Lecture 6

Physics of Audition

Sound

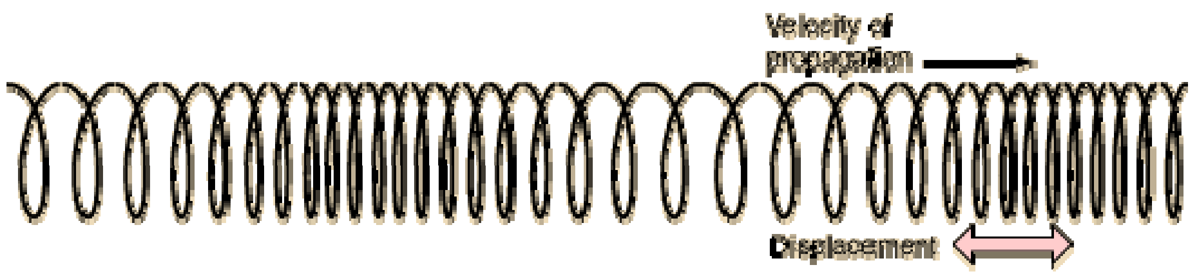
- Important way of communication for humans:
- music, conversation, noise
- Animals – sound is exclusive way of communication:
- alarm, food, giving love-call, finding their path

- **Sound is mechanical vibrations or waves transported by solids, liquids and gases.**

- The sense of hearing - mechanical vibration strike on eardrum – impulse in auditory nerves
- Physics of audition - nature of sound + mechanism of auditory system

Longitudinal waves

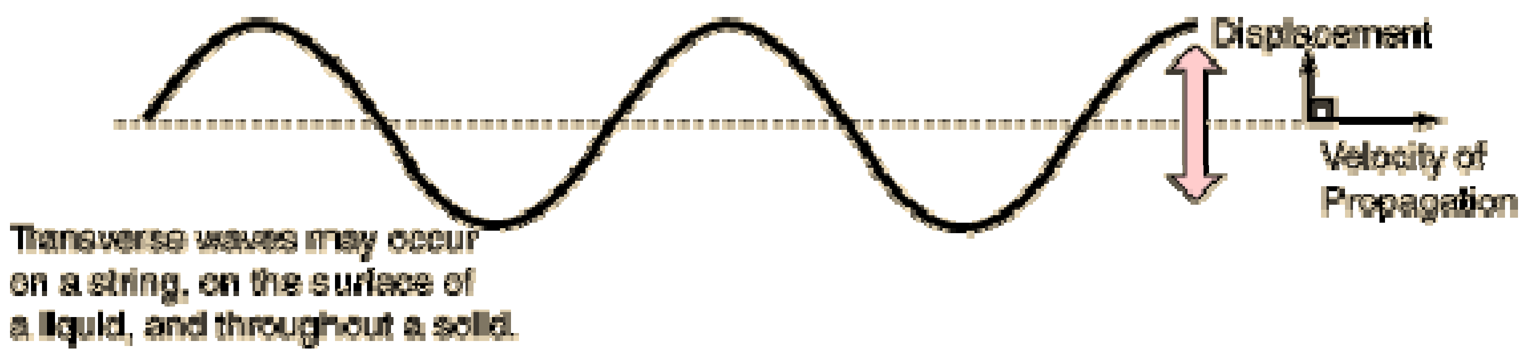
- In longitudinal waves the displacement of the medium is parallel to the propagation of the wave.



Transverse Waves

- For transverse waves the displacement of the medium is perpendicular to the direction of propagation of the wave.
- Examples: ripple on a pond, wave on a string.

- Transverse waves cannot propagate in a gas or a in liquid because there is no mechanism for driving motion perpendicular to the propagation of the wave

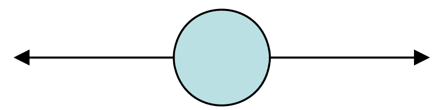


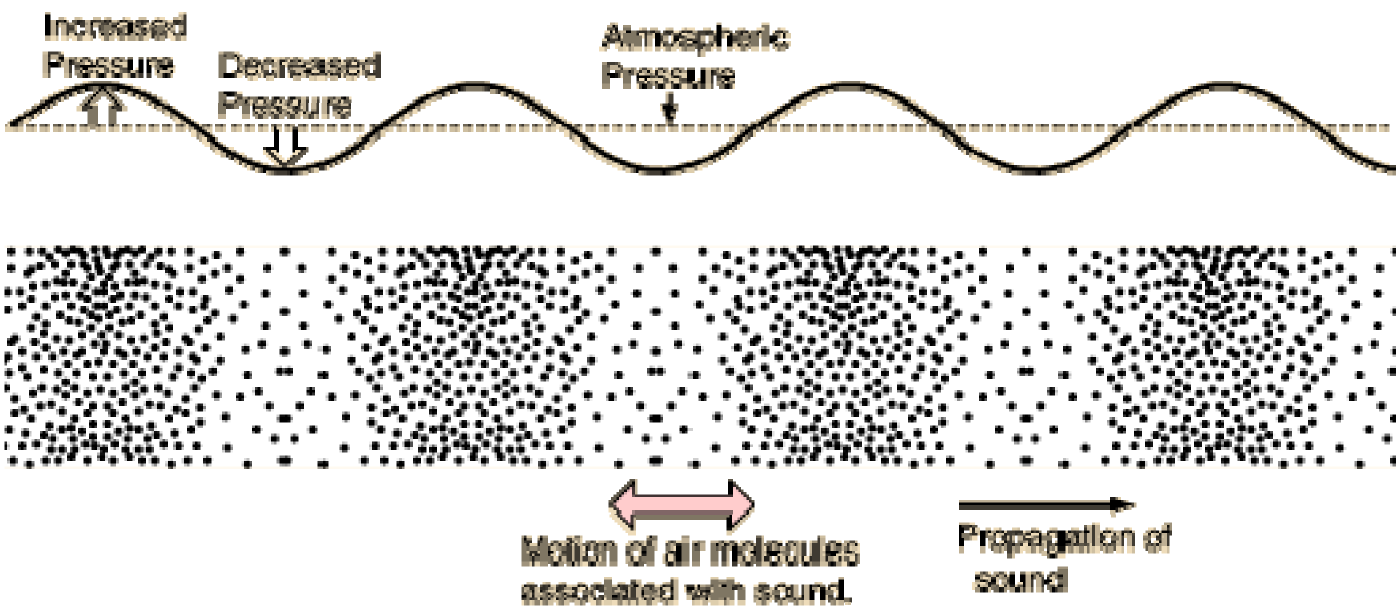
Sound waves are longitudinal waves.

Sound is a mechanical vibration of particles in air, liquid or solid.

Particles vibrate forth and back around equilibrium point – there is no net transfer of matter

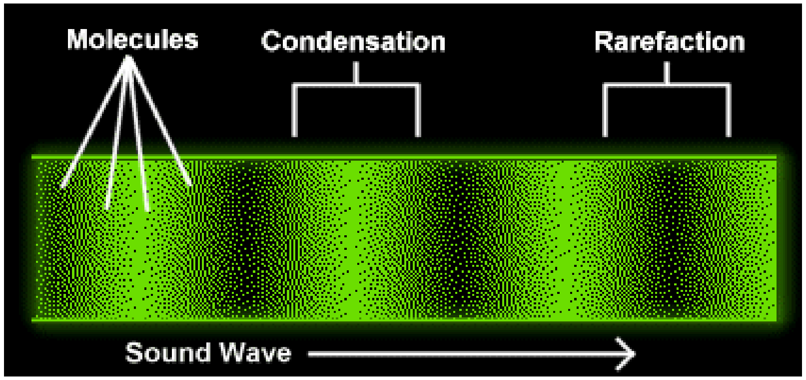
oscillations are very small

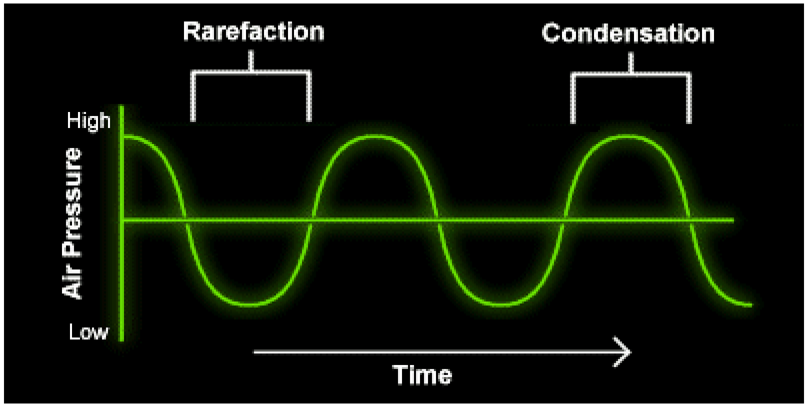




Sound waves are also called pressure waves

- sound is the vibration of any substance: air, water, wood, or any other material, and in fact the only place in which sound cannot travel is a vacuum. When these substances vibrate, or rapidly move back and forth, they produce sound.
- The vibrations that produce sound are not the result of an entire volume moving back and forth at once.
- Instead, the vibrations occur among the individual molecules of the substance, and the vibrations move through the substance in sound waves.
- As sound waves travel through the material, each molecule hits another and returns to its original position. The result is that regions of the medium become alternately more dense, when they are called condensations, and less dense, when they are called rarefactions.

