in understanding the nature of refraction. A column of troops approaching a medium where their speed is slower as shown will turn toward the right because the right side of the column hits the slow medium first and is therefore slowed down. The marchers on the left, perhaps oblivious to the plight of their companions, continue to march ahead full speed until they hit the slow medium.

Not only does the direction of march change, the separation of the marchers is decreased. When applied to waves, this implies that the direction of propagation of the wave is deflected toward the right and that the wavelength of the wave is decreased. From the basic wave relationship, $v = f\lambda$, it is clear that a slower speed must shorten the wavelength since the frequency of the wave is determined by its source and does not change.
Another visualization of refraction can come from the steering of various types of tractors, construction equipment, tanks and other tracked vehicle. If you apply the right brake, the vehicle turns right because you have slowed down one side of the vehicle without slowing down the other.

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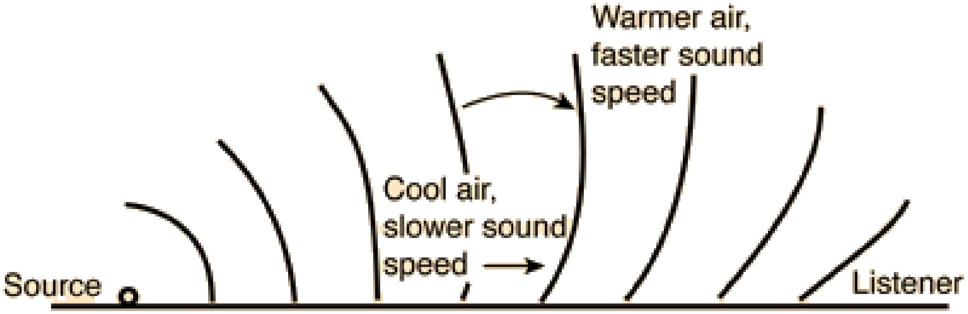
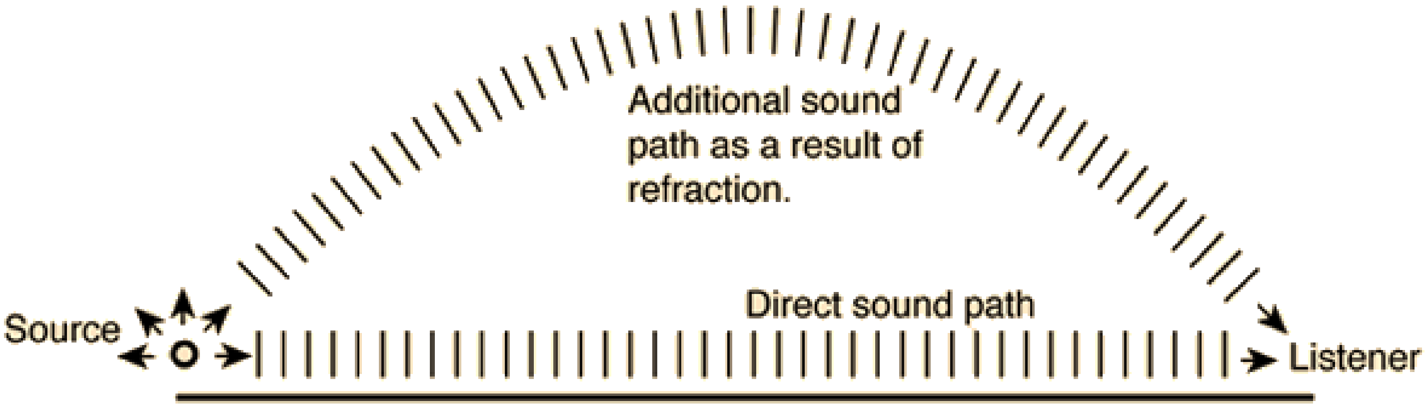
Refraction of Sound

If the air above the earth is warmer than that at the surface, sound will be bent back downward toward the surface by refraction.



Sound propagates in all directions from a point source. Normally, only that which is initially directed toward the listener can be heard, but refraction can bend sound downward. Normally, only the direct sound is received. But refraction can add some additional sound, effectively amplifying the sound. Natural amplifiers can occur over cool lakes.



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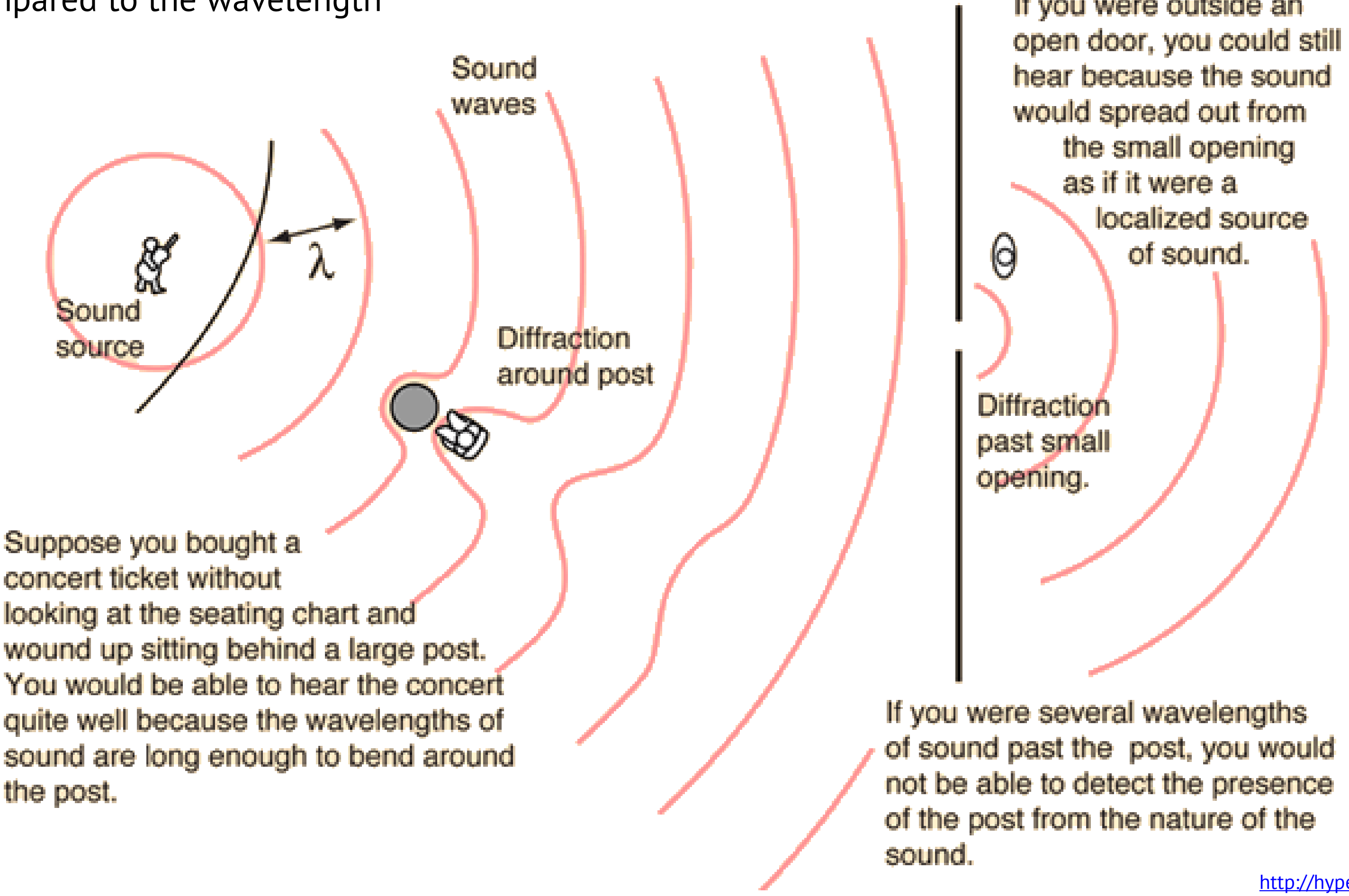
Diffraction of Sound

Diffraction: the bending of waves around small* obstacles and the spreading out of waves beyond small* openings.

