Physics of Ear and Hearing

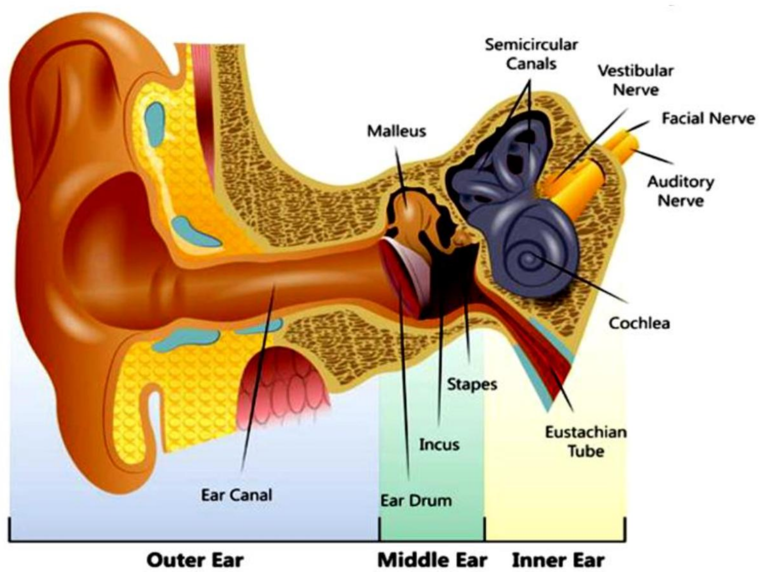
The sense of hearing involves:

1. The mechanical system that the hair cells in the cochlea.
2. The sensors that produce the action potentials in the auditory nerves.
3. The auditory cortex (the part of the brain that decodes and interprets the signals from the auditory nerves.

Deafness (or hearing loss) results if any of these three parts malfunctions.

From an anatomical point of view, the ear is divided into three parts: the outer, the middle and the inner ears. Each part of the ear serves a specific purpose in the task of detecting and interpreting sound.

The three parts are separated by membrane windows, *eardrum* or tympanic (between outer ear and middle ear), and *oval window* and round window (between middle ear and inner ear). The three parts of the ear are shown below.



1. The outer ear

It is the outer visible portion of the ear that collects and directs sound waves toward the tympanic membrane by way of a canal which extends inward through the temporal bone. It consists of pinna, auditory canal and the tympanic (eardrum) membrane as following:

a. Pinna; The Pinna collects sound, acting as a funnel to amplify sound and directing sound toward the ear canal and adding directional information to the sound.

b. Auditory canal; is a tube running from the outer ear to the middle ear. It is about 2.5cm in length and 0.7cm in diameter.

The external auditory canal can be thought as an organ pipe of about 2.5cm long closed at one end with a resonant frequency of about 3300Hz. It serves to increase the ear's sensitivity in the region of 3000 to 4000Hz.

The eardrum (or tympanic membrane) is 0.1mm thick and has an area of about $65 mm^2$. It couples the vibrations in the air to the small bones in the middle ear.

Because the thinness of the membrane large pressure variations due to intense noise, 160 db (see example) or large pressure differences between outer and middle ear cavities ($AP \approx 8*10^3$ Pa) can cause its rupture.

To avoid rapid development of pressure gradients (for example by rapid change of atmospheric pressure, Eustachian tube connects middle ear and mouth cavity for pressure equilibration. Eustachian tube is normally closed, but opens when swallowing.
A pressure gradient develops during the start and landing of aircraft, in rapidly moving elevators, swallowing avoids ear-popping!

By considered the auditory canal as an air-filled tube of length L with one end closed, the flow of air will produce a resonance (standing waves). The wavelength and frequency that will be resonated is given by:

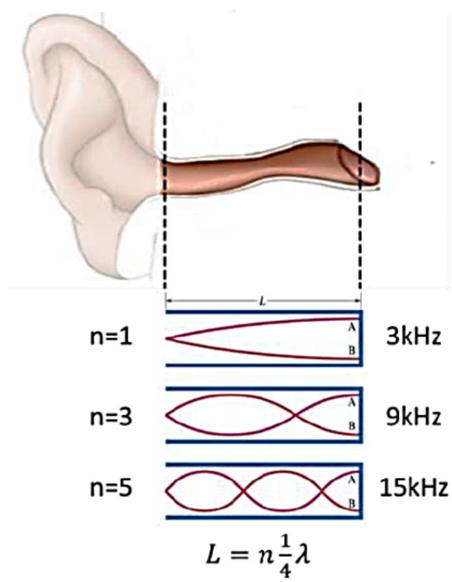
$$\lambda_n = \frac{4}{n} L \text{ and } f_n = \frac{v}{\lambda_n} = n \frac{v}{4L}$$

