Biophysics of Hearing

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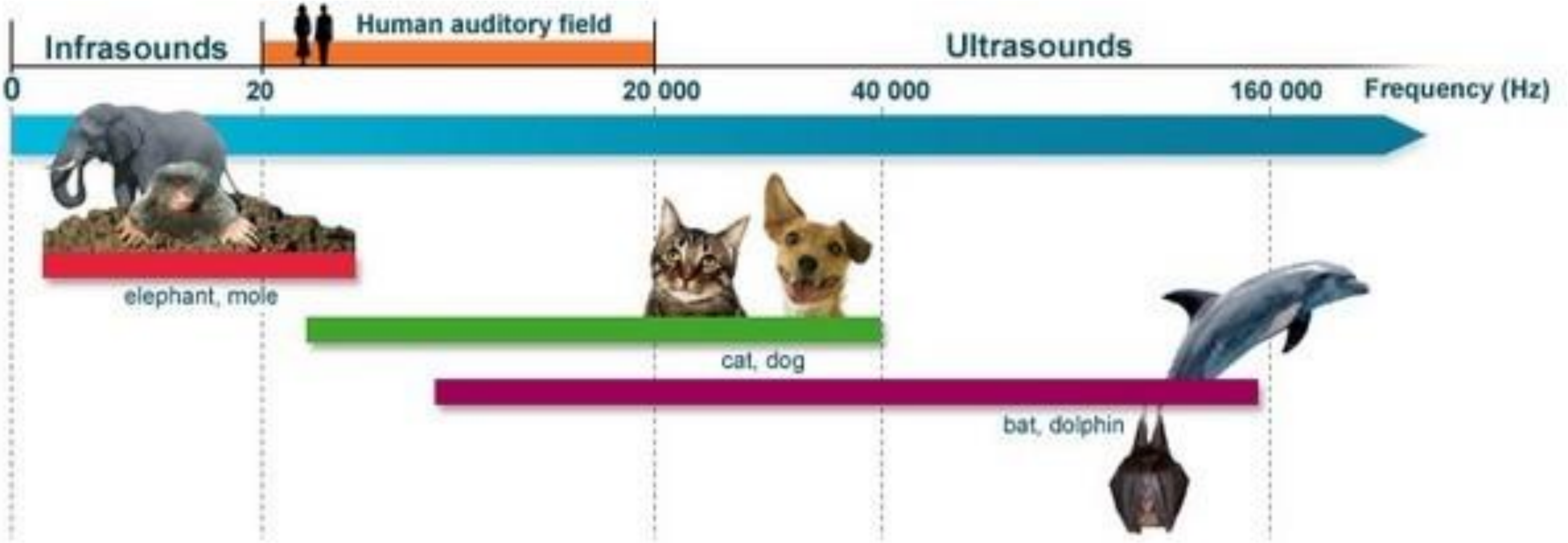
Lecture outline

- What is sound and wave?
- Types of Waves
- Properties of Waves
- Characteristic of the sound waves
- How does sound travel through the ear?
- Amplification of the sound in the middle ear
- Theories of hearing

What is sound?

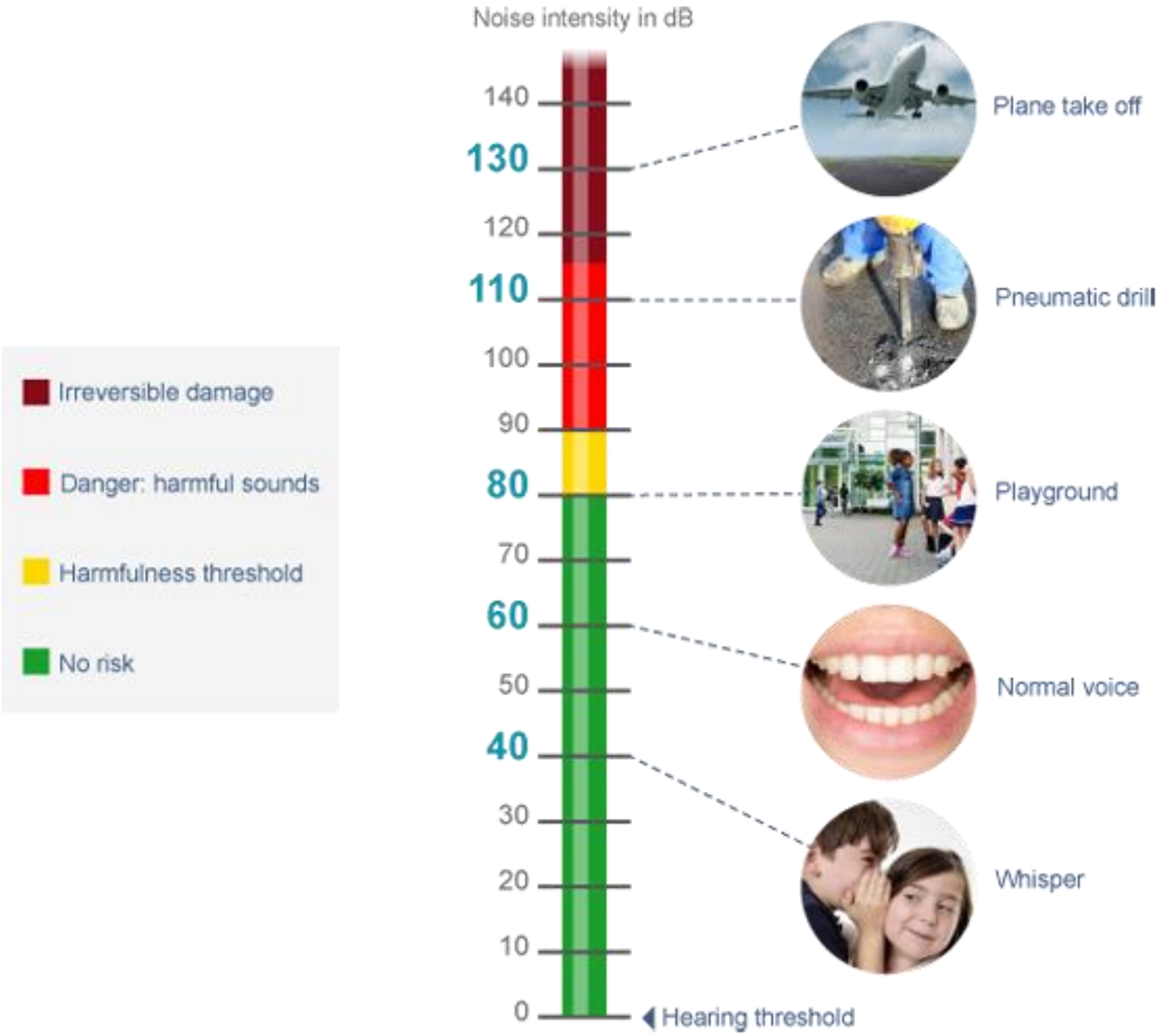
- **Sound** is a form of energy, propagates as an acoustic wave, through a transmission medium such as a gas, liquid or solid.
- Our ears alert us to events in the environment, and they detect that special human form of communication, speech.
- Human ear perceives frequencies between 20 Hz (lowest pitch) to 20 kHz (highest pitch). All sounds below 20 Hz are qualified as infrasounds.
- Similarly, all sounds above 20 kHz are qualified as ultrasounds.

Sense of hearing



Sense of hearing

- The human ear as a dynamic range from 0dB (threshold) to 120-130 dB.
- This is true for the middle frequency range (1-2 kHz). For lower or higher frequencies, the dynamic is narrowed.



How does noise travel to your ears?

- Humans and animals hear by picking up on vibrations caused by sound waves in the air (or in some cases, the ground and water).

- In the simplest terms, we ‘catch’ these vibrations in our middle-ear where they’re transferred into pressure waves. These waves are then passed through fluid into our inner-ear, or cochlea, where they’re translated into signals our brains can interpret.

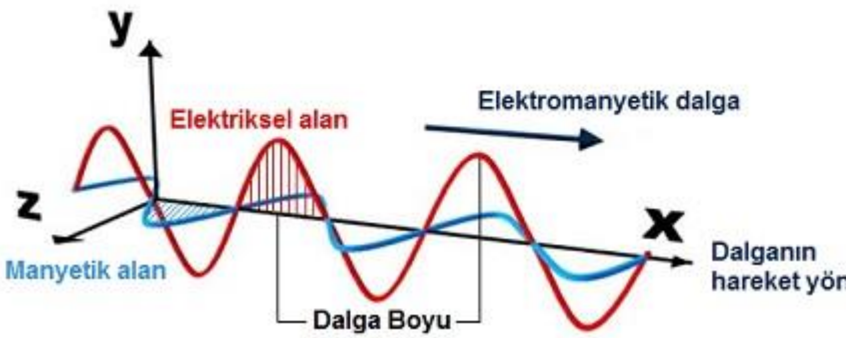
What is wave?

- A wave is a disturbance in a medium that carries energy without a net movement of particles. It may take the form of elastic deformation, a variation of pressure, electric or magnetic intensity, electric potential, or temperature.

Properties of the waves:

- Transfers energy.
- Usually involves a periodic, repetitive movement.
- Does not result in a net movement of the medium or particles in the medium (mechanical wave).

Types of Waves:



There 2 types of waves depends on the energy type

- Electromagnetic Waves:

They are produced due to various magnetic and electric fields. The periodic changes that take place in magnetic electric fields and therefore known as Electromagnetic.

Radio signals, light rays, x-rays, and cosmic rays.

- Mechanical waves:

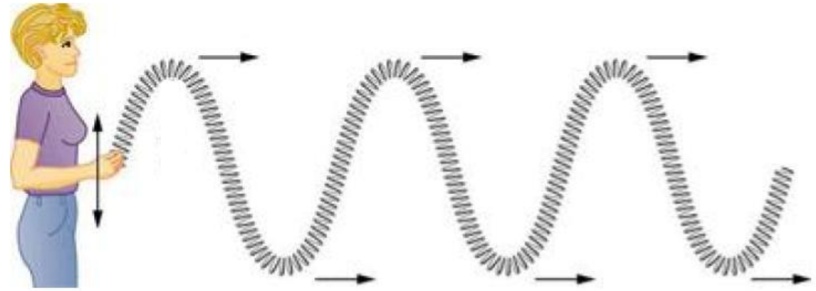
A wave which needs a medium in order to propagate itself. Sound waves, waves in a Slinky, and water waves are all examples of this.