* - small compared to the wavelength



If you were outside an open door, you could still hear because the sound would spread out from the small opening as if it were a localized source of sound.

Suppose you bought a concert ticket without looking at the seating chart and wound up sitting behind a large post. You would be able to hear the concert quite well because the wavelengths of sound are long enough to bend around the post.

If you were several wavelengths of sound past the post, you would not be able to detect the presence of the post from the nature of the sound.

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Diffraction of Sound

Important parts of our experience with sound involve diffraction. The fact that you can hear sounds around corners and around barriers involves both diffraction and reflection of sound. Diffraction in such cases helps the sound to "bend around" the obstacles. The fact that diffraction is more pronounced with longer wavelengths implies that you can hear low frequencies around obstacles better than high frequencies, as illustrated by the example of a marching band on the street. Another common example of diffraction is the contrast in sound from a close lightning strike and a distant one. The thunder from a close bolt of lightning will be experienced as a sharp crack, indicating the presence of a lot of high frequency sound. The thunder from a distant strike will be experienced as a low rumble since it is the long wavelengths which can bend around obstacles to get to you. There are other factors such as the higher air absorption of high frequencies involved, but diffraction plays a part in the experience.

You may perceive diffraction to have a dual nature, since the same phenomenon which causes waves to bend around obstacles causes them to spread out past small openings. This aspect of diffraction also has many implications. Besides being able to hear the sound when you are outside the door as in the illustration above, this spreading out of sound waves has consequences when you are trying to soundproof a room. Good soundproofing requires that a room be well sealed, because any openings will allow sound from the outside to spread out in the room - it is surprising how much sound can get in through a small opening. Good sealing of loudspeaker cabinets is required for similar reasons.

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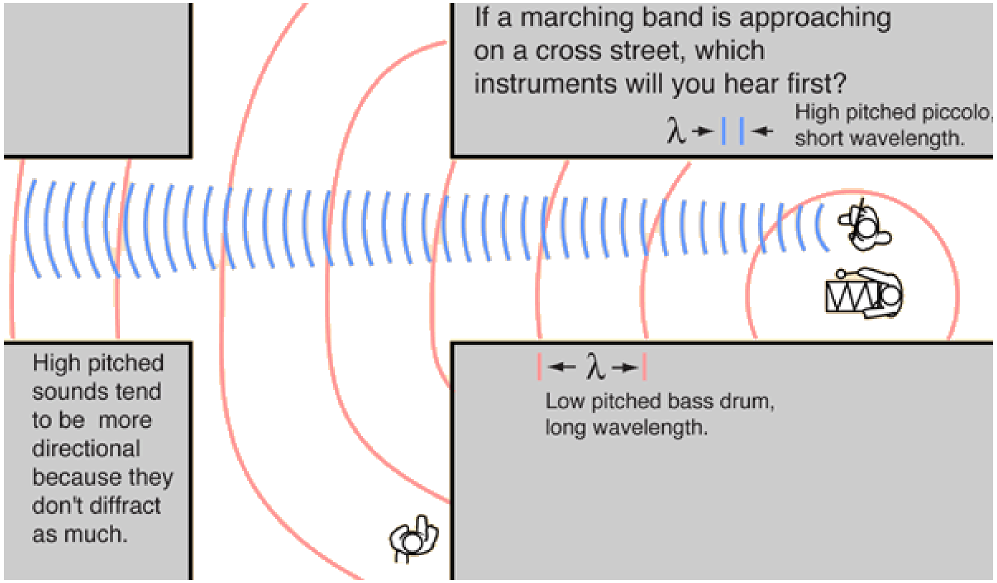
Lecture 6. Sound

Diffraction of Sound

Another implication of diffraction is the fact that a wave which is much longer than the size of an obstacle, like the post in the auditorium above, cannot give you information about that obstacle. A fundamental principle of imaging is that you cannot see an object which is smaller than the wavelength of the wave with which you view it. You cannot see a virus with a light microscope because the virus is smaller than the wavelength of visible light. The reason for that limitation can be visualized with the auditorium example: the sound waves bend in and reconstruct the wavefront past the post. When you are several sound wavelengths past the post, nothing about the wave gives you information about the post. So your experience with sound can give you insights into the limitations of all kinds of imaging processes.



The long wavelength sounds of the bass drum will diffract around the corner more efficiently than the more directional, short wavelength sounds of the higher pitched instruments.

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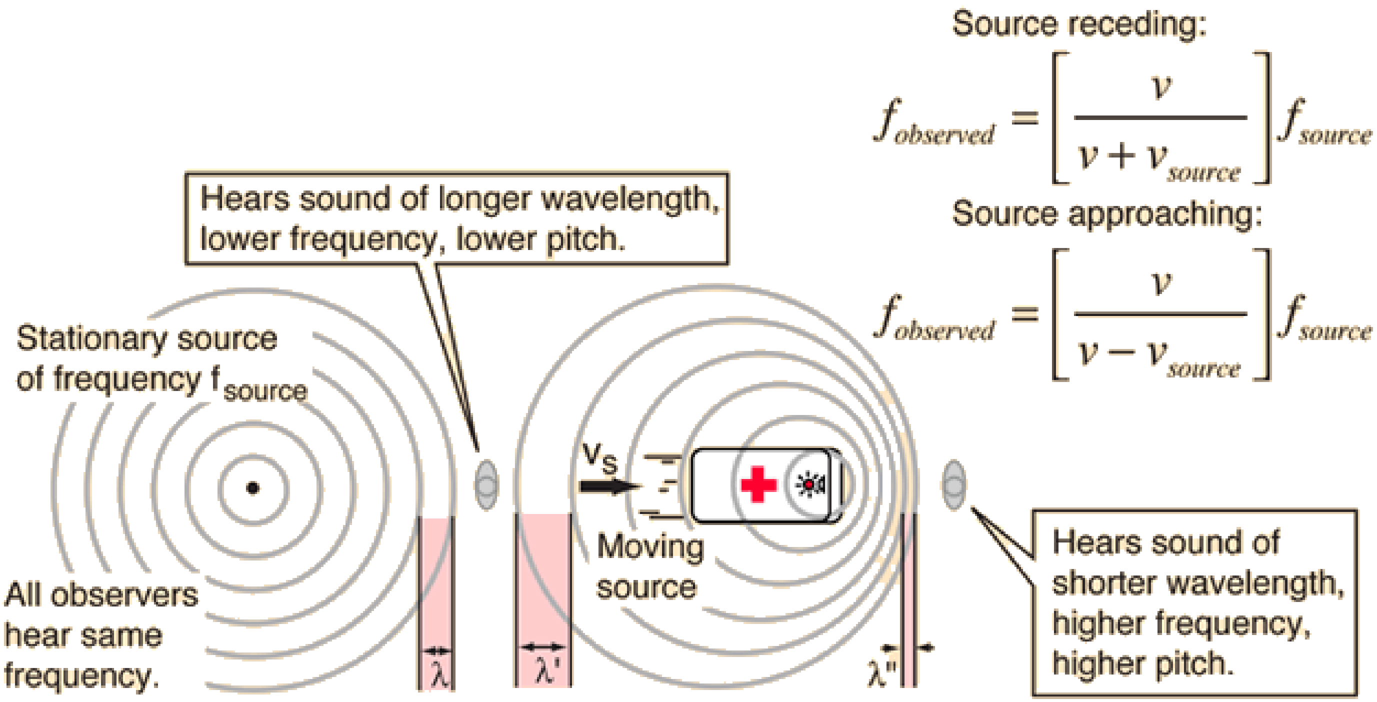
Doppler Effect