The other wavelengths or resonated frequencies (harmonies) are given by the following:

$$f_n = n \cdot \frac{v}{4 \cdot L} \qquad (n = 1, 3, 5, 7, \ldots)$$

So, $f_1 = 3300\ Hz,$
$f_3 = 9900\ Hz = 3f_1$

Where, (v) velocity of sound in air = 330 m/s

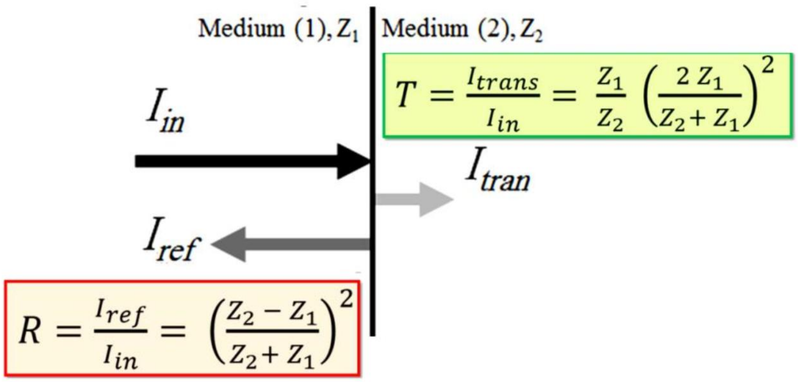


This resonance will enhance the sensitivity of ear in the higher frequency range 2000-10000 Hz and the best sensitivity of the ear will be in the region 2000- 4000 Hz.

Reflection and Transmission at the Tympanic Membrane

The acoustical signal that hits the eardrum is partially reflected and transmitted. To optimize the hearing sensitivity reflection should be minimized and transmission maximized.

From measuring the intensity ratios for reflected and transmitted acoustical waves at the eardrum, we can obtain the following (where, Z_{air}=430 kg/m^2.s, Z_{muscle} = 1.48*10^6 kg/m^2.s):



$$T = \frac{I_{trans}}{I_{in}} = \frac{Z_1}{Z_2}\left(\frac{2\,Z_1}{Z_2+Z_1}\right)^2$$

$$R = \frac{I_{ref}}{I_{in}} = \left(\frac{Z_2 - Z_1}{Z_2+Z_1}\right)^2$$

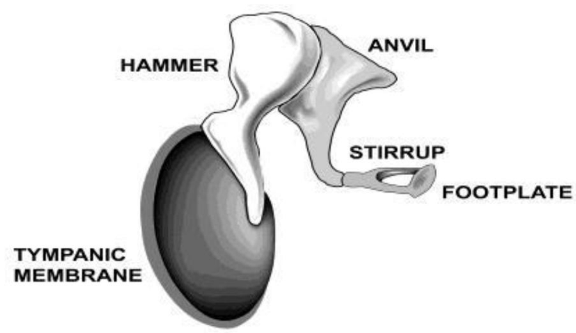
$$\frac{I_{ref}}{I_{in}} = 0.9988$$

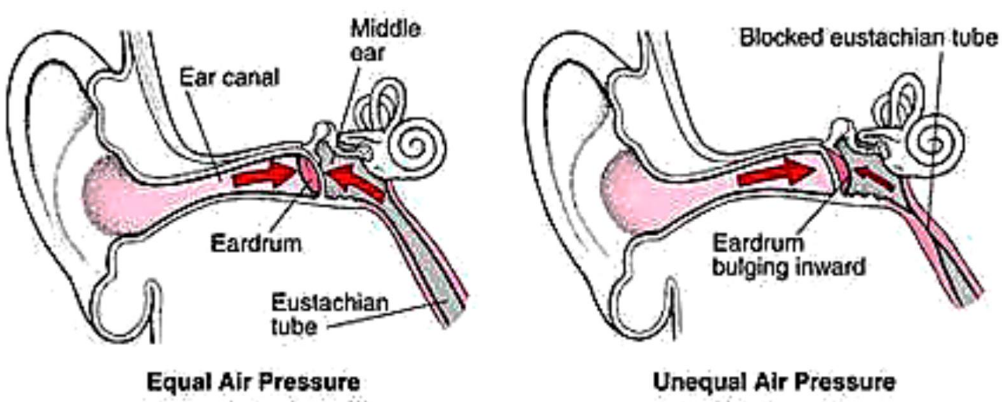
$$\frac{I_{trans}}{I_{in}} = 0.0012$$

From the above values, one can observe that most of the incoming wave intensity is reflected (bad impedance matching) and therefore lost for hearing process

2. The middle ear

It is the central part of the ear, behind the eardrum, through which sound travels. It consists of: *hammer*, the *anvil* and the *stirrup*. They transmit the vibrations of the tympanic membrane to the oval window of the inner ear.