Types of Waves:

- **Transverse Waves**

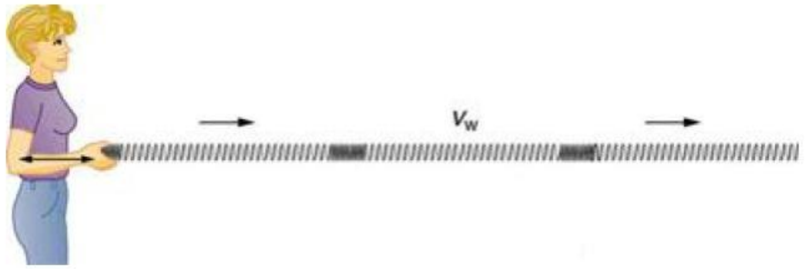
Waves in which the medium moves at right angles to the direction of the wave.

Such as, water waves, Light waves, S-wave earthquake waves



- **Longitudinal Wave:**

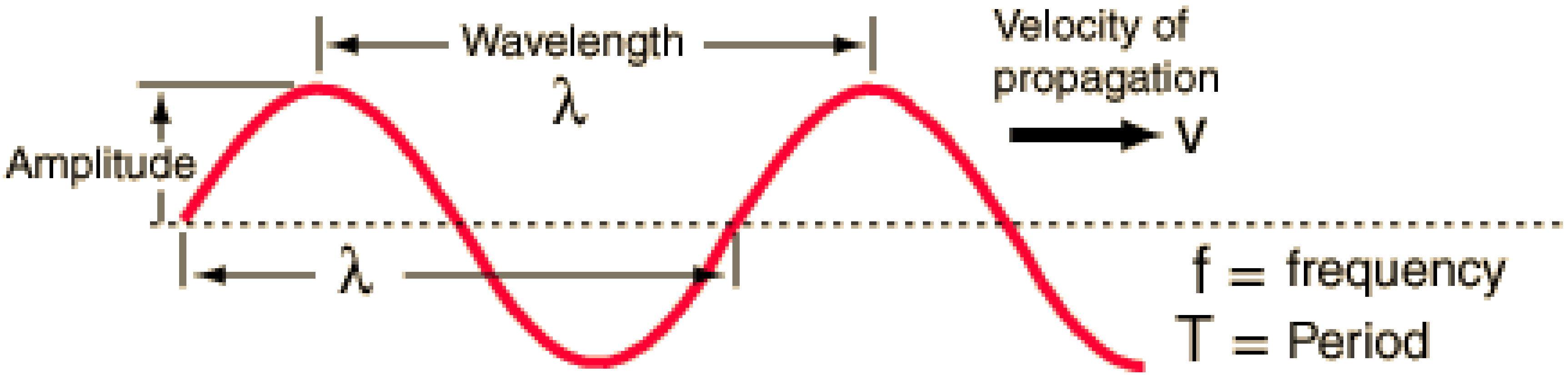
A longitudinal wave has the movement of the particles in the medium in the same dimension as the direction of movement of the wave.



- Such as, sound waves, P-type earthquake waves, compression wave

Properties of Waves

- **Frequency** is a measurement of how many cycles can happen in a certain amount of time… cycles per second. Hertz is the unit of frequency
- **Period** is the time reqiured for one cycle.
- **Wavelength** is defined as the distance from a particular height on the wave to the next spot on the wave where it is at the same height and going in the same direction.

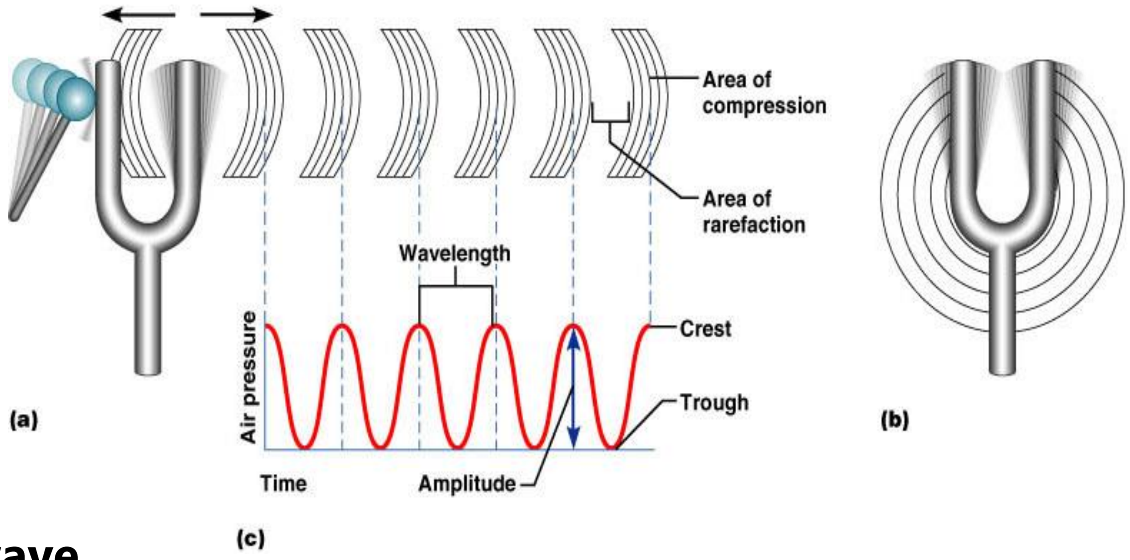


$$f = \frac{1}{T}$$

$$T = \frac{1}{f}$$

Sound waves

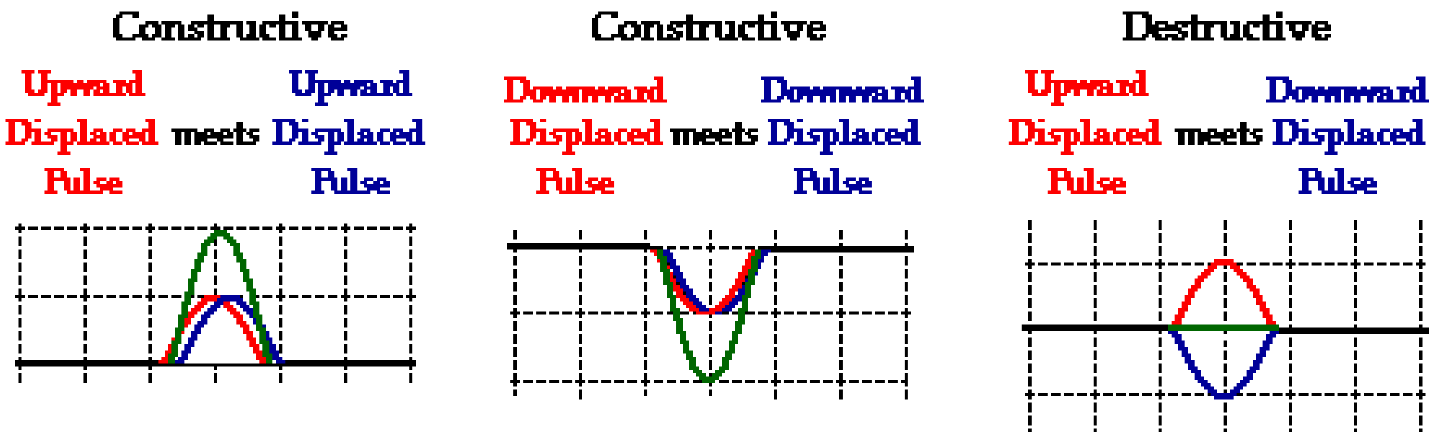
- Sound waves are the longitudinal waves
- Sound waves travel at 340 m/s through the air
- Sound waves travel at 1500 m/s through the water and most biological tissues



it is sometimes referred to as a **pressure wave**.

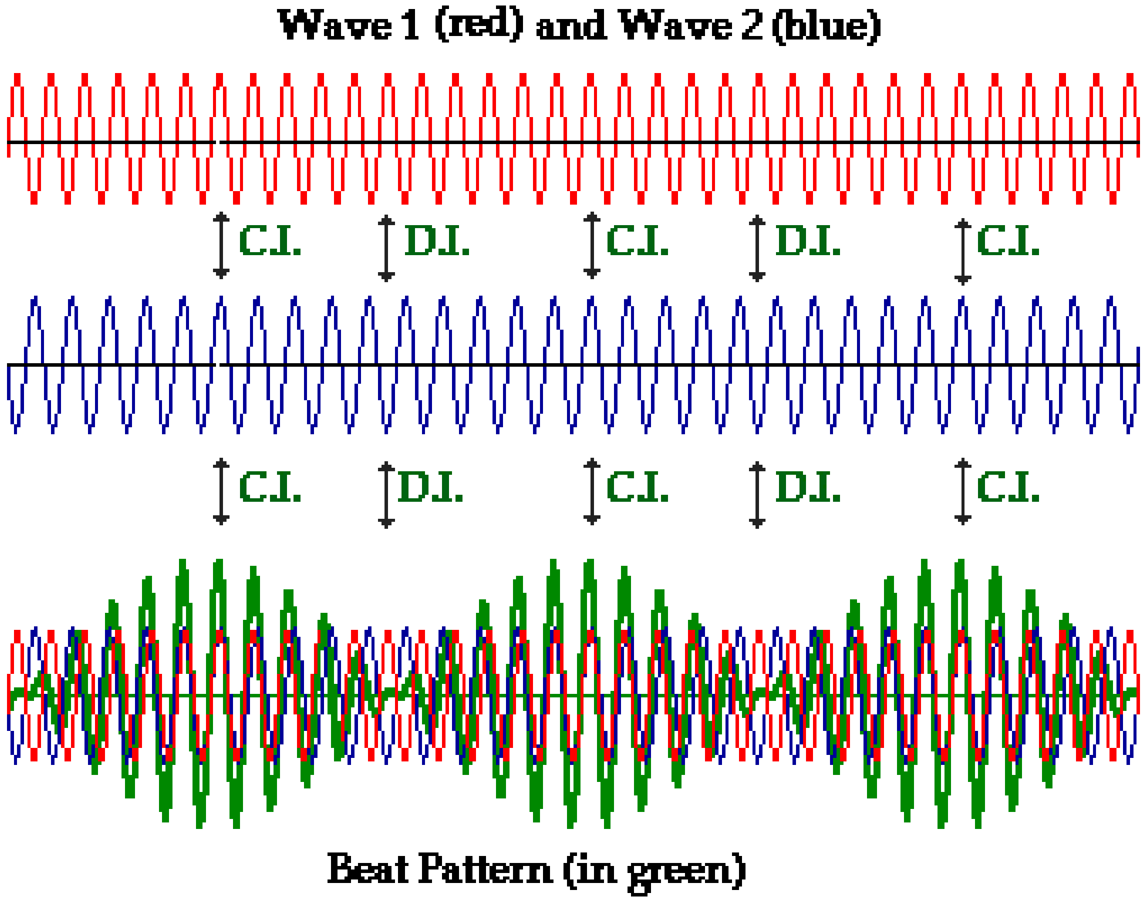
Interference and Beats

- Wave interference is the phenomenon that occurs when two waves meet while traveling along the same medium.
- if two upward displaced pulses having the same shape meet up with one another while traveling in opposite directions along a medium, the medium will take on the shape of an upward displaced pulse with twice the amplitude of the two interfering pulses. This type of interference is known as **constructive interference**.
- If an upward displaced pulse and a downward displaced pulse having the same shape meet up with one another while traveling in opposite directions along a medium, the two pulses will cancel each other's effect upon the displacement of the medium and the medium will assume the equilibrium position. This type of interference is known **as destructive interference**.