You hear the high pitch of the siren of the approaching ambulance, and notice that its pitch drops suddenly as the ambulance passes you. That is called the Doppler effect.



Source receding:

$$f_{observed} = \left[\frac{v}{v + v_{source}}\right] f_{source}$$

Source approaching:

$$f_{observed} = \left[\frac{v}{v - v_{source}}\right] f_{source}$$

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Doppler Wavelength Change

The speed of sound is determined by the medium in which it is traveling, and therefore is the same for a moving source. But the frequency and wavelength are changed. The wavelengths for a moving source are given by the relationships below. It is sometimes convenient to express the change in wavelength as a fraction of the source wavelength for a stationary source:

Source receding, wavelength increase.

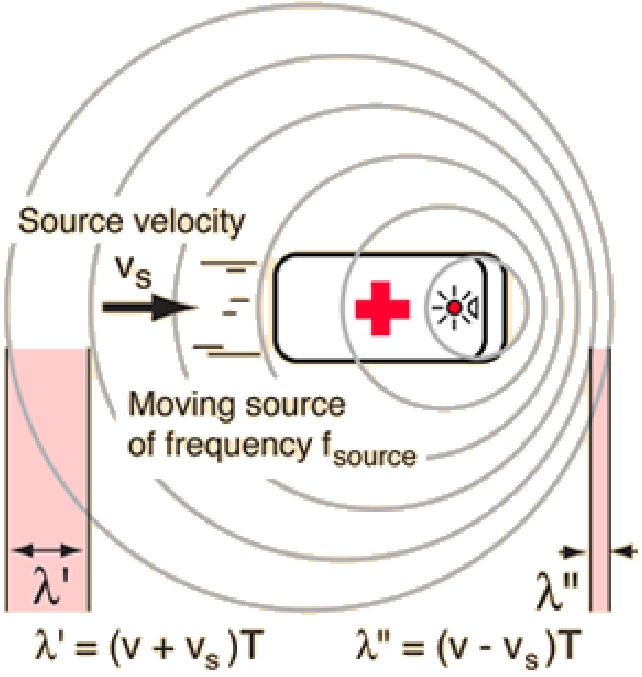
$$\lambda' = (v + v_s)T = (v + v_s)\frac{\lambda_s}{v} = (1 + \frac{v_s}{v})\lambda_s$$

$$\frac{\Delta\lambda}{\lambda} = \frac{(1 + \frac{v_s}{v})\lambda_s - \lambda_s}{\lambda_s} = \frac{v_s}{v}$$

Source approaching, wavelength decrease.

$$\lambda'' = (v - v_s)T = (v - v_s)\frac{\lambda_s}{v} = (1 - \frac{v_s}{v})\lambda_s$$

$$\frac{\Delta\lambda}{\lambda} = \frac{(1 - \frac{v_s}{v})\lambda_s - \lambda_s}{\lambda_s} = \frac{-v_s}{v}$$



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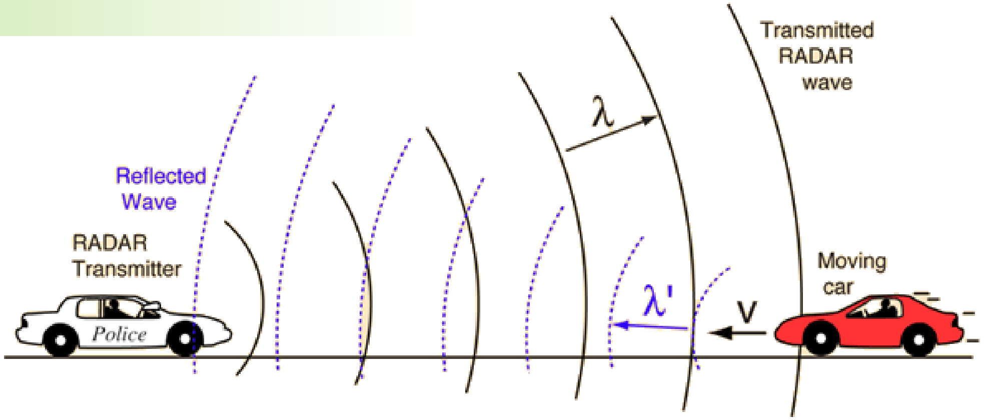
Police RADAR

RADAR speed detectors bounce microwave radiation off of moving vehicles and detect the reflected waves. These waves are shifted in frequency by the Doppler effect, and the beat frequency between the directed and reflected waves provides a measure of the vehicle speed.



The Doppler shift for relatively low velocity sources such as those encountered by police RADAR is given by

$$\frac{\Delta f}{f} = \frac{v_s}{c}$$

where c is the speed of light (and all electromagnetic waves in a vacuum). But in this case there are two shifts: one because the wave incident on the moving car is Doppler shifted and an additional shift because the reflection is from a moving object. The frequency shift of the reflected wave received at the source of the wave is

$$\frac{\Delta f}{f} = \frac{2v_{target}}{c}$$

This shift is detected by measuring the beat frequency with the transmitted wave.