Pressure differences between the middle ear and outside are equalized by air flow through the Eustachian tube. This connects the middle ear to the pharynx (back of the throat).

The functions of the bones of the middle ear are:

a. act a lever system, in which amplify the pressure on the oval window by a factor of about 20, as shown in the following:

- The force on the oval window (f_o) is about 1.5 times the force on the eardrum (f_m).
- The area of the oval window (A_o) is about 15 times smaller than the area of the eardrum (A_m).

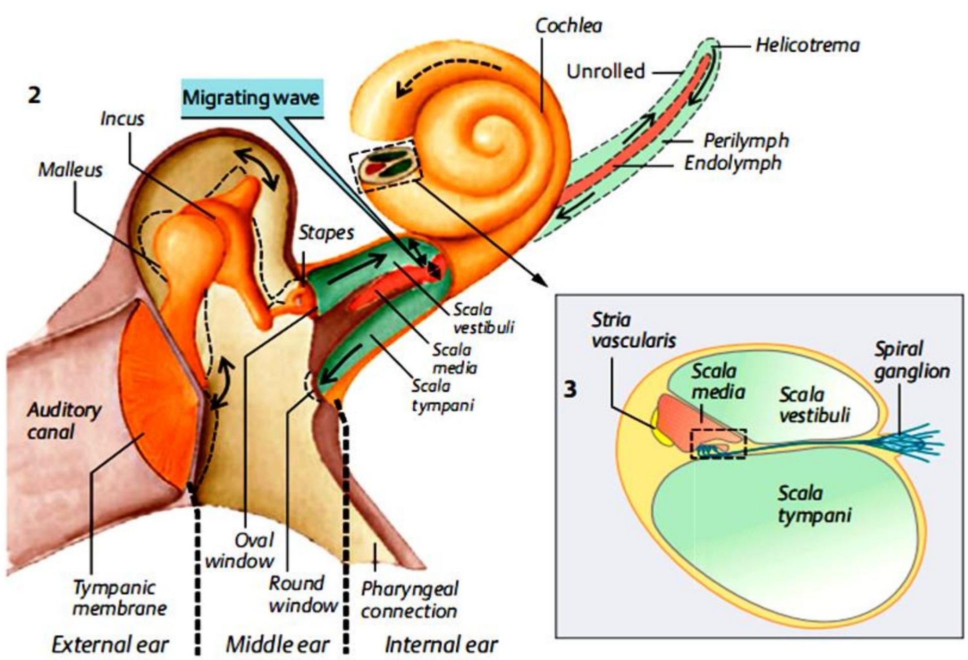
$$\frac{Pressure\ on\ oval\ window\ (P_o)}{Pressure\ on\ ear\ drum\ (P_m)} = \frac{f_o}{A_o} \div \frac{f_m}{A_m} \quad \rightarrow \quad \frac{f_o}{f_m} \times \frac{A_m}{A_o} = 1.5 \times 15 \approx 20$$

b. Filter out noise generated in the body.

c. Protect the ear from excessive vibrations by switching to a less-efficient mode of vibration at high sound levels.

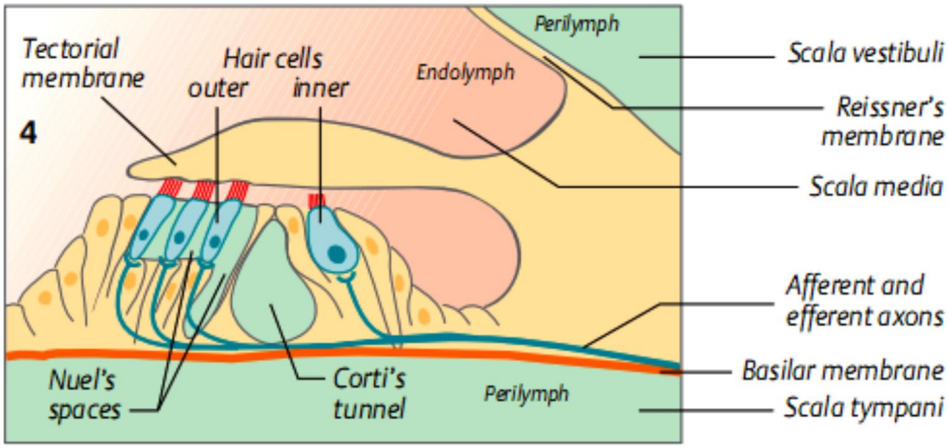
3. The inner ear

- Serves to transform the energy of the compressional wave within the inner ear fluid into nerve impulses which can be transmitted to the brain.
- The hearing portion of the inner ear is the cochlea, a snail shaped structure that is connected to the stirrup (or stapes). As the stapes moves in and out, it produces fluid waves within the cochlea.