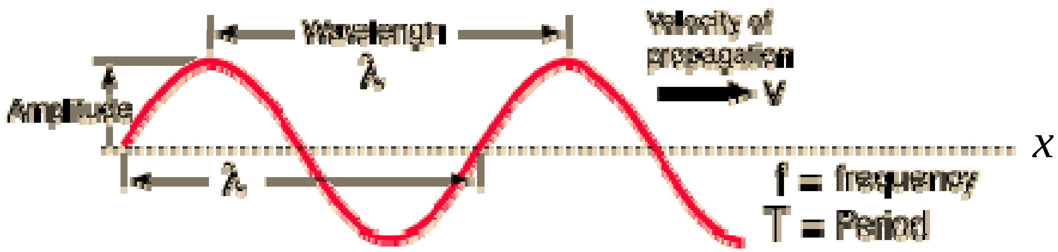




Wave parameters

- A single frequency traveling wave will take the form of a sine wave.
- relationship of the frequency, wavelength and propagation velocity:

- Displacement of particles as a function of distance:



$$v = f\lambda$$

$$f = 1/T$$

T-Period - is time for one complete oscillation (λ)

With time dependence:

$$y = y_0 \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right)$$

Amplitude – max displacement

- Sound is a pressure wave:
- displacement of molecules is proportional to the pressure

$$y = y_0 \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right)$$

$$p = p_m \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right)$$

$$p = p_m \sin 2\pi(ft - x/\lambda)$$

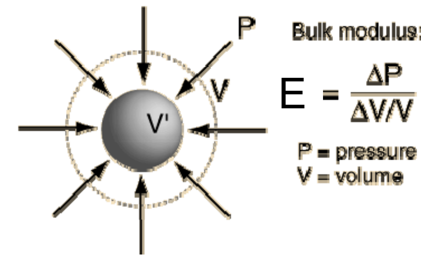
Pressure amplitude-max amount of change in pressure

sound 20 to 20,000 Hz – human

infrasonic - below 20Hz - elephants, hippos, rhinoceros, giraffe, alligator

ultrasonic - more 20,000 Hz - dogs up to 40KHz, whales and dolphins 100KHz, bats to 300KHz

Wave velocity



- Speed at which pressure oscillations travel in medium, depends on medium properties such as elastic compressibility and inertia

$$v = \sqrt{\frac{E}{\rho_0}}$$

E → bulk modulus

ρ_0 → equilibrium density

- For gases:

$$v = \sqrt{\frac{\gamma \cdot p_0}{\rho_0}} = \sqrt{\frac{\gamma \cdot kT}{M}}$$

p_0 → equilibrium pressure

k → Boltzmann constant

T → temperature

M → Molecular weight

$$\gamma = C_p / C_v$$

adiabatic constant

(no heat transfer, T=const)

- Speed of sound in air at 0°C and 1Atm is 332m/s
- Increases with T increase 0.6 m/s per each °C
- sound travels in solids faster than in liquids, and in liquids faster than in gases
- sound velocity in bones 3360m/s, in muscles 1570 m/s, soft tissues 1490 m/s

$$v = \sqrt{\frac{E}{\rho_0}} = \sqrt{\frac{\gamma \cdot p_0}{\rho_0}} = \sqrt{\frac{\gamma \cdot NkT}{\rho_0 V}} = \sqrt{\frac{\gamma \cdot NkT}{m}} = \sqrt{\frac{\gamma \cdot kT}{m / N}} = \sqrt{\frac{\gamma \cdot kT}{M}}$$

- Disturbance is small - no heat transfer – adiabatic process – therefore:

$$pV^{\gamma} = const = C$$

$$p = CV^{-\gamma}$$

$$\frac{dp}{dV} = -\gamma C V^{\gamma - 1}$$

$$E = -\frac{dp}{dV} V = \gamma C V^{\gamma - 1} = \gamma p$$

$$pV = nRT = NkT$$

n-number of moles

N-number of molecules

$$p = \frac{n \cdot k \cdot T}{V}$$

This slide is to explain how we get the formula for the wave speed in gases

- Physical characteristics of the sound wave :

- Energy
- Power
- Intensity

Energy of sound wave

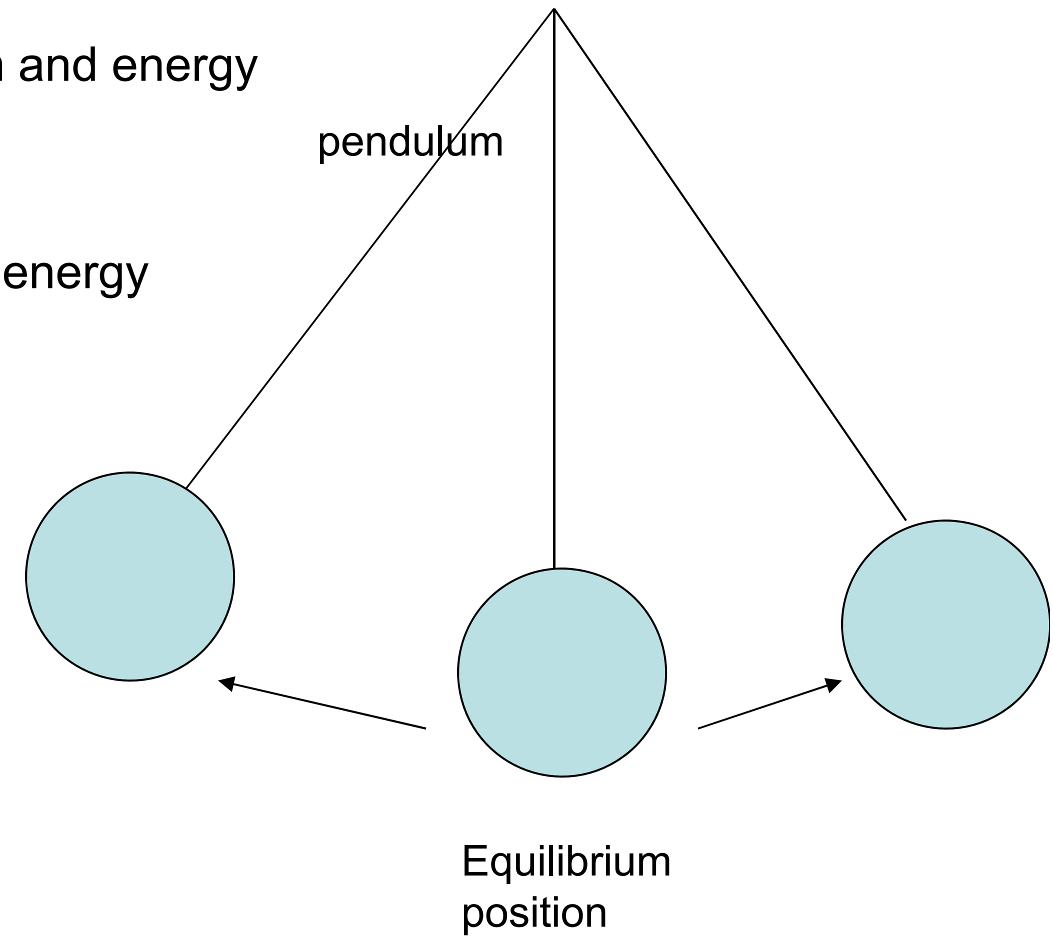
- The waves transport momentum and energy
- Oscillation of one particle:

- Kinetic energy $\Leftrightarrow$ potential energy

$$E_{Ki} = \frac{1}{2} m v_i^2$$

m – mass of the molecule

v_i – instantaneous velocity of molecule



Molecule displacement:

$$y = y_0 \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right) = y_0 \sin 2\pi f\left(t - \frac{x}{v}\right)$$

$$E_{Ki} = \frac{1}{2} m v_i^2 \qquad v_i = \frac{dy}{dt} = \frac{d}{dt} y_0 \sin 2\pi f\left(t - \frac{x}{v}\right)$$

Kinetic energy

$$E_{Ki} = 2\pi^2 m y_0^2 f^2 \left[\cos 2\pi f\left(t - \frac{x}{v}\right)\right]^2 \longrightarrow$$

E kinetic is maximum when

$$\cos 2\pi f\left(t - \frac{x}{v}\right) = 1$$

$$E_{\max} = 2\pi^2 m y_0^2 f^2$$

For one molecule

$$E_{\max} = 2\pi^2 m y_0^2 f^2$$

For volume V, medium of density ρ, the energy of the wave is:

$$E_{\max} = 2\pi^2 \rho y_0^2 f^2 V$$

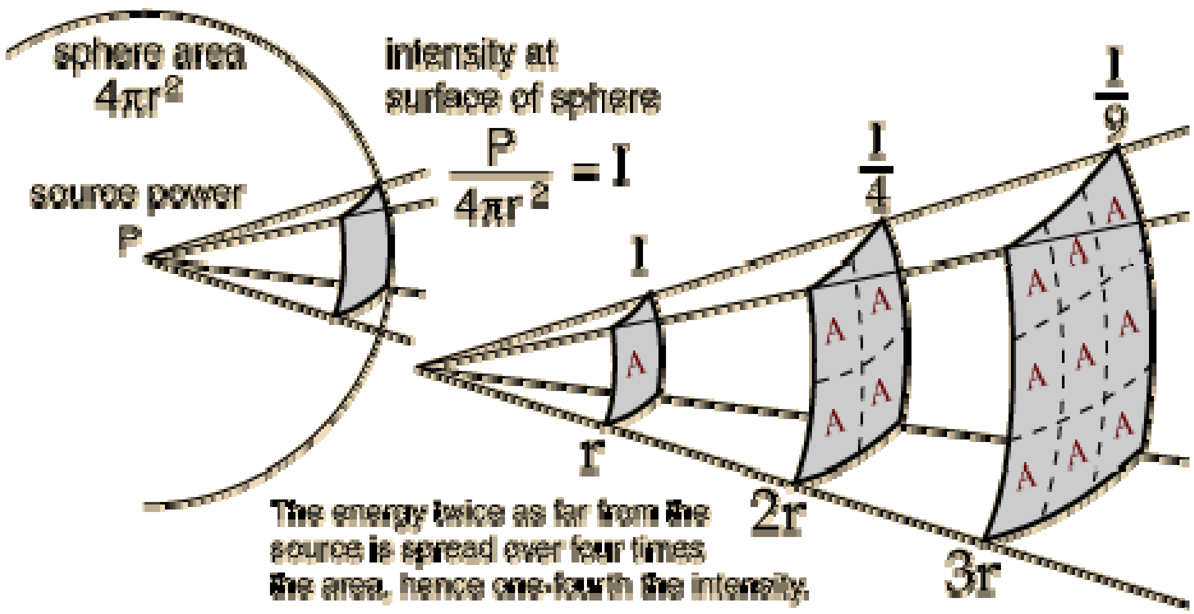
Power of the wave is energy per unit time:

$$P = \frac{E_{\max}}{t} = \frac{2\pi^2 \rho y_0^2 f^2 V}{t}$$

Intensity of sound wave

•Intensity of sound is average power (average energy flow per unit time) across unit area,

$$I = \frac{P}{A}$$



$$I = \frac{P}{4\pi r^2}$$

Example 1 Sound Intensity - distance

1. Calculate the intensity of the sound, which the listener will hear if he walks 100 m away from the sound source. The sound intensity that he hears at 1 m from the source is $I_1=10^{-8}$ Watt/m^2.

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} = 10000$$

$$I = \frac{P}{4\pi r^2}$$

$$r_1^2 = 1$$

$$r_2^2 = 10000$$

$$r_2 = 100m$$

$$I_2 = 10^{-8} / 10000 = 10^{-12}$$

Intensity of sound wave

- depends on speed - v, amplitude of particle displacement - y, frequency - f:

$$E_{\max} = 2\pi^2 \rho y_0^2 f^2 V$$

$$I = \frac{P}{A} = \frac{E_{\max}}{At} = \frac{E_{\max}}{V} v = 2\pi^2 v \rho \cdot f^2 y_0^2$$

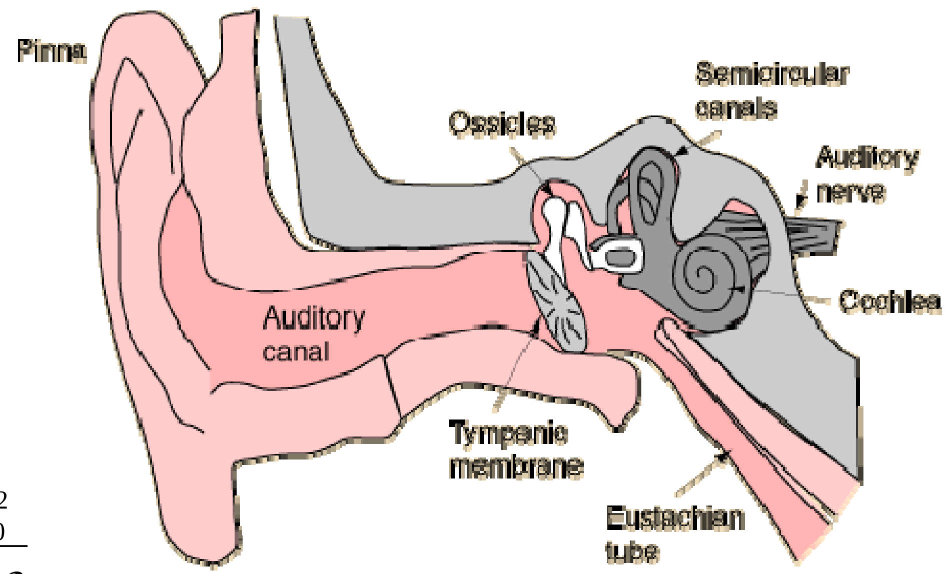
- Particle displacement amplitude is related to the pressure amplitude:

$$\boxed{p_0 = 2\pi \cdot \rho \cdot v \cdot f \cdot y_0}$$

$$\boxed{I = \frac{p_0^2}{2v\rho}}$$

- Intensity is related to pressure amplitude also
- Intensity is measured in Joules/(sec·m^2) = Watt/m^2

- The momentum transfer by sound waves produces force on tympanic membrane or eardrum and membrane vibrates
- Human ear can detect sounds with intensities as low as 10^{-16} W/cm^2



- This corresponds to a pressure amplitude: $I = \dfrac{p_0^2}{2v\rho}$

$$p_L = \sqrt{2\rho v I} \approx \left[2\times\left(1.3kg/m^3\right)\times\left(332m/s\right)\times\left(10^{-12}\frac{J}{s\cdot m^2}\right)\right]^{1/2} \approx 3\times10^{-5}\,N/m^2$$

- This is very small pressure variation $3\cdot10^{-10}$ atm
- Max displacement of air molecules caused by such a pressure for frequency 1000 Hz – the weakest audible frequency:

$$y_L = \frac{p_L}{2\pi\rho v f} = \frac{3\times10^{-5}}{2\times3.14\times1.3\times332\times10^3} \approx 10^{-11}\,m$$

0.1 A - one tenths of a size of H atom

Example 2

- A painfully loud sound – $I_H=10^{-4}$ W/cm^2 is 10^{12} times higher than barely audible sound $I_L=10^{-16}$ W/cm^2 ($y_L=10^{-11}$m)

- what is respective pressure and particle amplitude of painfully loud sound at frequency 1000Hz and 100Hz

- $$\frac{I_1}{I_2}=\frac{f_1^{\,2}}{f_2^{\,2}}\frac{y_1^2}{y_2^2}$$

Example 2 solution

- A painfully loud sound – $I_H=10^{-4}$ W/cm^2 is 10^{12} times higher than barely audible sound $I_L=10^{-16}$ W/cm^2 ($y_L=10^{-11}$m)
- what is respective pressure and particle amplitude at 1000Hz and 100Hz?

$$\frac{I_1}{I_2} = \frac{f_1^{\,2}}{f_2^{\,2}}\frac{y_1^2}{y_2^2}$$

- particle displacement amplitude:

For $f_L=f_H=1000$ Hz $\Rightarrow$

$$y_H = y_L\sqrt{\frac{I_H}{I_L}} = 10^{-5}m(or\,0.01mm)$$

For $f_L=1000$, $f_H=100$ Hz $\Rightarrow$

$$y_H = \sqrt{\frac{(1000)^2}{(100)^2}\times(10^{-5})^2} = 0.1mm$$

- pressure amplitude:

$$p_H = p_L\sqrt{\frac{I_H}{I_L}} = 3\times10^{-5}\times\sqrt{\frac{10^{-4}}{10^{-16}}} = 30N/m^2$$

This is a small pressure variation = pressure of 3mm of water column

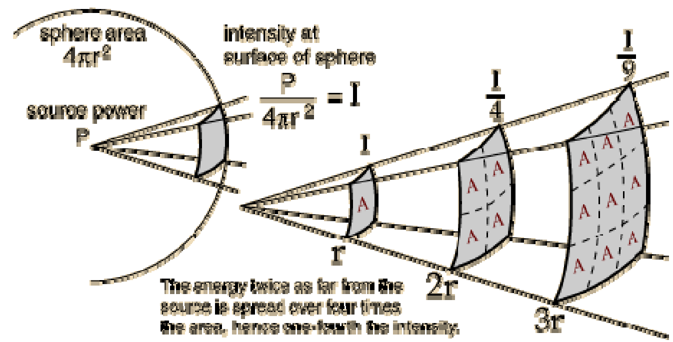
The pain is caused by amplitude of particle displacement rather than pressure itself

- Example person speaking with average loudness – sound intensity 10^{-6} W/cm^2
- Mouth aperture is 10cm^2, hence the sound energy emitted by a speaking person is E=IA= 10^{-6} Joules/sec

- **The intensity of the sound decreases with distance from the source due to 2 reasons:**