Interference and Beats

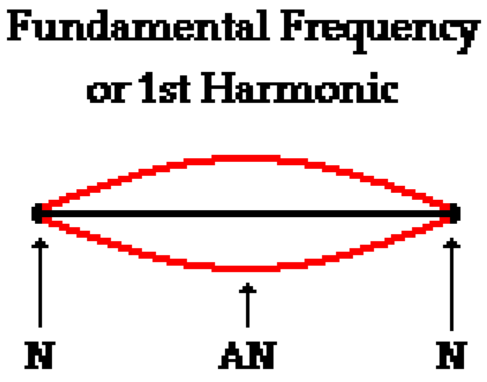
- **Beats** are the periodic and repeating fluctuations heard in the intensity of a sound when two sound waves of very similar frequencies interfere with one another.

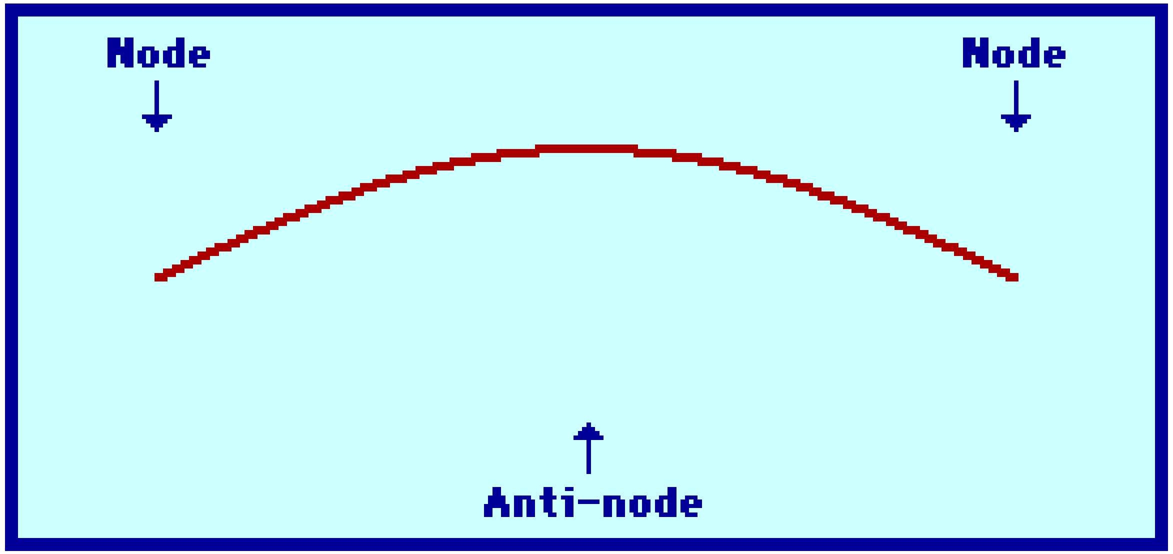


Fbeat=Fw1-Fw2

Tubes with two open ends

- The longest standing wave in a tube of length L with two open ends has displacement antinodes (pressure nodes) at both ends.
  It is called the **fundamental** or **first harmonic**.



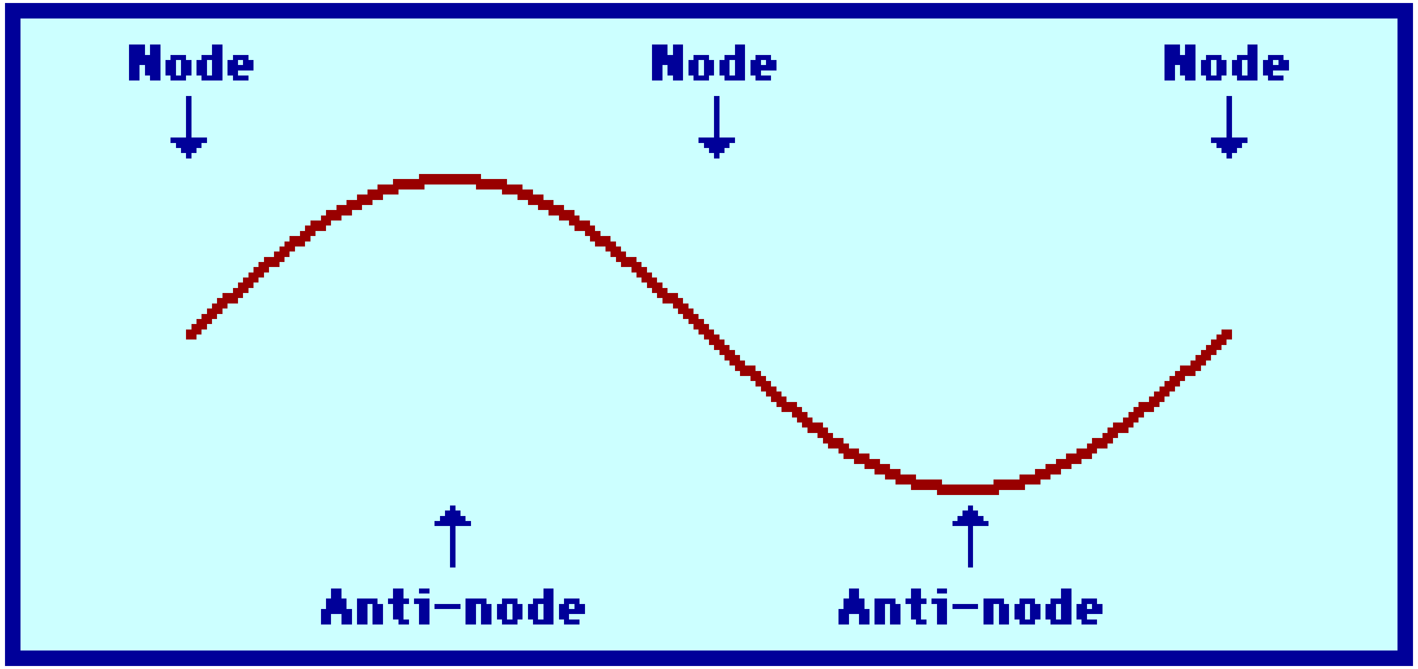


L= λ/2

f1= v/2L

Tubes with two open ends

- Second harmonic
- The next longest standing wave in a tube of length L with two open ends is the second harmonic.
  It also has displacement antinodes at each end.