The cochlea is divided into three fluid-filled chambers:

1. Scala vestibule
2. Scala media
3. Scala Tympani



Scala vestibule and scala tympani contain perilymph fluid, while scala media contains endolymph fluid.

Reissner's membrane separates the scala vestibule from the scala media. Basilar membrane separates the scala media from the scala tympani.

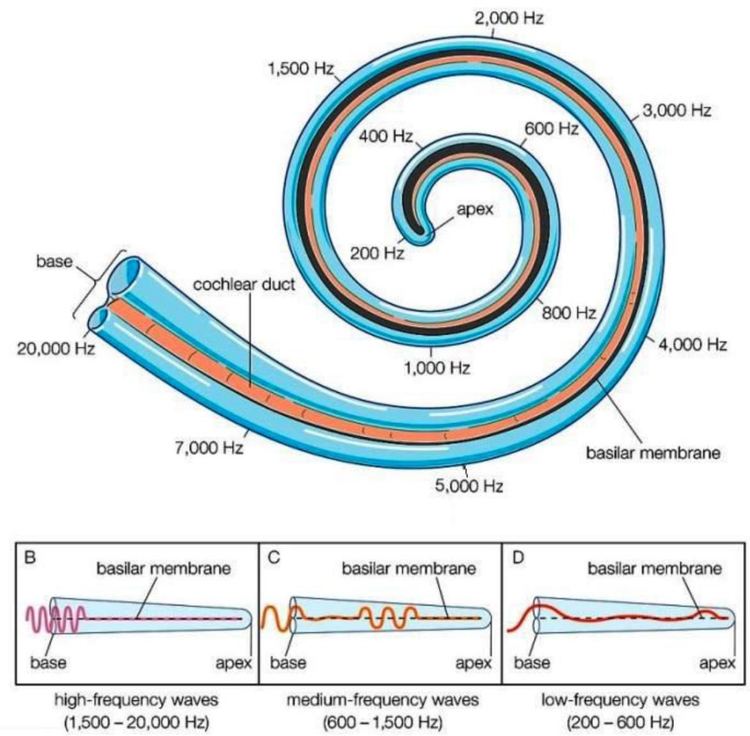
Along the basilar membrane there are two types of sensory cells (or hair cells) called the outer and the inner cells. These are arranged to response to the frequency (or pitch) of that they detect and they are covered by the tectorial membrane.

When sound energy is transmitted to the cochlea, the basilar membrane vibrates up and down causing the hair cells to shear on the tectorial membrane above them. These shearings causes the hair cells to undergo a chemical change the results in electrical charge inside the cells. The electrical charges make neural impulses which travel along the auditory nerve to the brain. These impulses are interpreted in the brain into sounds.

A sound wave entering the oval window produces a wave-like ripple in the basilar membrane of the cochlear duct. This duct contains the sensors that convert the sound into nerve signals. Stimulation of the nerves in the cochlear duct near the oval window indicates high-frequency sounds. Low-frequency sounds cause "large" motion in the basilar membrane and stimulation of nerves in the cochlear duct near the tip of the spiral.

The transducers that convert the mechanical vibrations into electrical signals are located in the bases of fine hair cells in the organ of Corti.

The basilar membrane has variable sensitivity to sound wave frequency along its length. Since, the frequency of sound waves determines the displacement of the basilar membrane. The location of active hair cells creates a code that the brain translates as information about the pitch of sound.



- High frequency sounds produce the greatest motion of the basilar membrane near the oval window.

- Low frequency sounds produce the greatest motion of the basilar membrane farthest from the oval window.

- This results in triggering different nerve cells, distributed along the organ of Corti, producing electrical pulses depending on the frequency of the sound waves

4. **Hearing loss (Deafness)**

In more general terms, hearing loss can be grouped into two main types:

1- **Conduction hearing loss**, in which the sound vibrations do not reach the inner ear, this is may be due to:

● Plug of wax blocking the eardrum.
● Fluid in the middle ear.

The result is an overall lowering of volume and inability to hear faint sounds. This hearing loss is usually temporary and can sometimes be reduced or eliminated by medical intervention or surgery.

2- **Nerve hearing loss,** in which the sound vibrations reach the inner ear but no nerve signals are sent to the brain. In most cases, nerve hearing loss is permanent and usually affects both ears. This type of hearing loss is commonly treated through the fitting of hearing aids.