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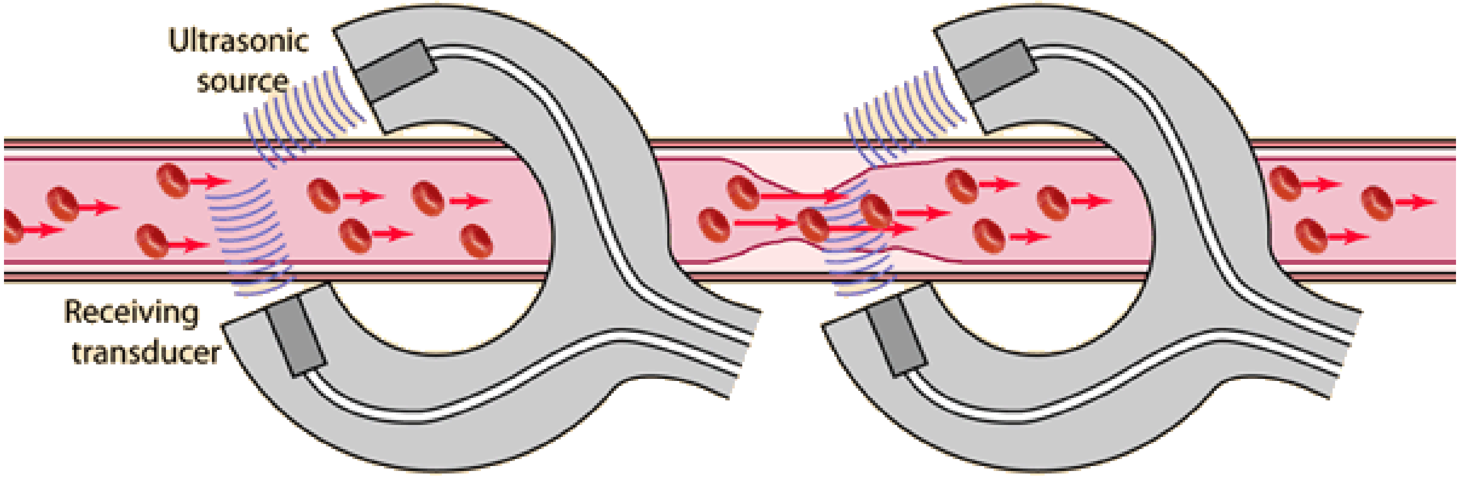
Doppler Pulse Detection

The Doppler effect in an ultrasonic pulse probe detects the reflected sound from moving blood. The frequency of the reflected sound is different, and the beat frequency between the direct and reflected sounds can be amplified and used in earphones to hear the pulse sound



The surges in blood speed with the pumping action of the heart cause detectable changes in the beat frequency.

The increase in blood speed caused by a constriction or obstruction in an artery can be detected as a change in beat frequency.

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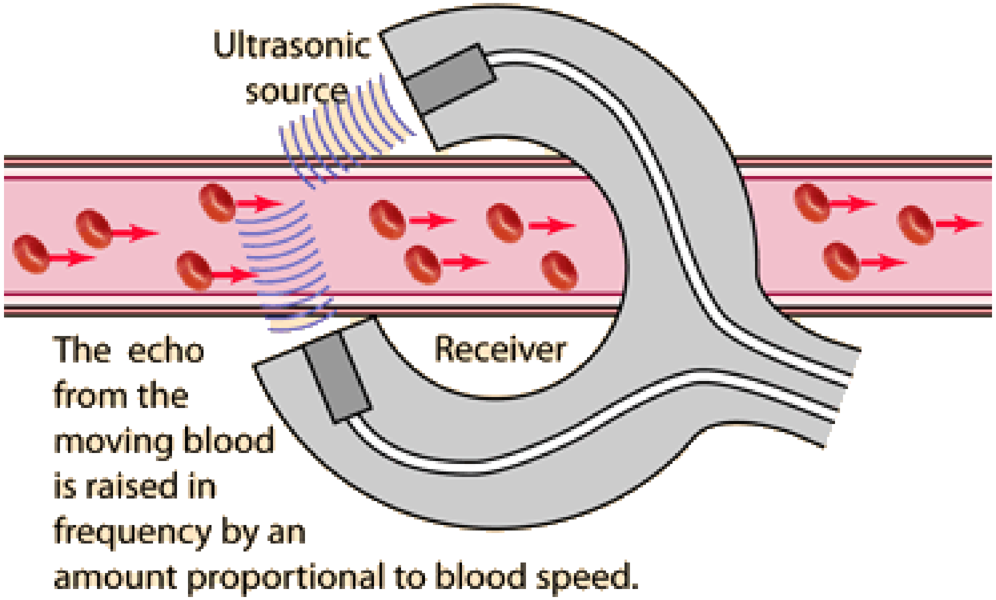
Doppler Pulse Probe

The pulse of a premature infant may be very difficult to detect with a stethoscope since the sound produced is extremely faint. A sensitive Doppler pulse probe can be used to advantage because it detects the movement of the blood through an artery. The ultrasonic echo from the moving blood can be mixed with the source frequency to produce a beat frequency. As the blood surges with the pumping action of the heart, the beat frequency signal changes in frequency and amplitude.

Remarkably, in clinical Doppler pulse detectors the sound output is similar in nature to what you hear with a stethoscope; you immediately recognize it as a pulse sound.



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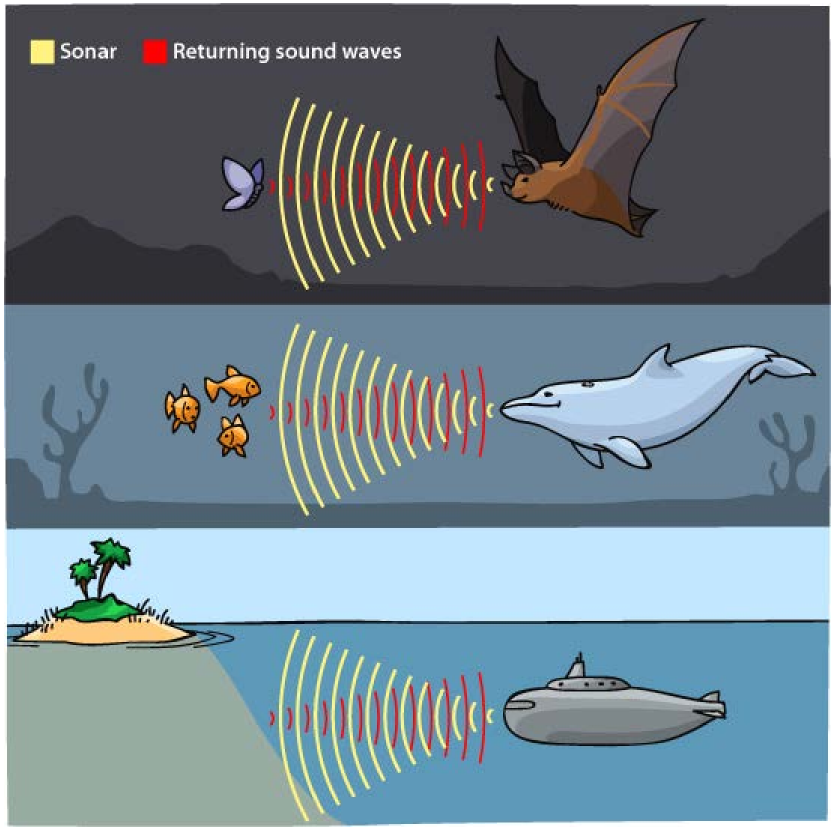
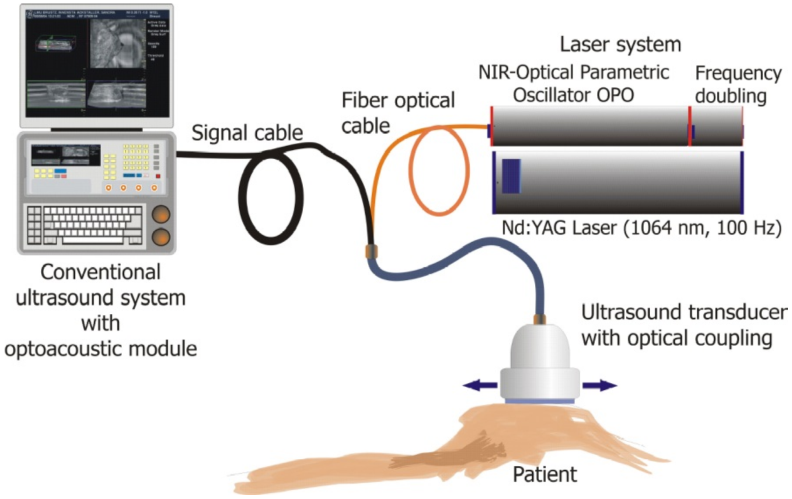
Ultrasonic sound

The term "***ultrasonic***" applied to sound refers to anything above the frequencies of audible sound, and nominally includes anything over 20,000 Hz. Frequencies used for medical diagnostic ultrasound scans extend to 10 MHz and beyond.