$$v = f\,\lambda$$

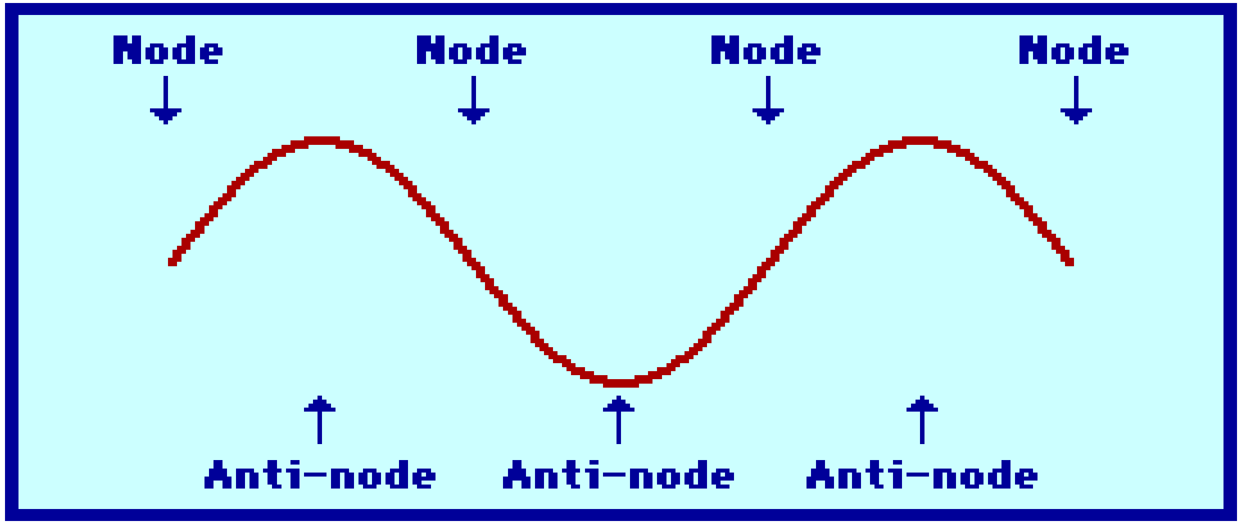
λ=L

f= v/L **f1=v/2L**

f=2f1

Tubes with two open ends

- Third harmonic



$L = 3\lambda/2$ $\lambda=2L/3$

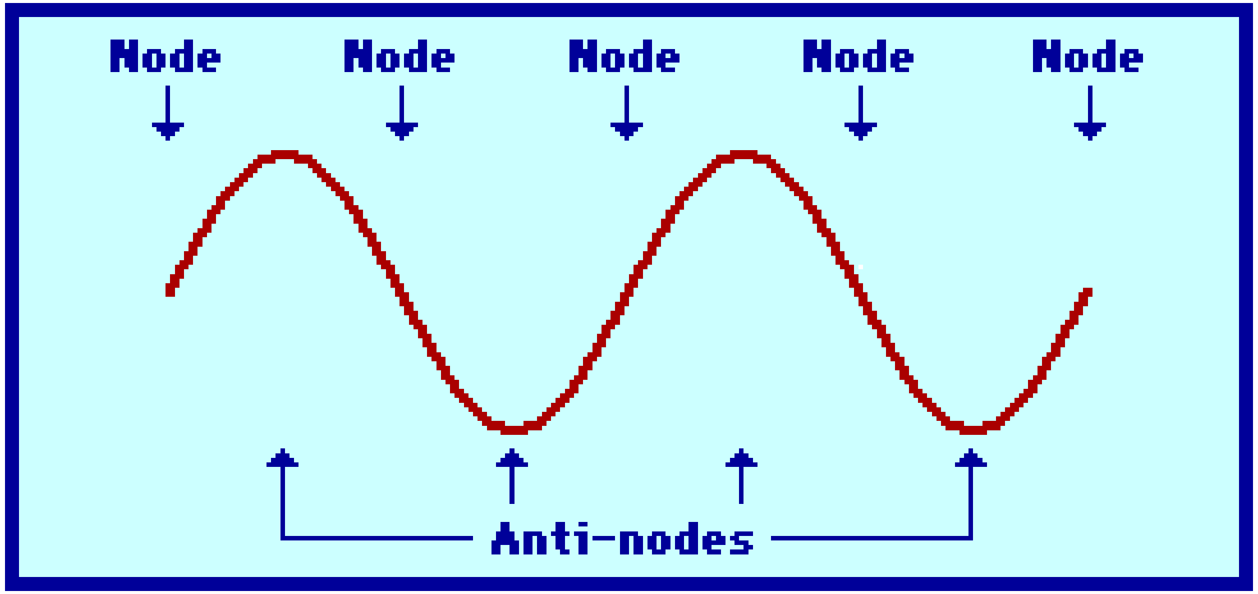
$f= v/(2L/3)$ $f=3v/2L$

$f1=v/2L$

$f=3f1$

Tubes with two open ends

- Fourth harmonic

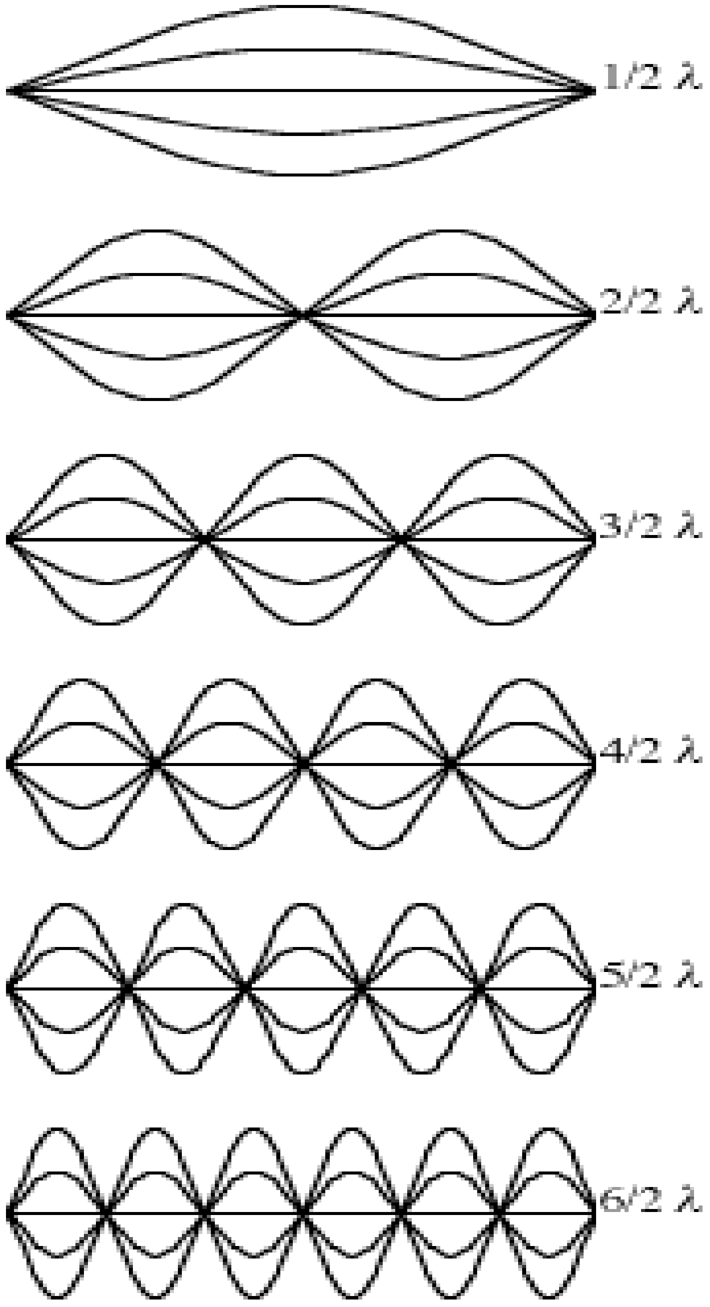


$L = 2\lambda$ $\lambda=L/2$

$f= v/(L/2)$ $f=2v/L$

$f1=v/2L$

$f=4f1$



Tubes with two open ends

if,

$L = n.\ \lambda/2$

$n=1, 2, 3$

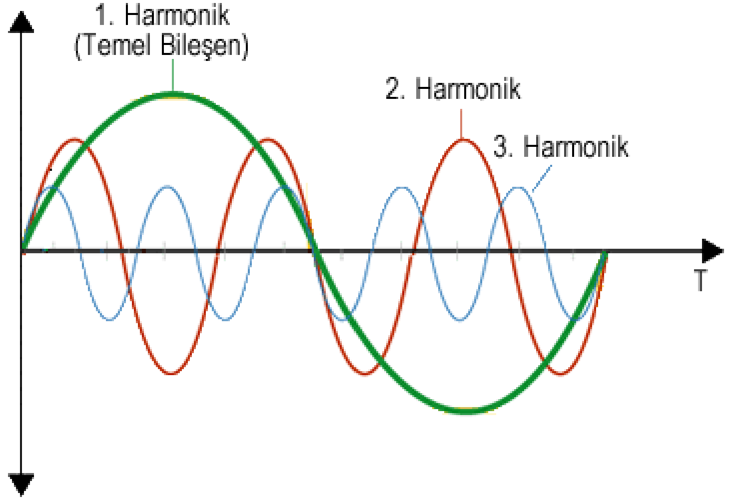
$f_n = v/\lambda_n = n\ v\ /2.L$

Fundamental frequency: **$n=1$**

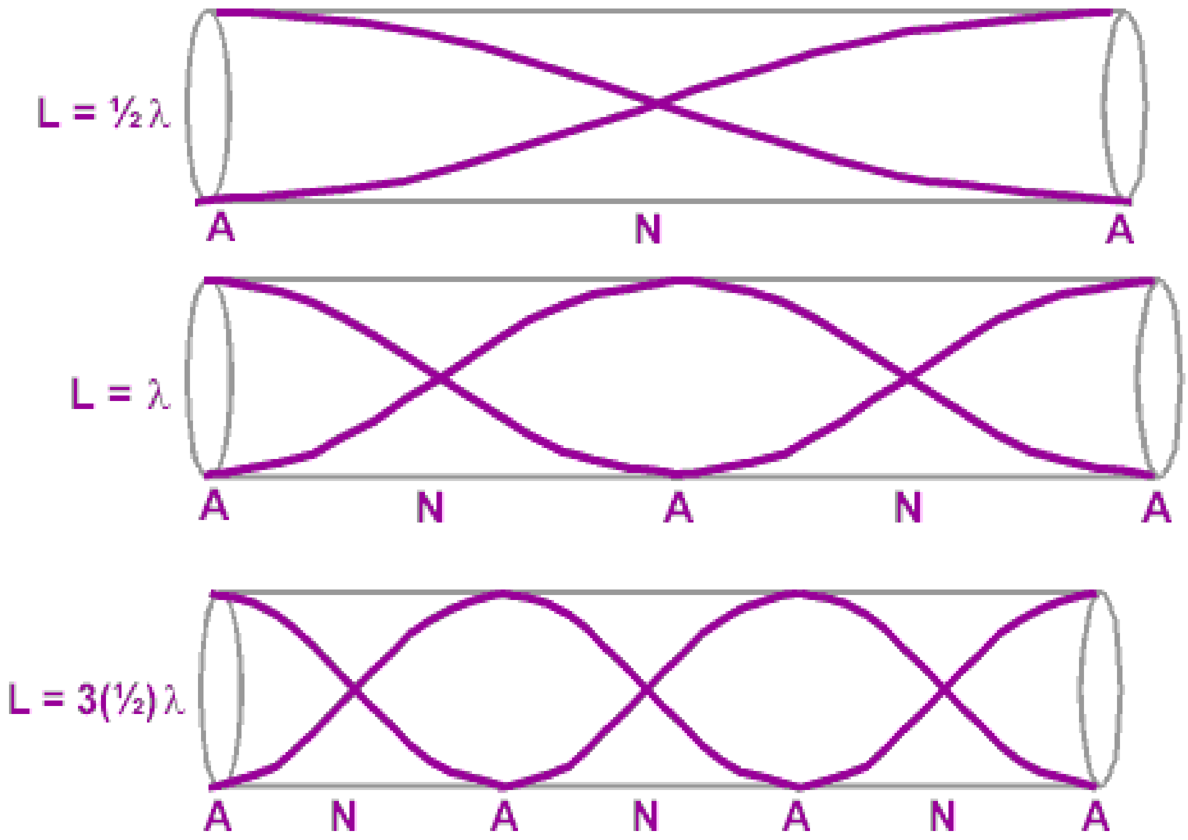
$f_1 = v/2L$

Other frequencies

$2f_1, 3f_1, 4f_1$



Tubes with two open ends



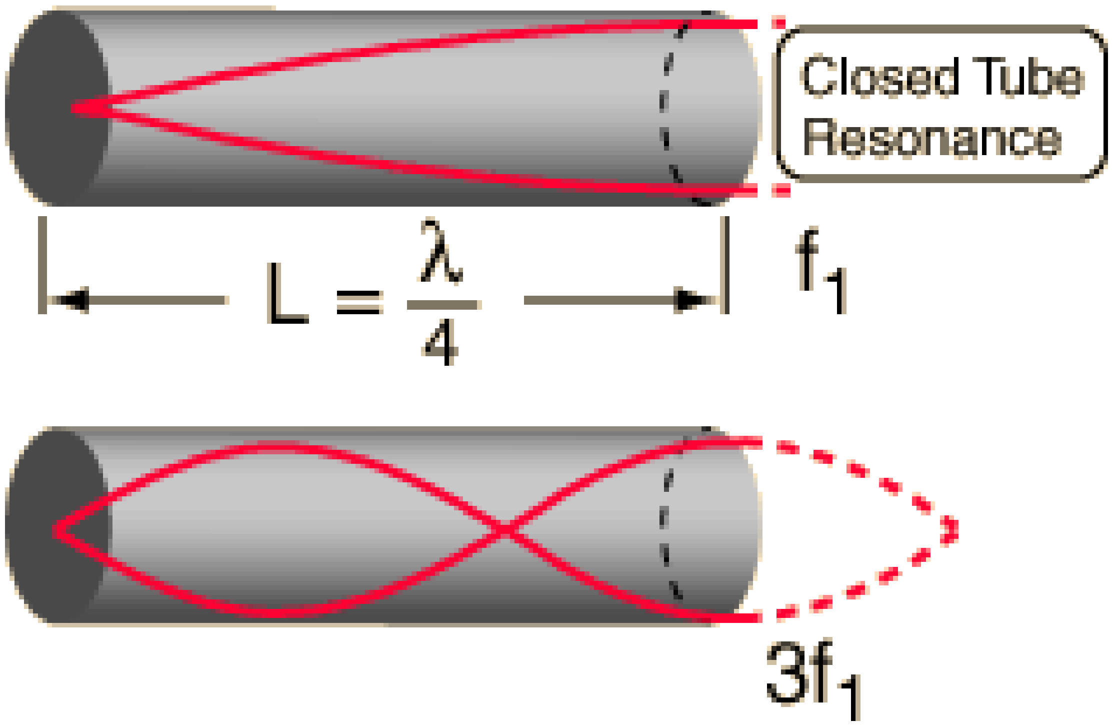
Fundamental frequency: f_1 1. harmonic

2. harmonic $f_2 = \mathbf{2}f_1$

3. harmonic $f_3 = \mathbf{3}f_1$

Tubes with one open and one closed end

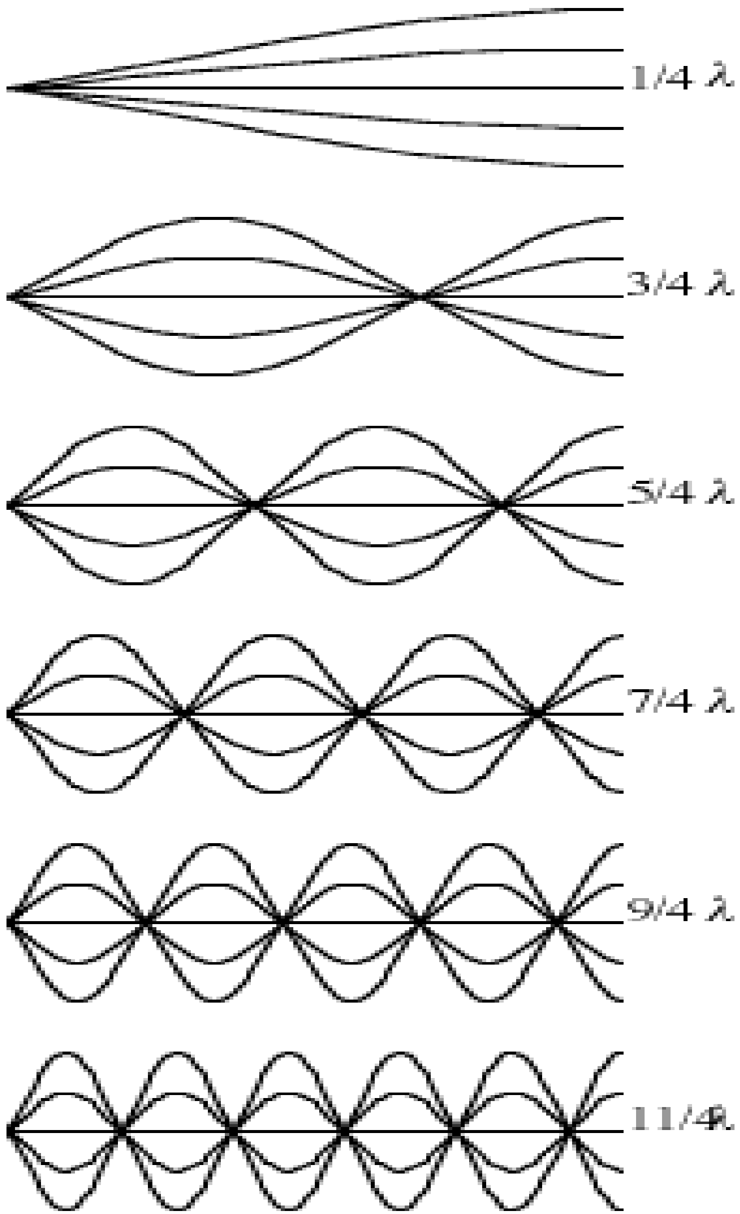