- 1. inverse square fall of intensity:

$$I \propto \frac{1}{r^2}$$



- 2. absorption or dissipation of energy in medium

$$I = I_0 e^{-\alpha x}$$

α-absorption coefficient of the medium

larger for larger frequencies

For frequency 10^6Hz

α=0.26 cm^{-1} – muscle,

α=0.1 cm^{-1} – fat,

α=3 cm^{-1} – bones of human scull

Physiological characteristics of sound

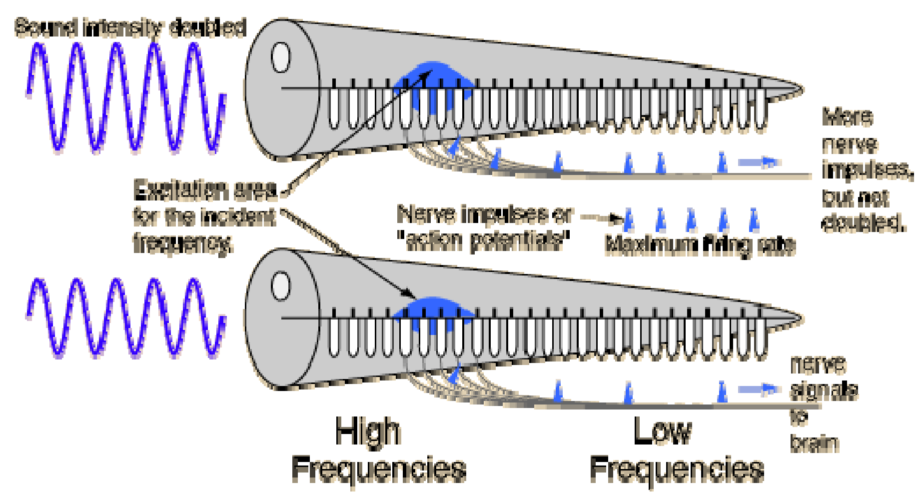
- **Loudness, Pitch, Quality**
- **Loudness** related to intensity or amplitude, characterized by reference Intensity level β:
- Lowest level β=0db, $I=I_0=10^{-16}$ W/cm^2
- Maximum β=120db, $I=10^{-4}$ W/cm^2
- - is maximum that human can tolerate
- Depends on strength of ear perception (nerve sensation)
- Weber-Fechner Law log dependence between response and physical stimulus

$$\beta = 10\log\frac{I}{I_0}$$

bels or

db (decibels)

Lowest intensity
$I=10^{-16}$ W/cm^2



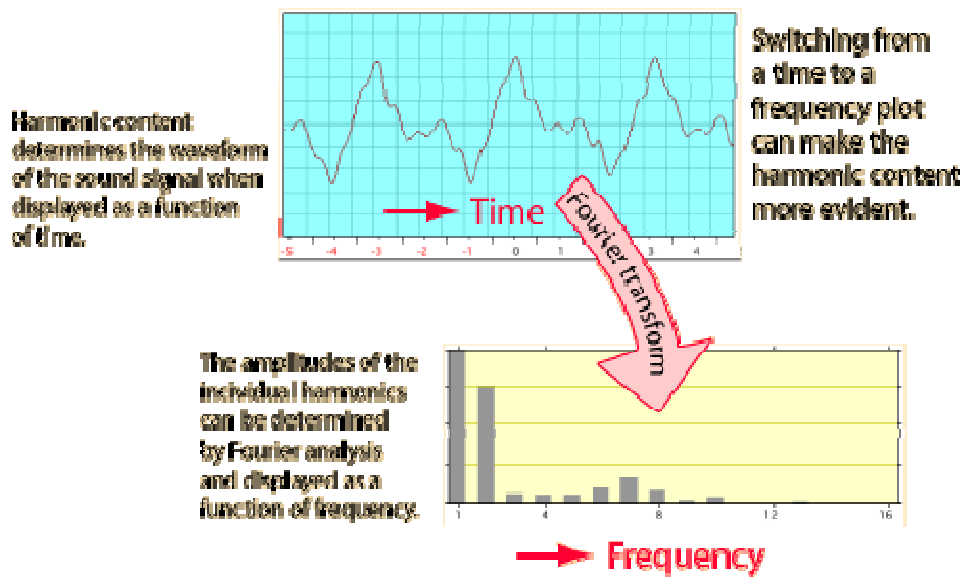
- **Pitch** is a frequency, that ear detects, normally between 20-20000Hz
- Lower frequency require higher intensity to be heard
- The minimum intensity level of a given frequency is called a threshold of hearing
- The intensity level above which hearing becomes painful is called threshold of feeling – it is 120db for all frequencies

- The just noticeable difference in pitch is expressed in cents, and the standard figure for the human ear is 5 cents.

- **Quality** – distribution of variety of frequencies with variety of intensities

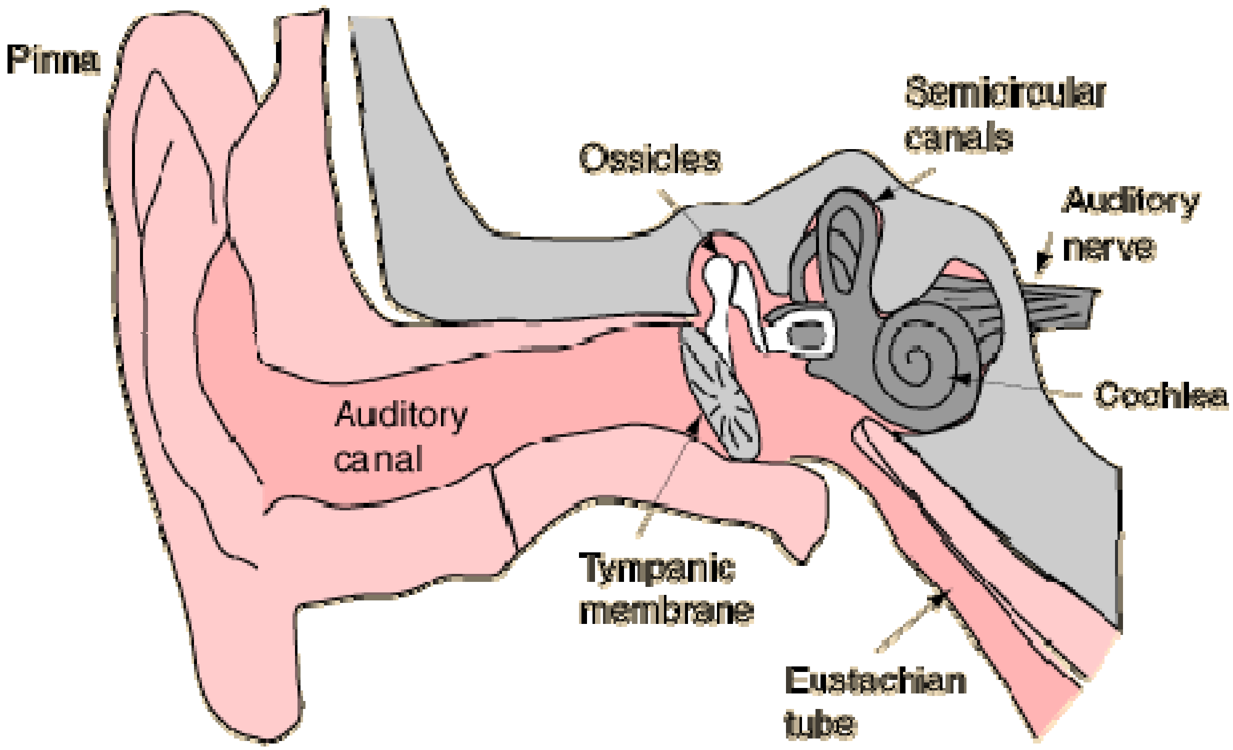
- Musical instruments:
- – few frequencies

- Street noise:
- – big variety of frequencies
  and intensities

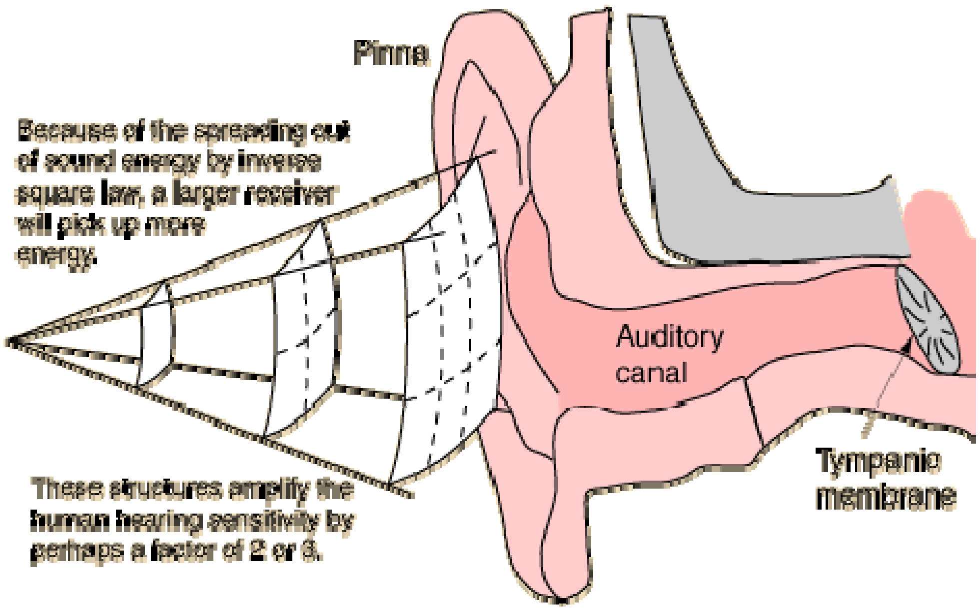


Human Ear

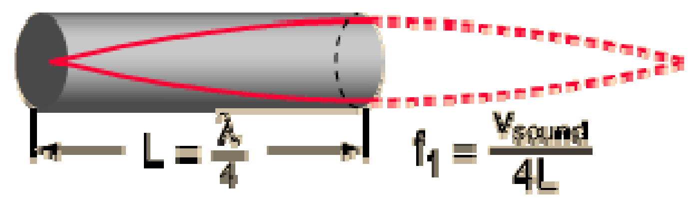
- The ear is a transducer – convert sound waves in air into electrical signals of auditory nerves
- Ear – three parts: outer, middle and inner ear



Outer ear - amplification of important frequencies



- The outer ear acts as a cavity resonator, enhancing sounds in the range 2-5 KHz.
- a resonant frequency is a natural frequency of vibration determined by the physical parameters of the vibrating object.