Sounds in the range 20-100kHz are commonly used for communication and navigation by bats, dolphins, and some other species.

Much higher frequencies, in the range 1-20 MHz, are used for medical ultrasound. Such sounds are produced by ultrasonic transducers.



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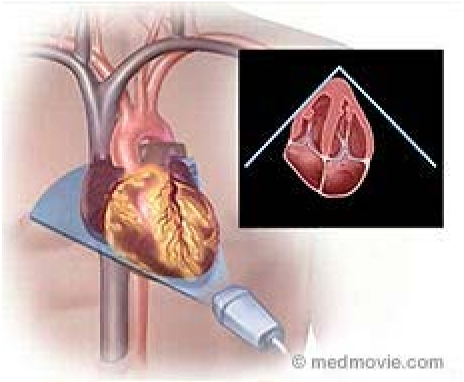
https://askabiologist.asu.edu/echolocation
http://spie.org/Images/

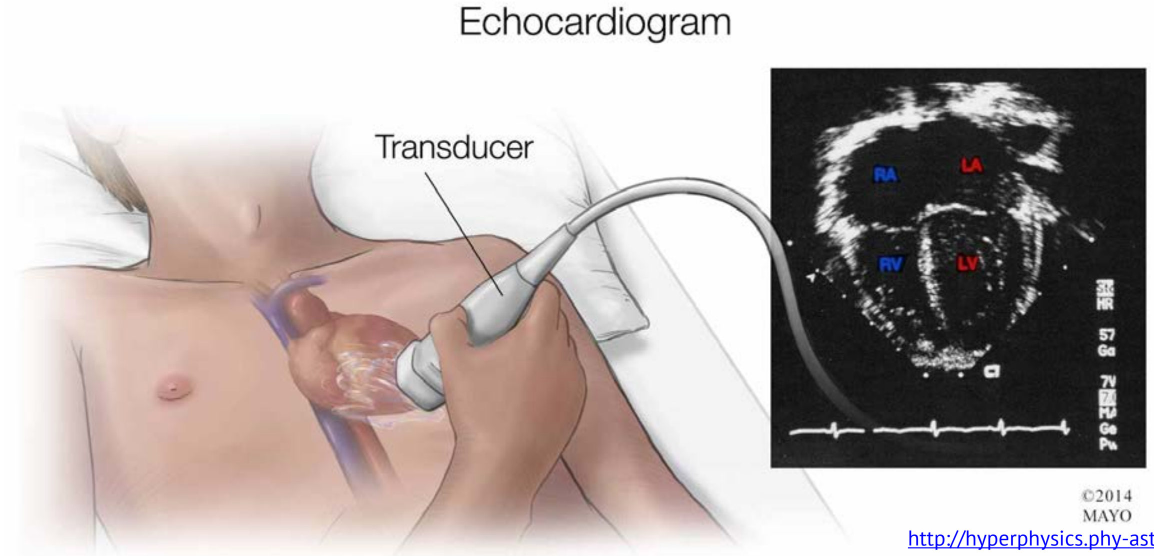
Ultrasonic sound

A wide variety of medical diagnostic applications use both *the echo time* and *the Doppler shift* of the reflected sounds to measure the *distance* to internal organs and *structures* and *the speed* of movement of those structures.

Typical is the ***echocardiogram***, in which a moving image of the heart's action is produced in video form with false colors to indicate the speed and direction of blood flow and heart valve movements.

Ultrasound imaging near the surface of the body is capable of *resolutions less than a millimeter*. The resolution decreases with the depth of penetration since lower frequencies must be used (the attenuation of the waves in tissue goes up with increasing frequency.) The use of longer wavelengths implies lower resolution since the maximum resolution of any imaging process is proportional to the wavelength of the imaging wave.




Echocardiogram

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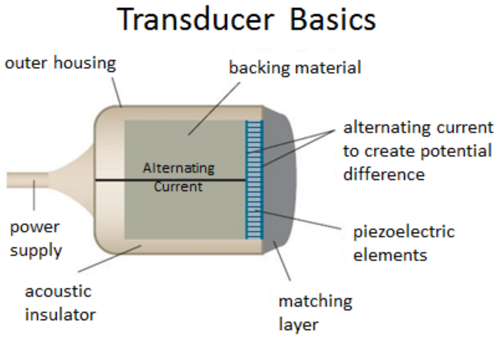
Ultrasonic Transducers

Ultrasonic sound can be produced by ***transducers*** which operate either by the ***piezoelectric effect*** *(crystals which acquire a charge when compressed, twisted or distorted are said to be* ***piezoelectric****)* or the ***magnetostrictive effect*** *(ferromagnetic material respond mechanically to magnetic fields)*. The magnetostrictive transducers can be used to produce high intensity ultrasonic sound in the 20-40 kHz range for ultrasonic cleaning and other mechanical applications.

Ultrasonic medical imaging typically uses much higher ultrasound frequencies in the range 1-20 MHz.

Such ultrasound is produced by applying the output of an electronic oscillator to a thin wafer of piezoelectric material such as lead ***zirconate titanate***. The higher frequencies imply shorter wavelengths and therefore higher resolution for the imaging process. The application of the basic ideas of imaging suggests that the resolution of any imaging process is limited by diffraction to a dimension similar to the wavelength of the wave used for the imaging process.



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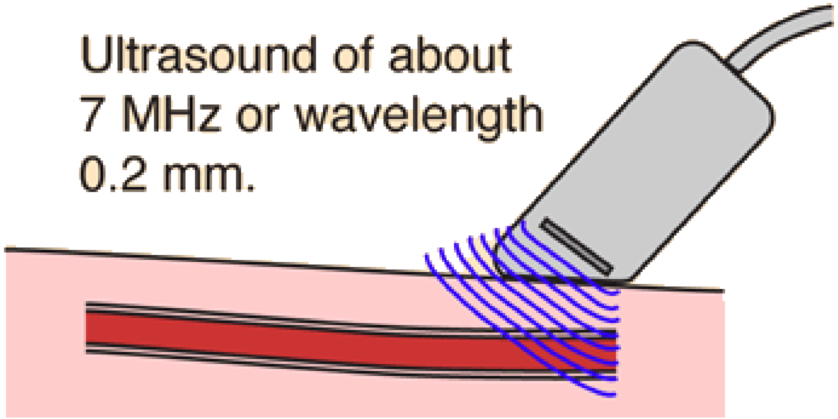
Arterial Ultrasound Scan

High frequency ultrasound in the 7-12 MHz region is used for high resolution imaging of arteries which lie close to the surface of the body, such as the carotid arteries. Using a nominal sound velocity of 1540 m/s in tissue, the sound wavelength in tissue for a 7 MHz sound wave can be obtained from the wave relationship v = fλ.



$$\lambda = \frac{1540 m/s}{7 \times 10^{6} Hz} \approx 0.2\ mm$$

Using the general principle of imaging that you can't see anything smaller than the wavelength suggests a 0.2 mm ultimate resolution limit.