- The longest standing wave in a tube of length L with one open end and one closed end has a displacement antinode at the open end and a displacement node at the closed end.



Fundamental frequency: f_1

$L = \lambda/4$

$f1 = v/4L$



Tubes with one open and one closed end

$L = n.\lambda/4 \quad n=1,3,5\ldots$

$f_n = v/\lambda_n = n\, v/4L$

Fundamental frequency

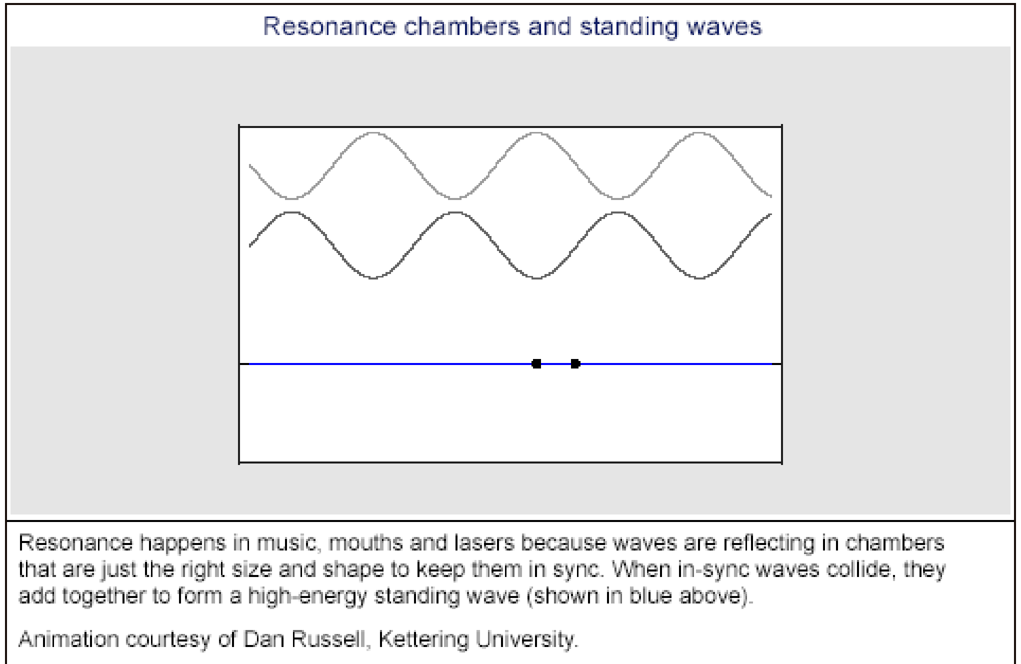
$f_1 = v/4L$

The next longest standing wave in a tube of length L with one open end and one closed end is the third harmonic. And the others:

f1, 3f1, 5f1, 7f1

Resonance

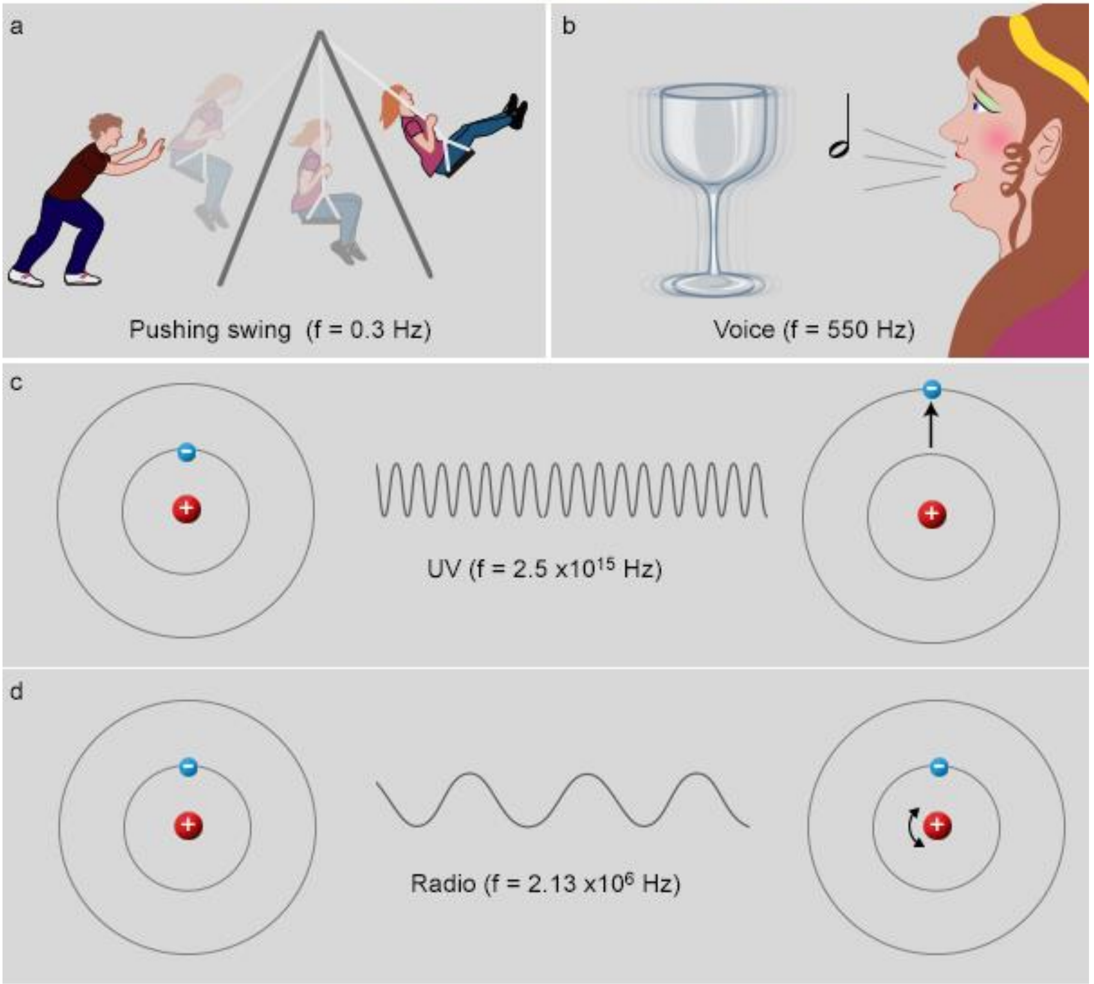
- Resonance describes the phenomenon of increased amplitude that occurs when the frequency of a periodically applied force is equal or close to a natural frequency of the system on which it acts.
- when one object vibrating at the same natural frequency of a second object forces that second object into vibrational motion.