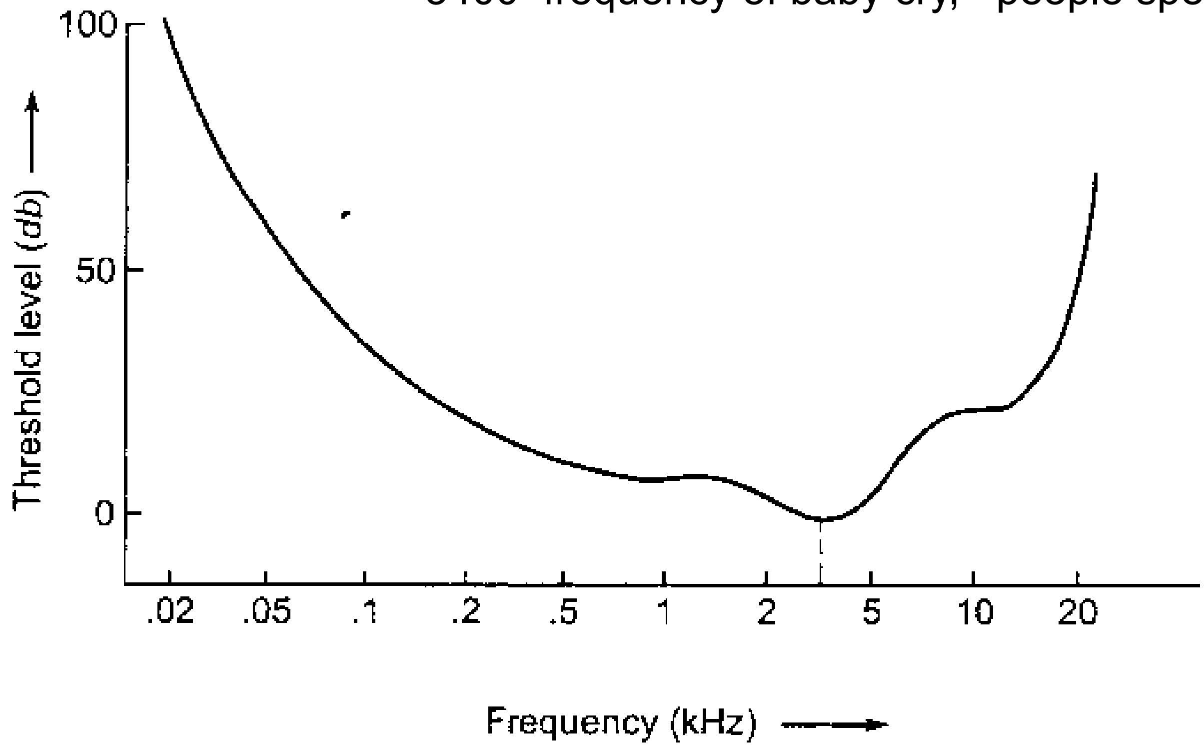
Outer ear - external ear canal, ends at tympanic membrane, it is 2.5 cm long, diameter 5-6 mm

$$frequency = \frac{v}{\lambda} = \frac{v}{4l} = \frac{330m/s}{10cm} = 3300Hz$$

Our ears are more sensitive to this frequency

$$frequency = \frac{v}{\lambda} = \frac{v}{4l} = \frac{330m/s}{10cm} = 3300Hz$$

Our ears are more sensitive to the frequency 3300-3400 frequency of baby cry, people speaking

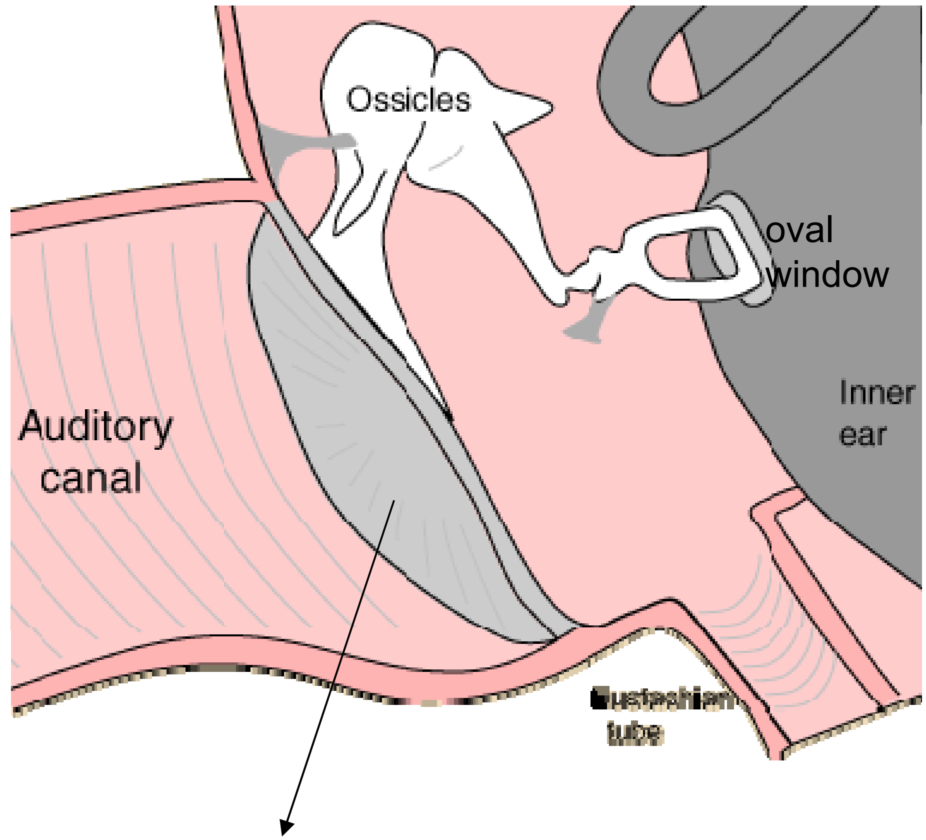


Tympanic membrane (middle ear) – transduction and amplification

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

- The eardrum is 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, has area 65 mm^2 and is resilient and strong.

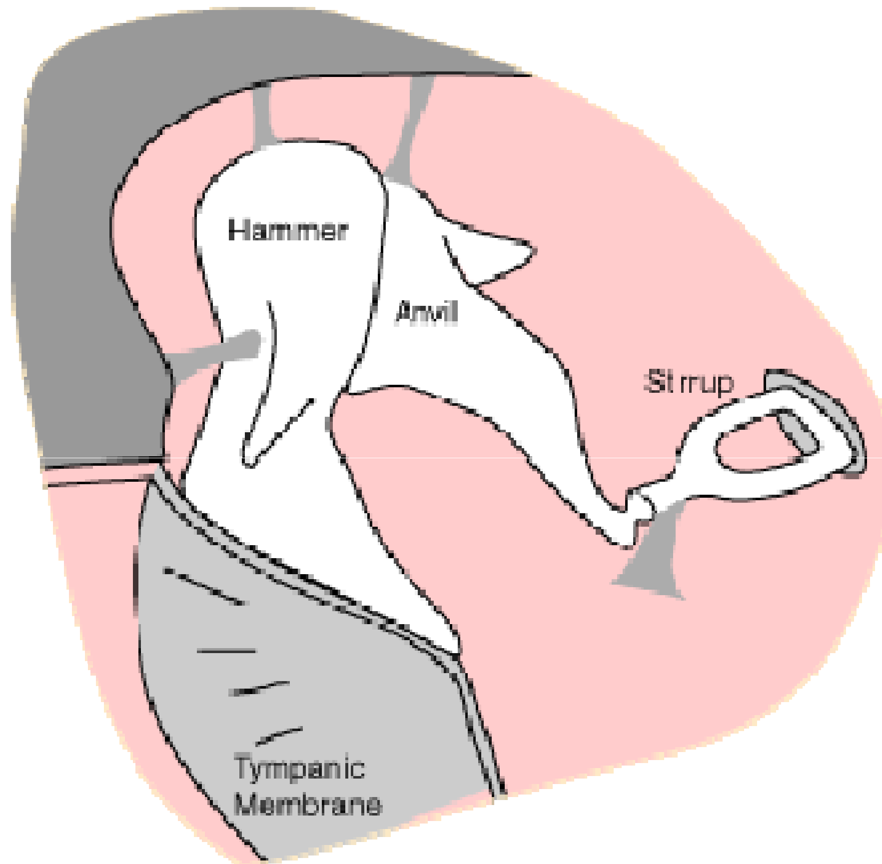
A healthy eardrum looking from the ear canal