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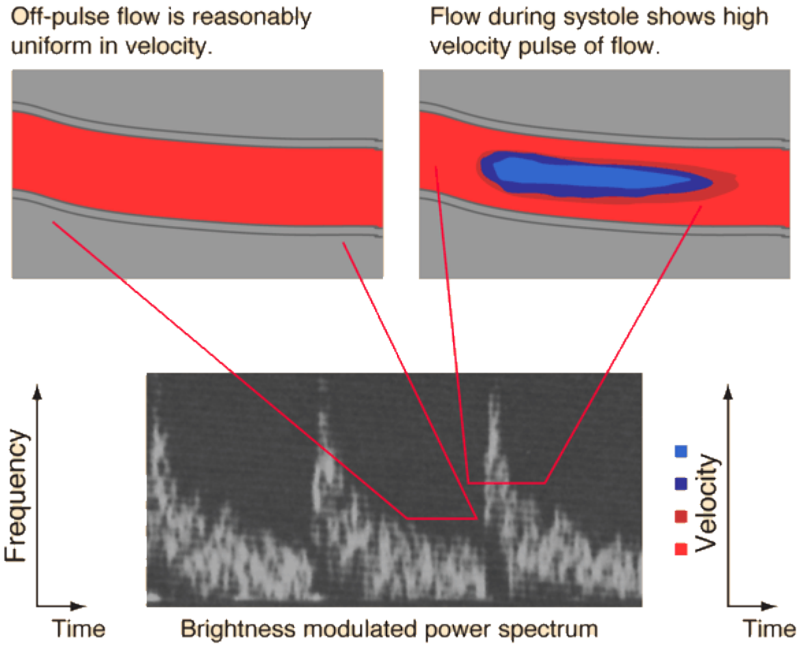
Arterial Ultrasound Scan

In addition to imaging the arterial walls, the ultrasound techniques can measure the blood flow velocity by making use of the Doppler effect. The reflected ultrasound is shifted in frequency from the frequency of the source, and that difference in frequency can be accurately measured by detecting the beat frequency between the incident and reflected waves. The beat frequency is directly proportional to the velocity of flow, so continuous recording of the beat frequencies from the different parts of the artery gives you an image of the velocity profile of the blood flow as a function of time.



Speed of Sound in Tissue

Material	Sound speed (m/s)	Acoustic impedance
air (0 C)	331	0.0004
fat	1450	1.38
water	1540	1.54
human soft tissue	1540	..
brain	1541	1.68
liver	1549	1.65
kidney	1561	1.62
blood	1570	1.61
muscle	1585	1.70
lens of eye	1620	1.84
skull-bone	4080	7.8

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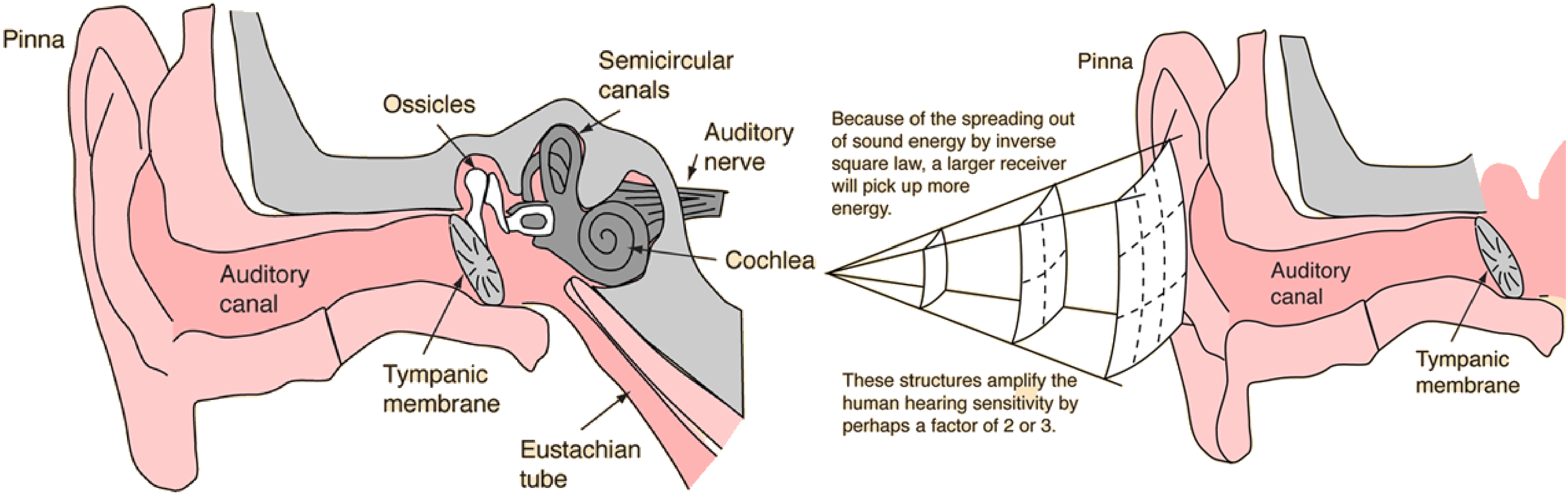
Ear and Hearing



Because of the spreading out of sound energy by inverse square law, a larger receiver will pick up more energy.

These structures amplify the human hearing sensitivity by perhaps a factor of 2 or 3.

Sound energy spreads out from its sources. For a point source of sound, it spreads out according to the inverse square law. For a given sound intensity, a larger ear captures more of the wave and hence more sound energy.

The outer ear structures act as part of the ear's preamplifier to enhance the sensitivity of hearing.

The auditory canal acts as a closed tube resonator, enhancing sounds in the range 2-5 kiloHertz.

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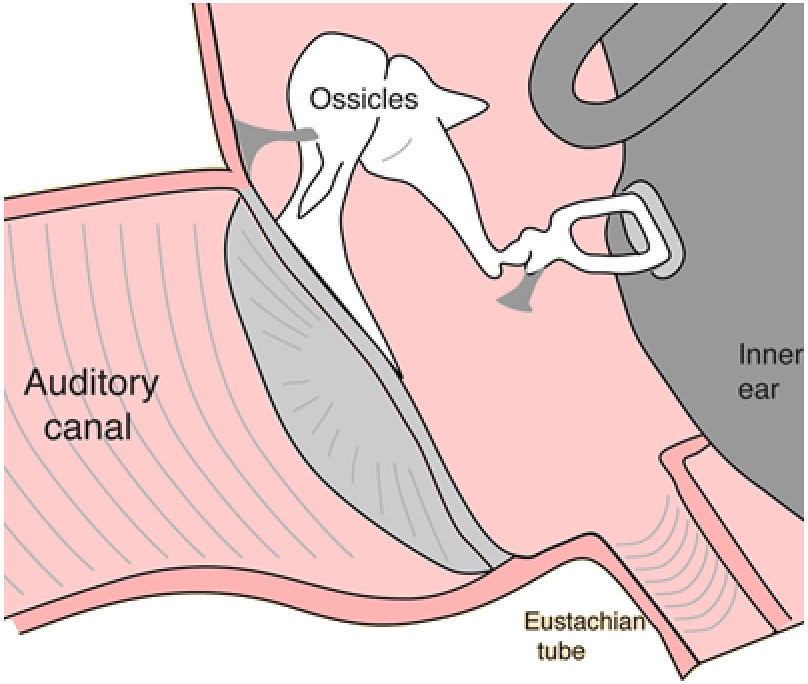
The Tympanic Membrane

The tympanic membrane or "eardrum" receives vibrations traveling up the auditory canal and transfers them through the tiny ossicles to the oval window, the port into the inner ear.