Resonance

- With a tiny push on the swing each time it comes back to you, you can continue to build up the amplitude of swing. If you try to force it to swing at twice that frequency, you will find it very difficult.

Resonance: just add energy (... at the right frequency)

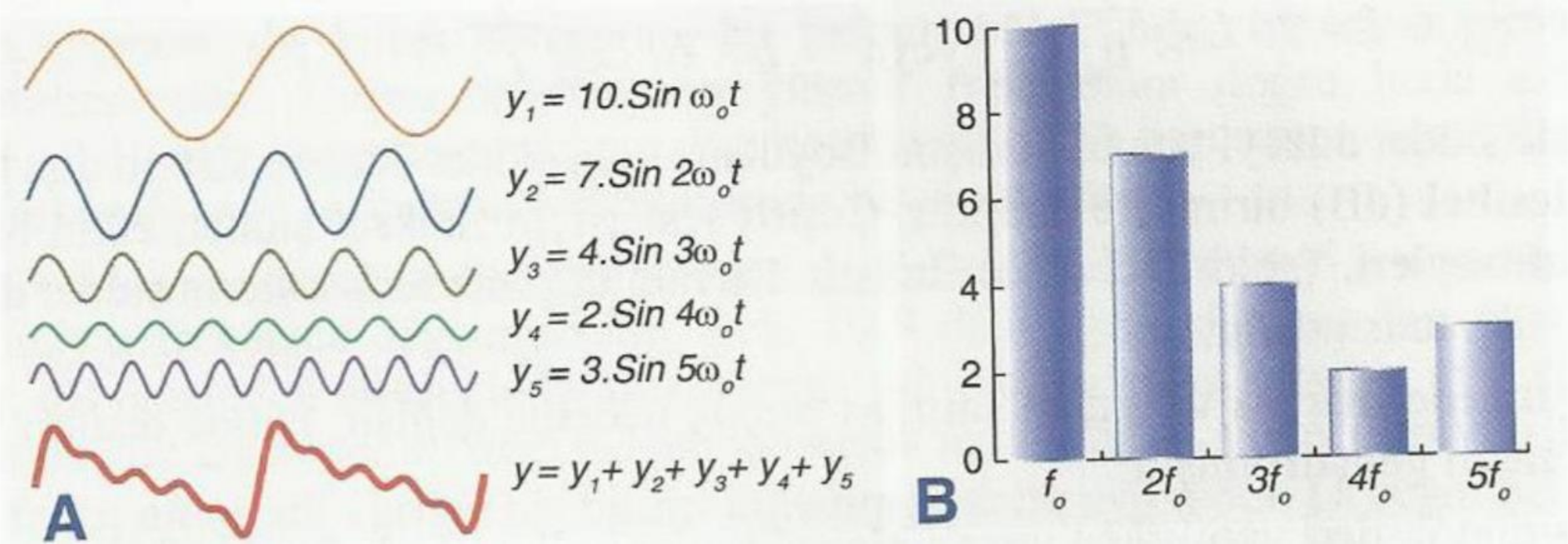


Everything can store extra energy – as long as it's delivered at a resonant frequency. Kinetic energy at the right frequency makes swings or glasses resonate through vibration. The right frequency of UV light can make a hydrogen electron resonate by jumping to a higher energy level (c), while a particular radio frequency can make protons resonate by rotating (d).

Fourier analysis

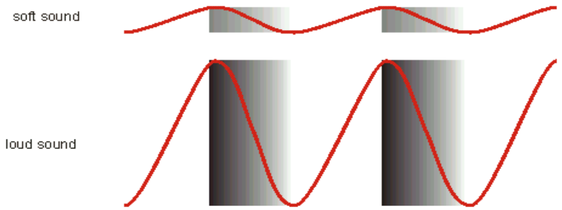
- The quality of a sound depends on the relative intensities of the waves with the natural frequencies. It depends on the spectrum of the sound.
- A sinusoidal sound wave of frequency f is a pure tone. A note played by a musical instrument is not a pure tone. Its wave function is not sinusoidal,
  - i.e. it is not of the form $\Delta P(x,t) = \Delta P_{max}\sin(kx - \omega t + \varphi)$.
- The wave function is a sum of sinusoidal wave functions with frequencies nf, (n = 1, 2, 3, ...,) with different amplitudes, which decrease as n increases.
- The harmonic waves with different frequencies which sum to the final wave are called a **Fourier series**. Breaking up the original sound wave into its sinusoidal components is called **Fourier analysis**.

Fourier analysis

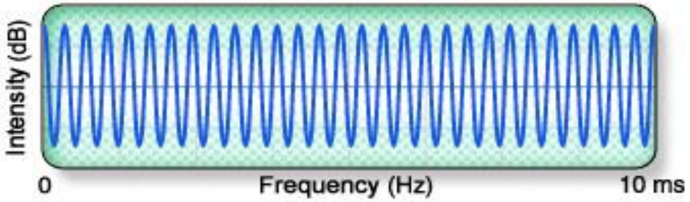


Characteristic of sound waves

- Loudness (Intesity)



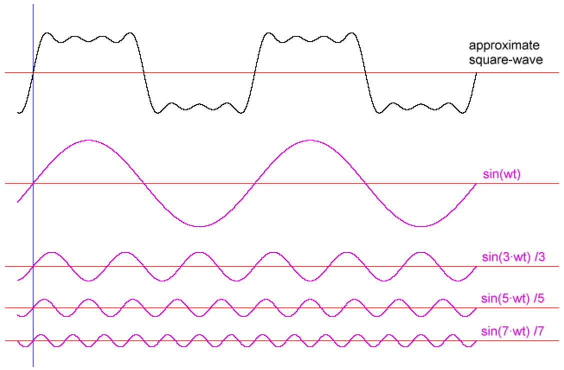
- Frequency (pitch)

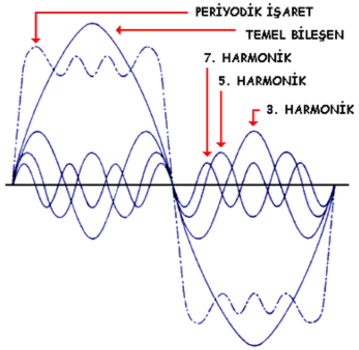


high-pitched voice

low-pitched voice

- Timbre (quality)