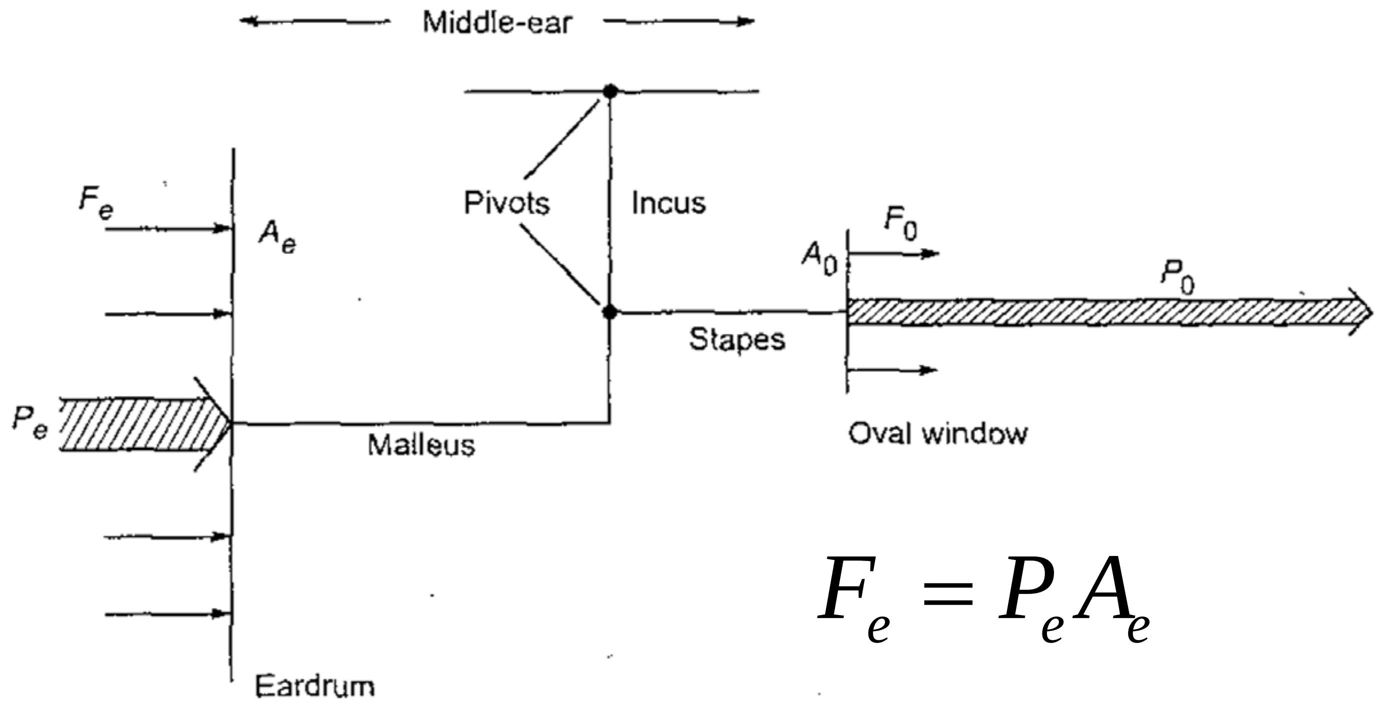
tympanic membrane

Ossicles – pressure intensifier

- The three tiniest bones – ossicles - 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.



Amplification by middle ear



$$F_e = P_e A_e$$

This force is transmitted from Ae to Ao

$$P_e A_e = P_o A_o \qquad P_o = P_e \frac{A_e}{A_o} \approx 15 P_e$$

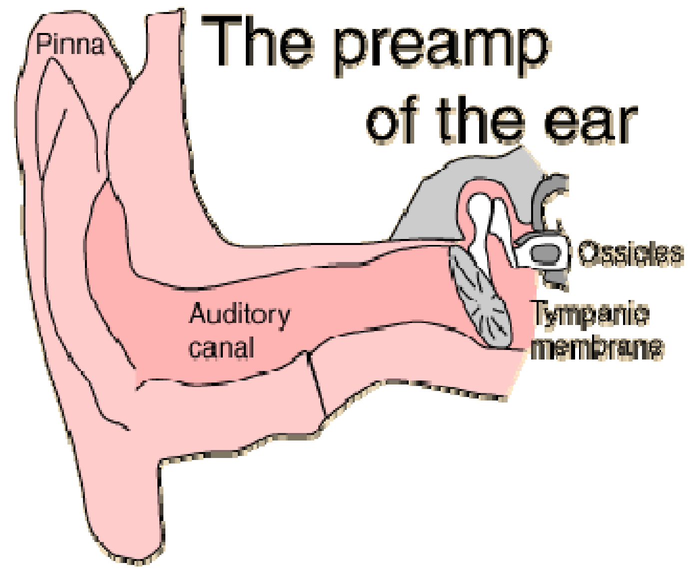
Total amplification by ear

- Closed tube resonance of the auditory canal enhances 2000-5000 Hz:
- Outer ear
- 2x

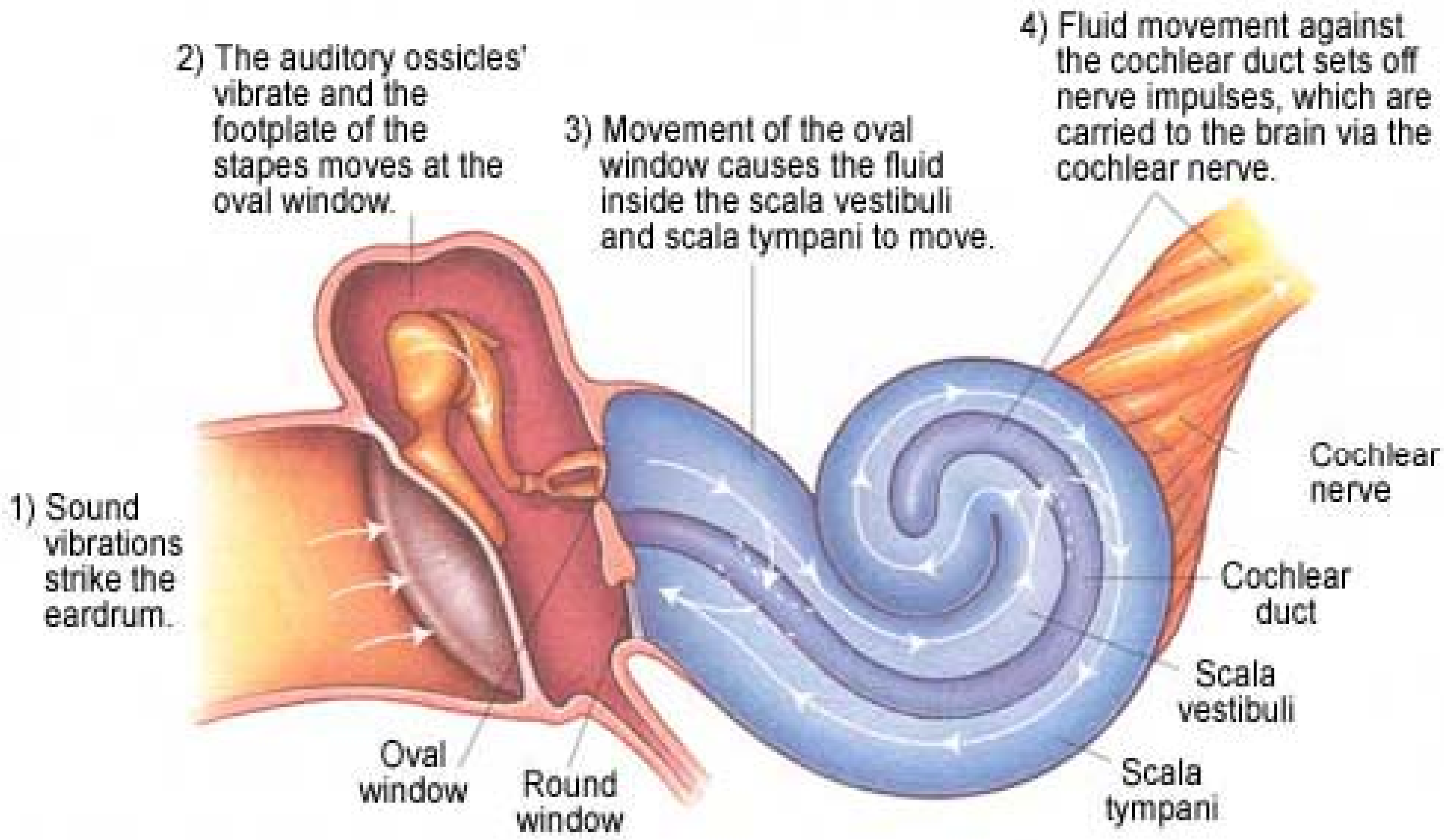
- Tympanic membrane (eardrum) has some 15x area of oval window contributing an area amplification:
- Tympanic membrane
  15x

- Ossicles (hammer, anvil and stirrup) contribute a lever-type amplification:
- Ossicles
  3x

- The outer and middle ears amplify signal by a factor of 100 or about 20 db under optimum conditions.