The eardrum is some fifteen times larger than the oval window of the inner ear, giving an amplification of about fifteen compared to a case where the sound pressure interacted with the oval window alone.

The tympanic membrane is very thin, about 0.1 mm, but it is resilient and strong. It is made up of three layers: the outer layer of skin, a layer of fibrous connective tissue, and a layer of mucous membrane.



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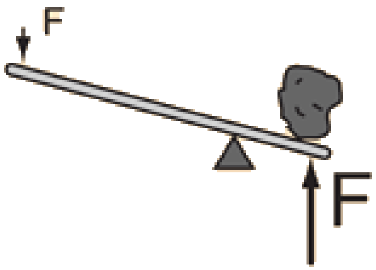
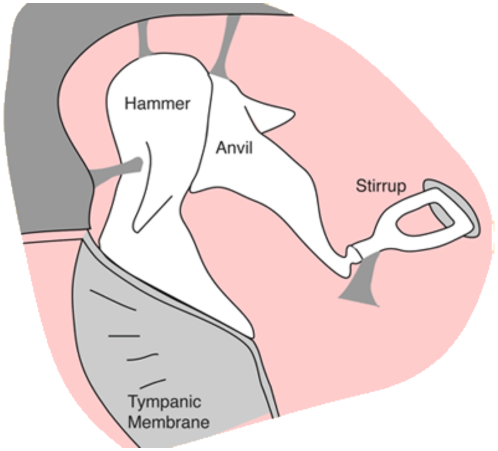
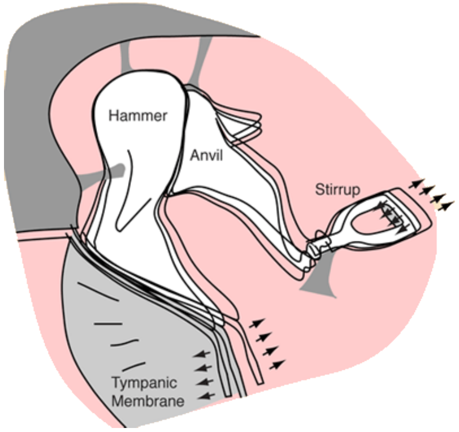
The Ossicles

The three tiniest bones in the body form the coupling between the vibration of the eardrum and the forces exerted on the oval window of the inner ear. Formally named the malleus, incus, and stapes, they are commonly referred to in English as the hammer, anvil, and stirrup.

With a long enough lever, you can lift a big rock with a small applied force on the other end of the lever. The amplification of force can be changed by shifting the pivot point.







The ***ossicles*** can be thought of as a compound lever which achieves a multiplication of force. This lever action is thought to achieve an amplification by a factor of about three under optimum conditions, but can be adjusted by muscle action to actually attenuate the sound signal for protection against loud sounds.

The vibration of the eardrum is transmitted to the oval window of the inner ear by means of the ossicles, which achieve an amplification by lever action. The lever is adjustable under muscle action and may actually attenuate loud sounds for protection of the ear.

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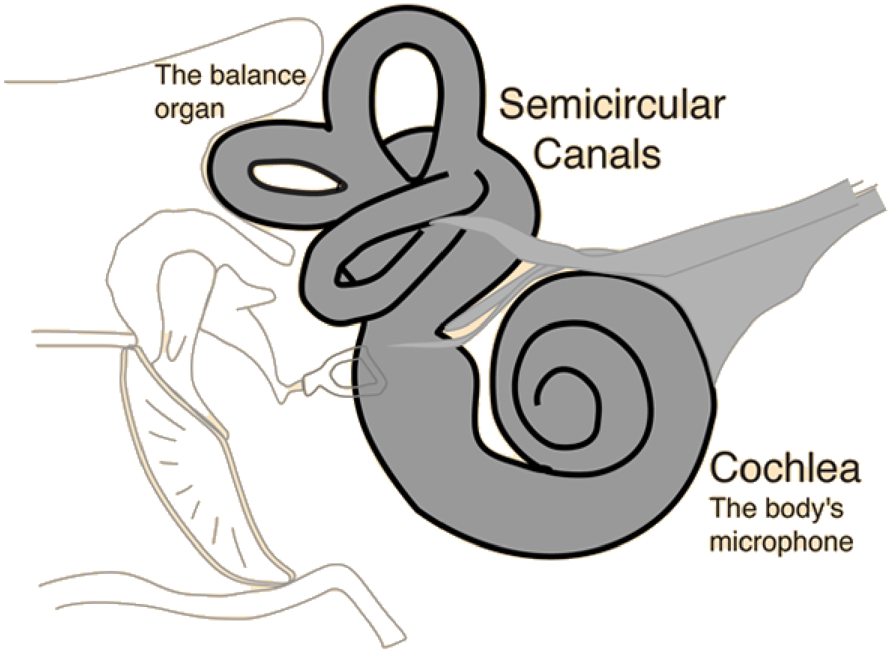
The Inner Ear

The small bone called the ***stirrup***, one of the ossicles, exerts force on a thin membrane called the ***oval window***, transmitting sound pressure information into ***the inner ear***.

The inner ear can be thought of as two organs: the semicircular canals which serve as the body's balance organ and the cochlea which serves as the body's microphone, converting sound pressure impulses from the outer ear into electrical impulses which are passed on to the brain via the auditory nerve.

The basilar membrane of the inner ear plays a critical role in the perception of pitch according to the place theory.