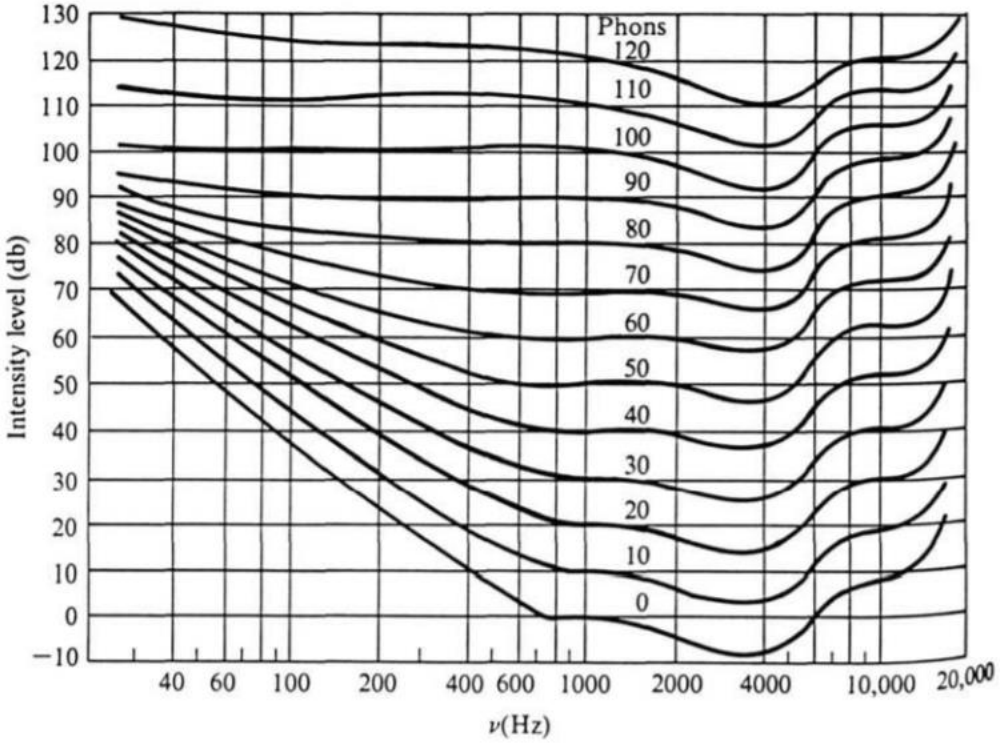


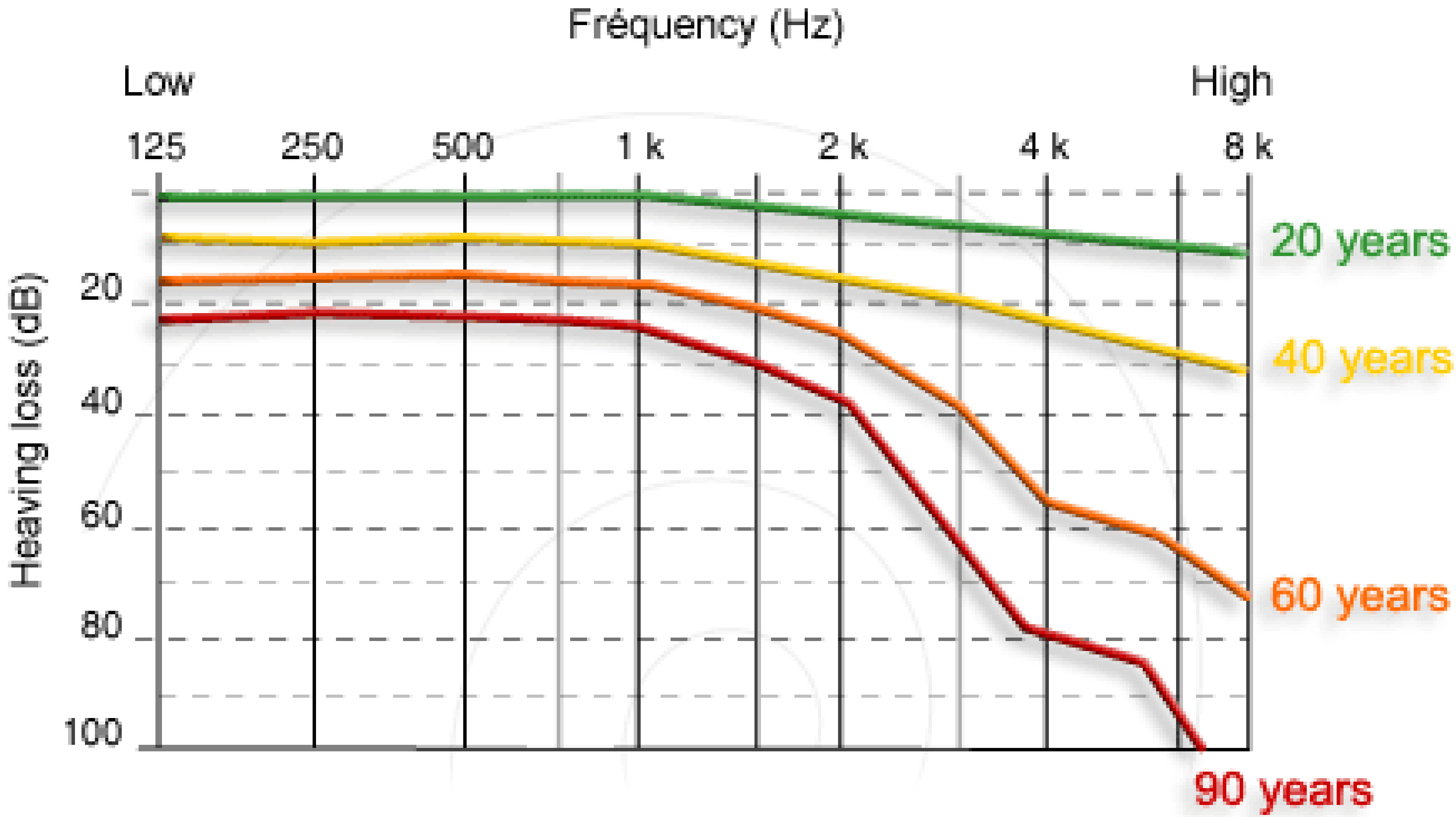


Characteristic of sound waves

- The sensitivity of the ear changes with frequency and can be described in terms of the loudness. Constant loudness (isophone) varies with intensity and frequency.
- The unit for the loudness is the phon which is normalized to the intensity at the fixed frequency of f=1000Hz.

$$1\,[phon] \equiv 1\,[db] \quad at\ f = 1000\,[Hz]$$





Fréquency (Hz)
Low
High
125
250
500
1 k
2 k
4 k
8 k
Heaving loss (dB)
20
40
60
80
100
20 years
40 years
60 years
90 years

Question: The ear canal in human is approximately 25 mm in length. If the sound waves travel at 346 m/s through the air, What is the fundamental frequency and harmonics ?

$f=v/4L$

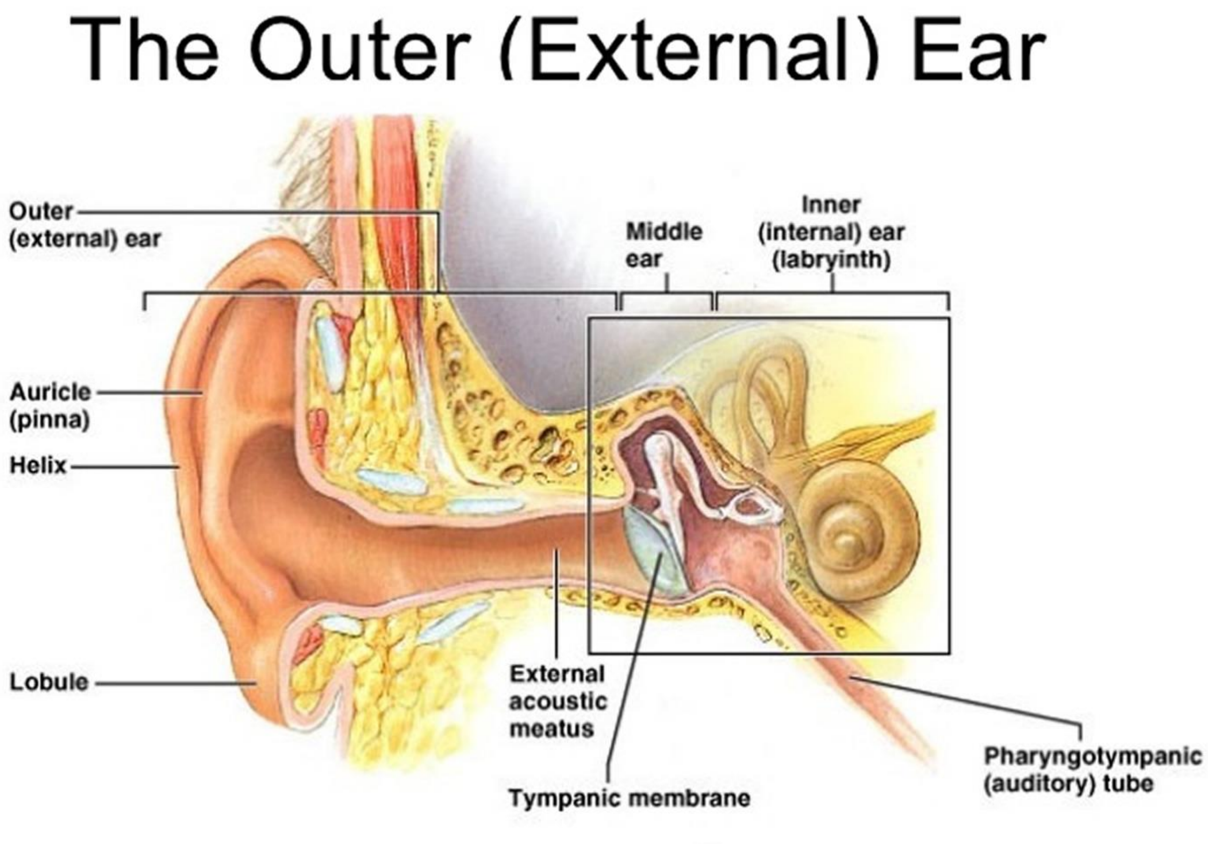
$f_1= 346/ 4 X 0,025= 3460$ Hz. (Fundamental frequency)

$f_3=3v/4L = 3x346 / 4x0.025 = 10380$ Hz.

How does sound travel through the ear?

The outer ear

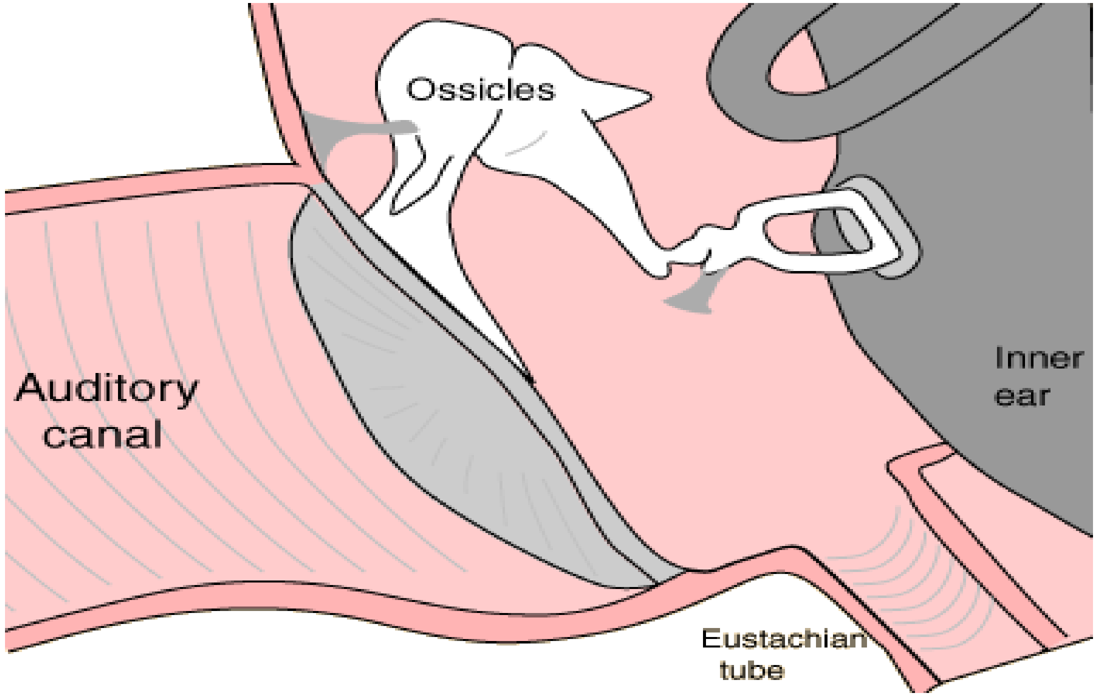
- The visible part of the outer ear (pinna) is nearly negligible for the hearing process.
- The ear canal is approximately 25 mm in length, and 7 mm in diameter with a corresponding quarter-wavelength resonance near 2.5 kHz with an approximate pressure gain of about 10 dB.