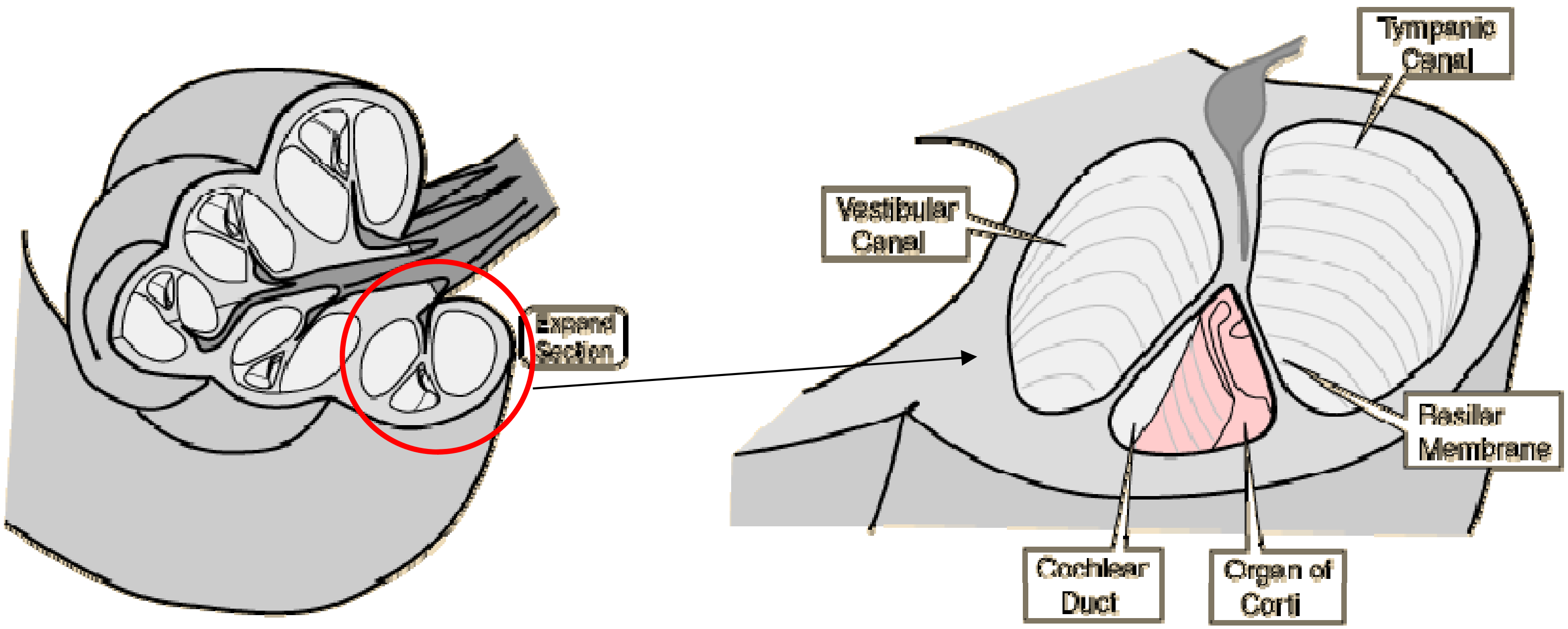
Inner ear



http://www.youtube.com/watch?v=dCyz8-eAs1I&feature=related

Inner ear

- 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 is inside the cochlea, and detects pressure impulses and responds with electrical impulses which travel along the auditory nerve to the brain.

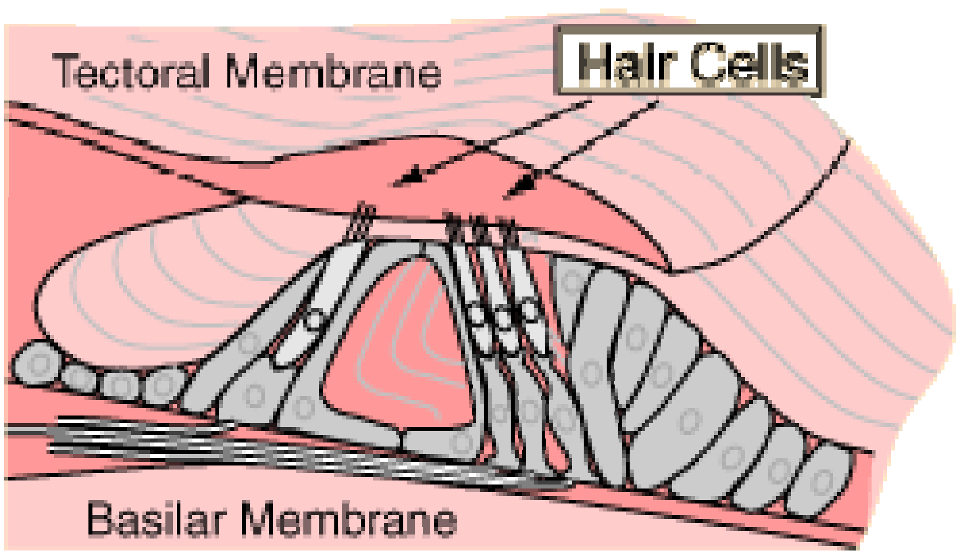


media canal

- The cochlea has three fluid filled sections. 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.

Organ Corti

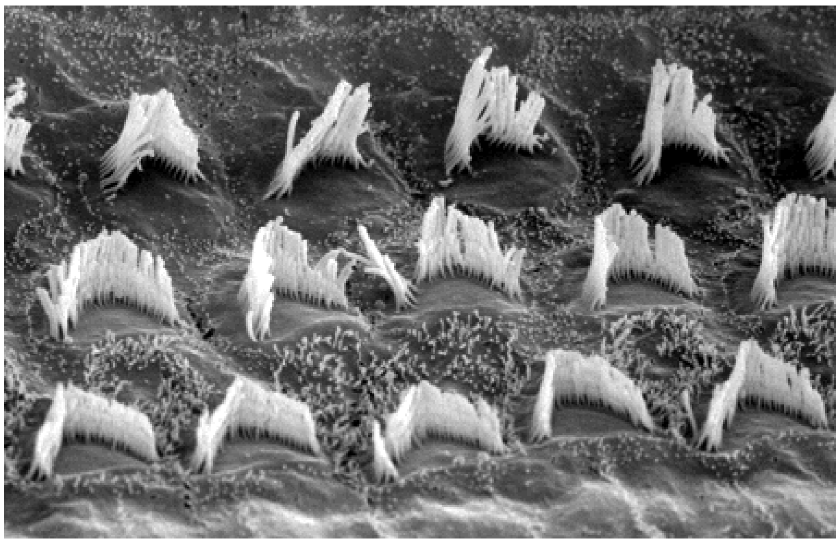
- The organ of Corti is the sensitive element in the inner ear and can be thought of as the body's microphone.
- It contains four rows of hair cells which protrude from its surface. Above them is the tectoral membrane which can move in response to pressure variations in the fluid- filled tympanic and vestibular canals. There are some 16,000 -20,000 of the hair cells distributed along the basilar membrane which follows the spiral of the cochlea.

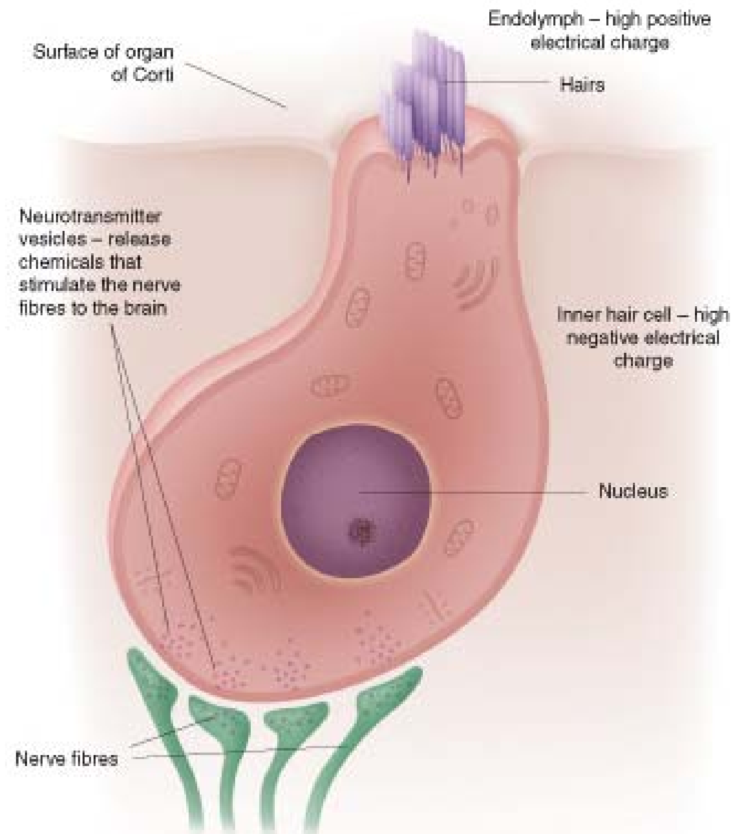


The place along the basilar membrane where maximum excitation of the hair cells occurs determines the perception of pitch.
Tiny relative movements of the layers of the membrane are sufficient to trigger the hair cells.

http://www.youtube.com/watch?v=8wgfowbbTz0&feature=related

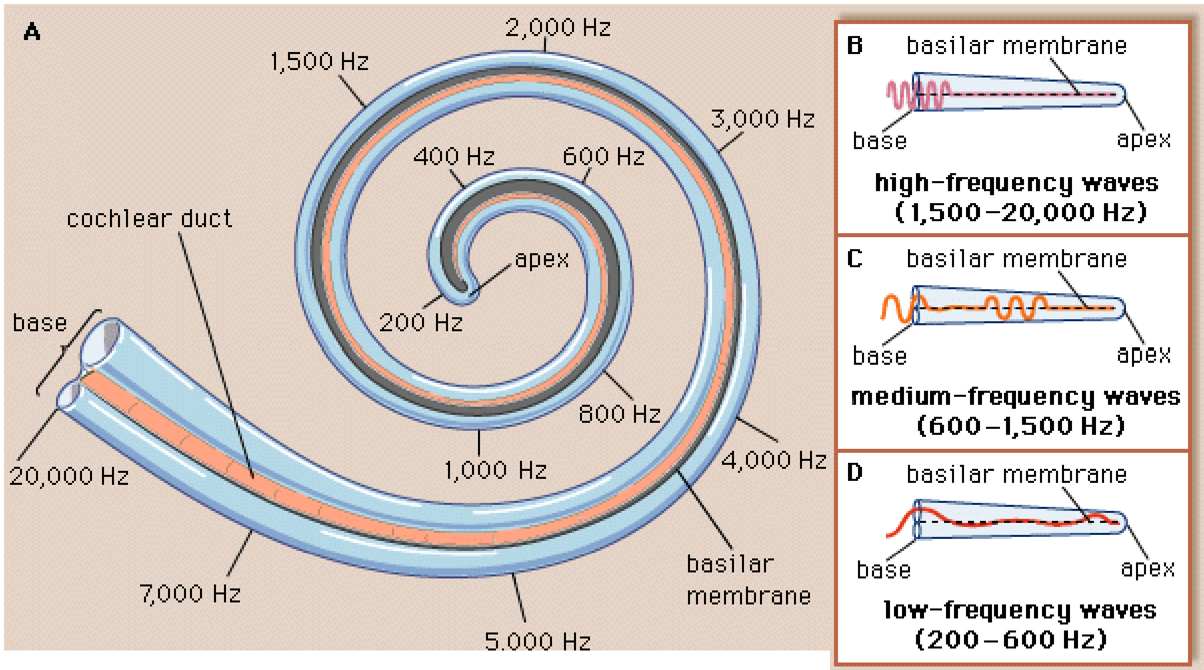
Transmission of a signal to the nerve fibers





Like other nerve cells, their response to stimulus is to send a tiny voltage pulse called an "action potential" down the associated nerve fiber (axon). These impulses travel to the auditory areas of the brain for processing.