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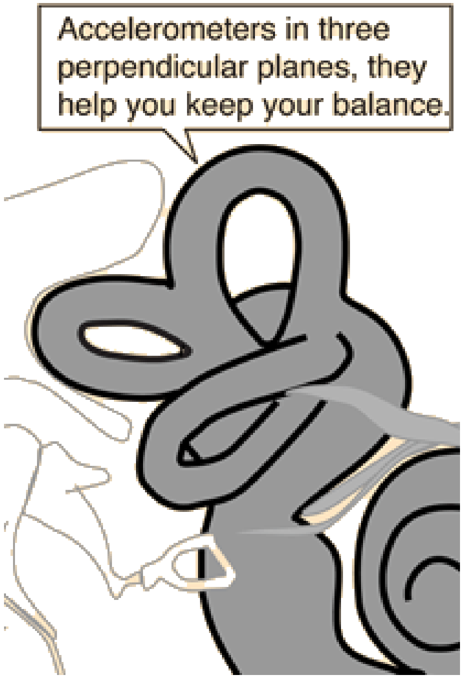
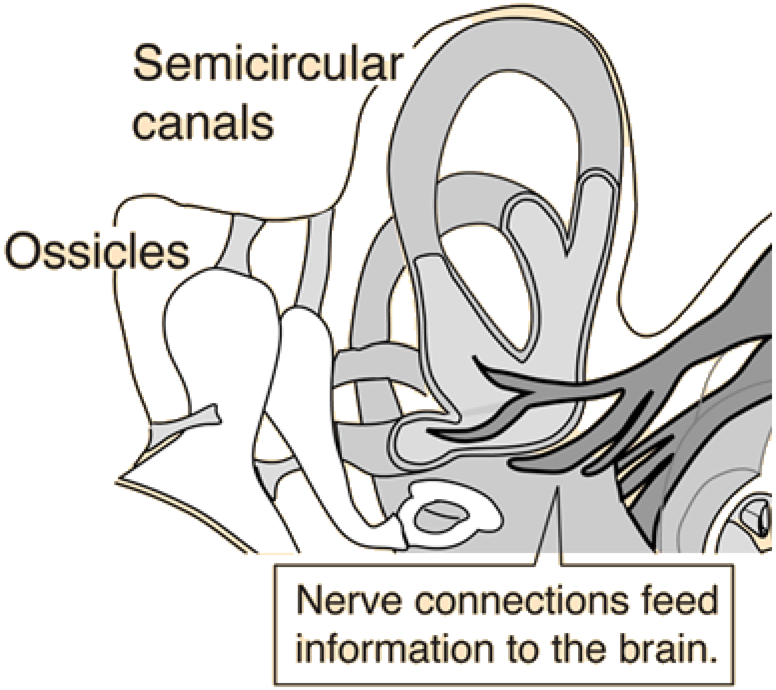
The Semicircular Canals

The semicircular canals, part of the inner ear, are the body's balance organs, detecting acceleration in the three perpendicular planes. These accelerometers make use of hair cells similar to those on the ***organ of Corti***, but these hair cells detect movements of the fluid in the canals caused by angular acceleration about an axis perpendicular to the plane of the canal. Tiny floating particles aid the process of stimulating the hair cells as they move with the fluid. The canals are connected to the auditory nerve.



Accelerometers in three perpendicular planes, they help you keep your balance.



Nerve connections feed information to the brain.

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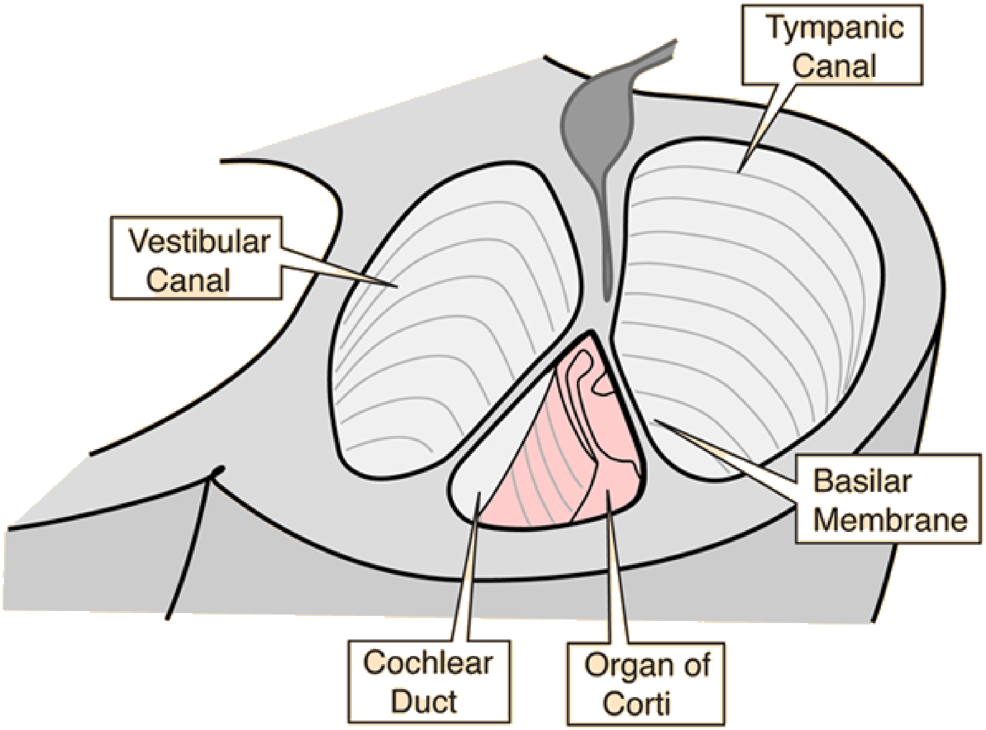
The Cochlea

The inner ear structure called the ***cochlea*** is a snail-shell like structure divided into three fluid-filled parts. Two are canals for the transmission of pressure and in the third is the sensitive organ of Corti, which detects pressure impulses and responds with electrical impulses which travel along the auditory nerve to the brain.

The perilymph fluid in the canals differs from the endolymph fluid in the cochlear duct. The organ of Corti is the sensor of pressure variations



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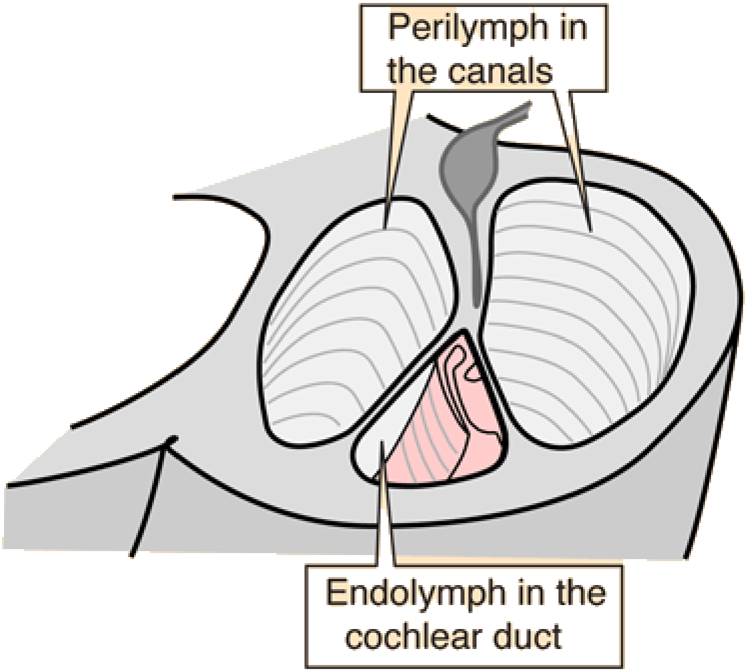
The Fluid Filled Cochlea

The pressure changes in the cochlea caused by sound entering the ear travel down the fluid filled tympanic and vestibular canals which are filled with a fluid called ***perilymph***. This perilymph is almost identical to spinal fluid and differs significantly from the endolymph which fills the cochlear duct and surrounds the sensitive organ of Corti. The fluids differ in terms of their electrolytes and if the membranes are ruptured so that there is mixing of the fluids, the hearing is impaired.



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