Frequency resolution by basilar membrane



Oscillations in the fluid in the canals cause transverse displacement of the basilar membrane.

Each tone stimulates a different region of the basilar membrane – maximum displacement occurs at different regions for different frequencies.

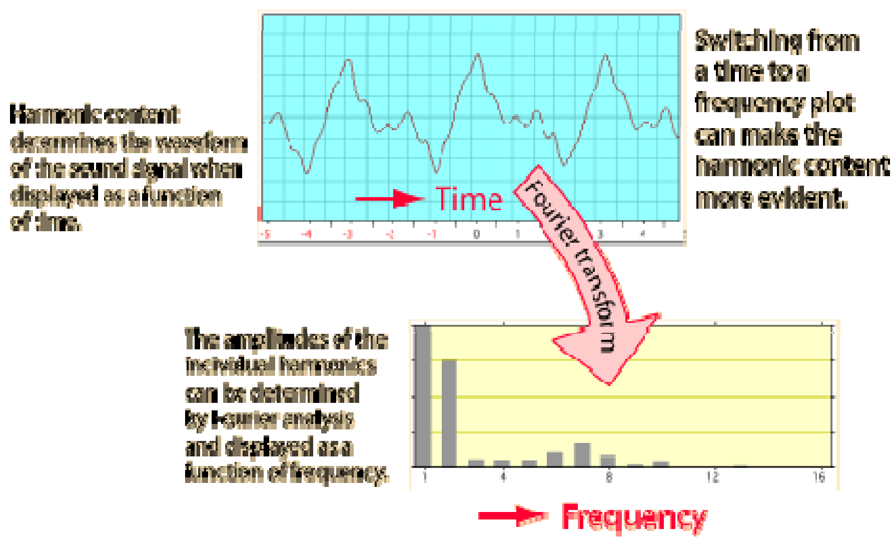
Lower frequencies stimulate the apex region, higher frequencies stimulate the base region of basilar membrane

Phase sensitivity and Determination of Direction

- If there are two or more sources of sound, emitting different frequencies – the resultant sound is modulated – superimposition of waves
- The ear does not respond to the cumulative signal, but resolves them into their frequency components – Fourier transform and then stimulates the corresponding areas of basilar membrane. Ear recognizes each frequency

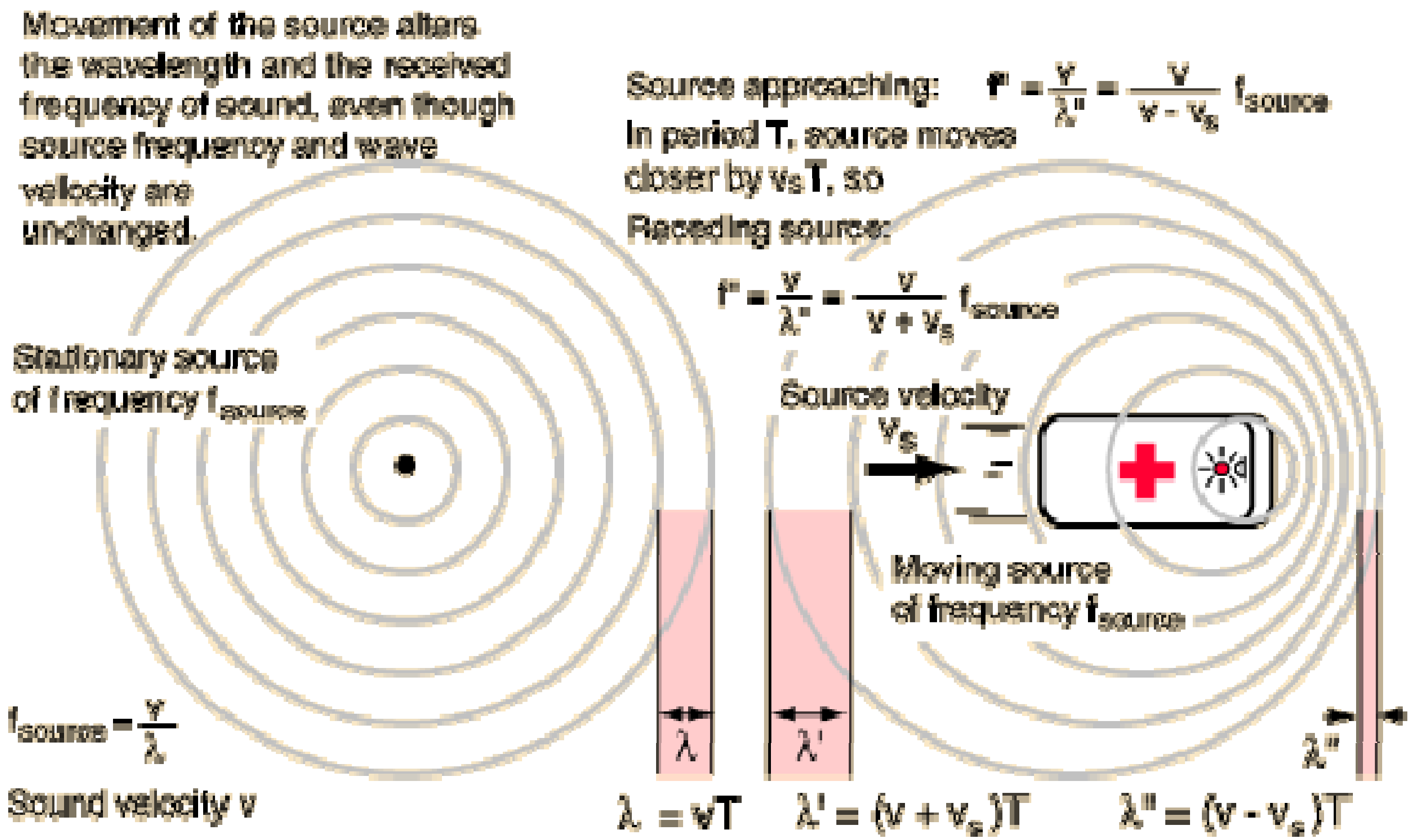
Direction is determined by auditory system by

1. Time lag between sound entry into one ear and another ear. This is relevant to phase difference. Human brain can detect a time lag 10^{-4} sec, between the sounds reaching two ears
2. Intensity difference of sound reaching two ears



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.



Doppler Effect

$$f' = f_s \frac{(v_s - v_{rec})}{(v_s - v_{trans})}$$

Vrec=0, *V*trans=1m/s

Ftrans=4000Hz,

Vsound=340m/s

Frec-?

If transmitter moves towards

and away from receiver

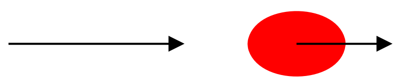
http://www.youtube.com/watch?v=-t63xYSgmKE

Funny movie to explain Doppler effect

Doppler Effect and blood motion

- Can be used to measure the speed of a moving object by observing a frequency shift. Speed of blood flow, motion of fetal heart.
- The blood cell reflects the sound, because the cells moves, the reflected sound (*f''*) is shifted:

Sound v



v_{B}

$$f' = f\frac{v - v_B}{v}$$

Blood "hears" lower frequency as blood cells flow away

$$f'' = f'\frac{v}{v + v_B}$$

Even lower frequency is detected after reflection by cells moving away from detector

Av speed of sound in stationary blood

Blood speed

$$f'' = f\frac{v - v_B}{v + v_B}$$

Frequency of the source

$$\Delta f = f - f'' = \frac{2 f v_B}{v + v_B}$$

$$\Delta f = \frac{2 f v_B}{v}\cos\theta$$

Angle between detector and blood flow

$$v + v_B \approx v$$

By measuring Doppler shift one can detect speed of blood

example

- 1. The speed of blood in aorta is 30 cm/s. What is the Doppler shift and beat frequency of ultrasonic waves of frequency 4 MHz incident along the flow. Take speed of sound in blood = in water =1500m/s.
- Beat frequency = Doppler shift =difference between the source frequency f and f- reflected from the blood cells

$$\Delta f = \frac{2 f v_B}{v} = \frac{2 \times 4 \times 10^6 \times 0.3}{1.5 \times 10^3} = 1.6 kHz$$