How does sound travel through the ear?

Middle ear:

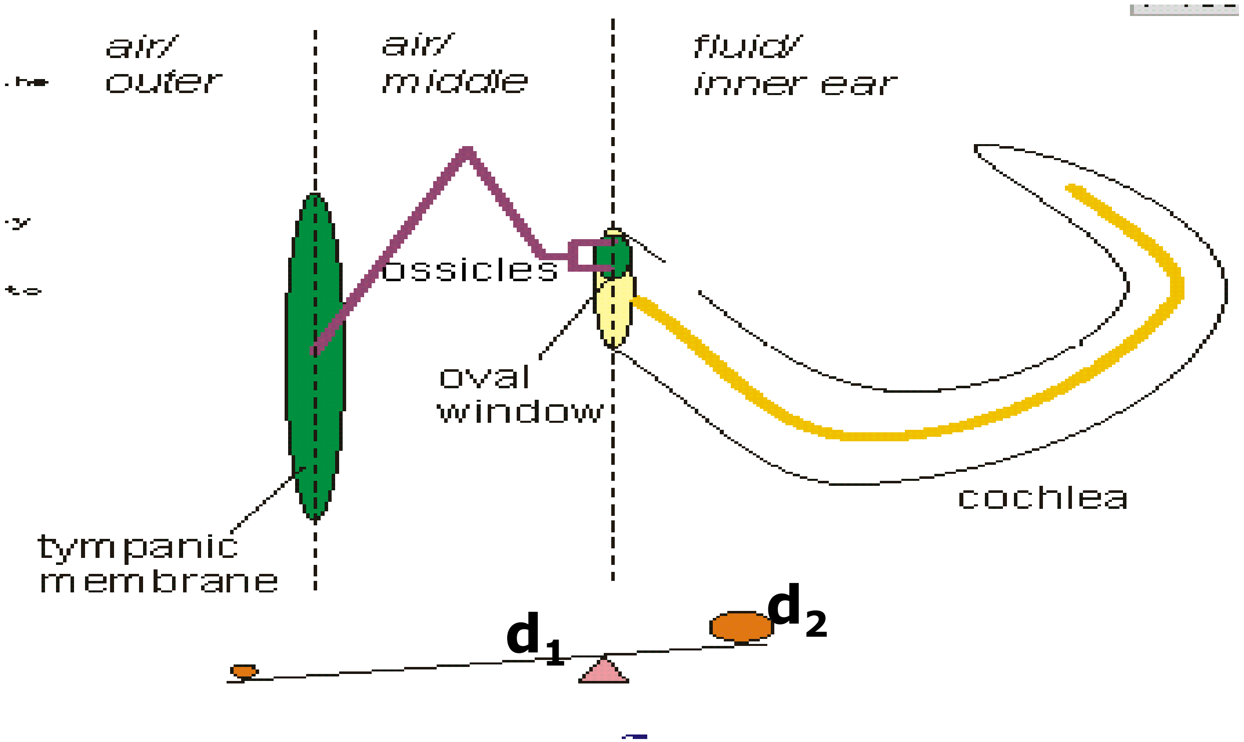
- The ear canal is filled with air that is continuous with the free field. On the other hand the cochlea is filled with cerebro-spinal and other salty fluids.
- Dominant feature of the middle ear are three small bones, the ossicles, malleus, incus and stapes.
- The ossciles act as a lever system causing a substantial amplification of the eardrum membrane vibrations



How does sound travel through the ear?

Amplification of the sound in the middle ear

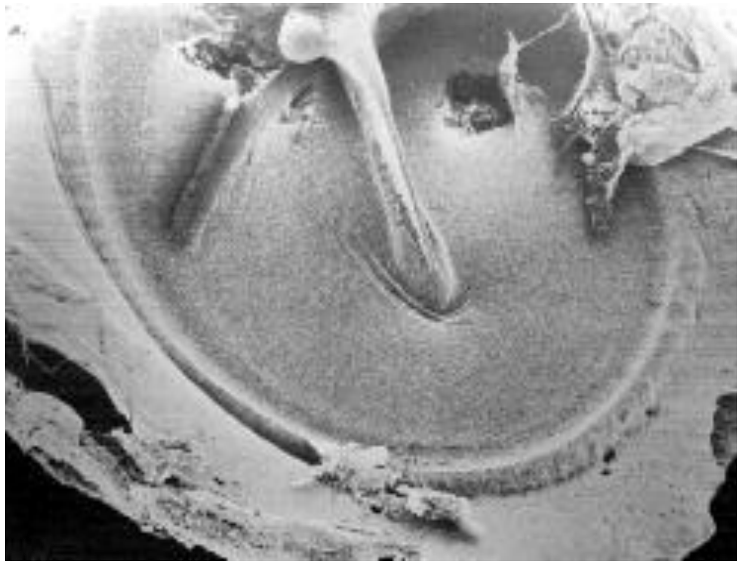
- Solids generally transmit force, and fluids transmit pressure as it is.



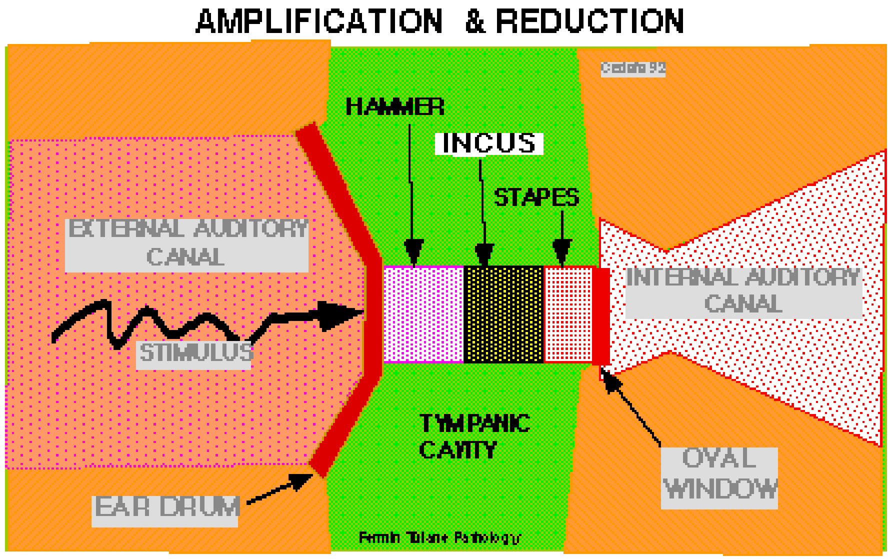
How does sound travel through the ear?

Amplification of the sound in the middle ear

- The pivot point or fulcrum is located farther from the tympanic membrane than from the stapes, and the ratio of the lengths of the lever arms is 1.3:1



Timpan membrane area: 64 mm^2 , malleusa area : 55 mm2



The area of the tympanic membrane is 0.55 cm2, whereas that of the oval window is only 0.032 cm2.

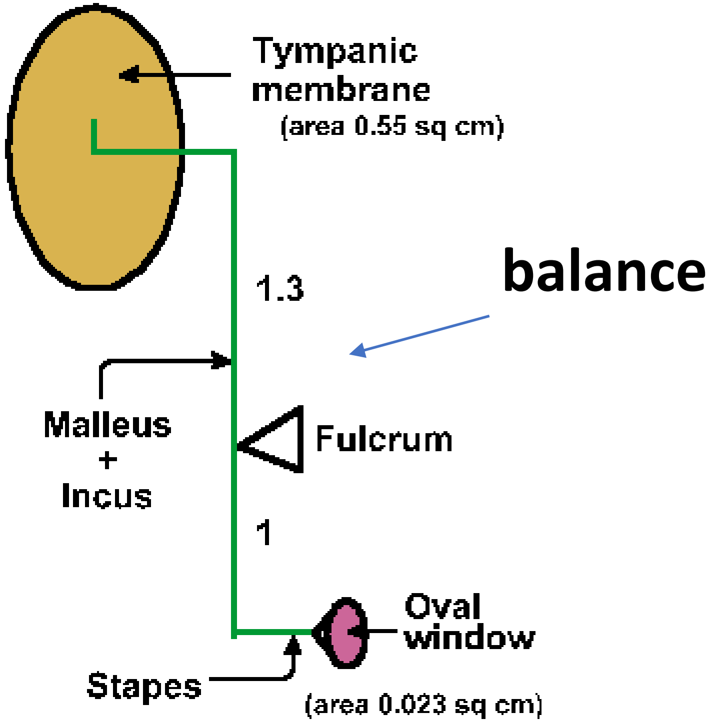
Amplification of the sound in the middle ear

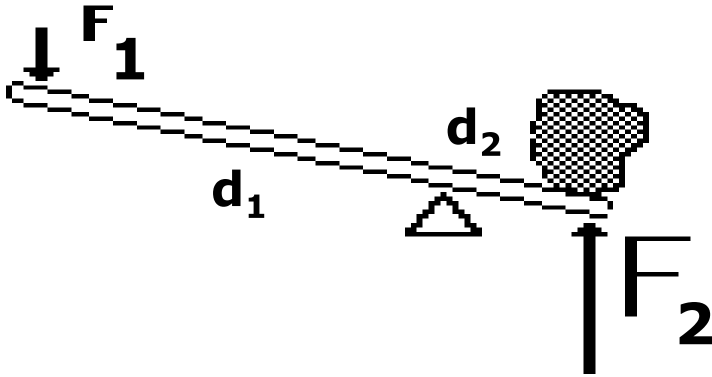
Amplification of the sound in the middle ear

$$F_{st} \times d_2 = F_{mal} \times d_1$$

$$F_{st} \times 1 = 1.3 \times F_{mal}$$

$$F_{st} = 1.3 \times F_{mal}$$

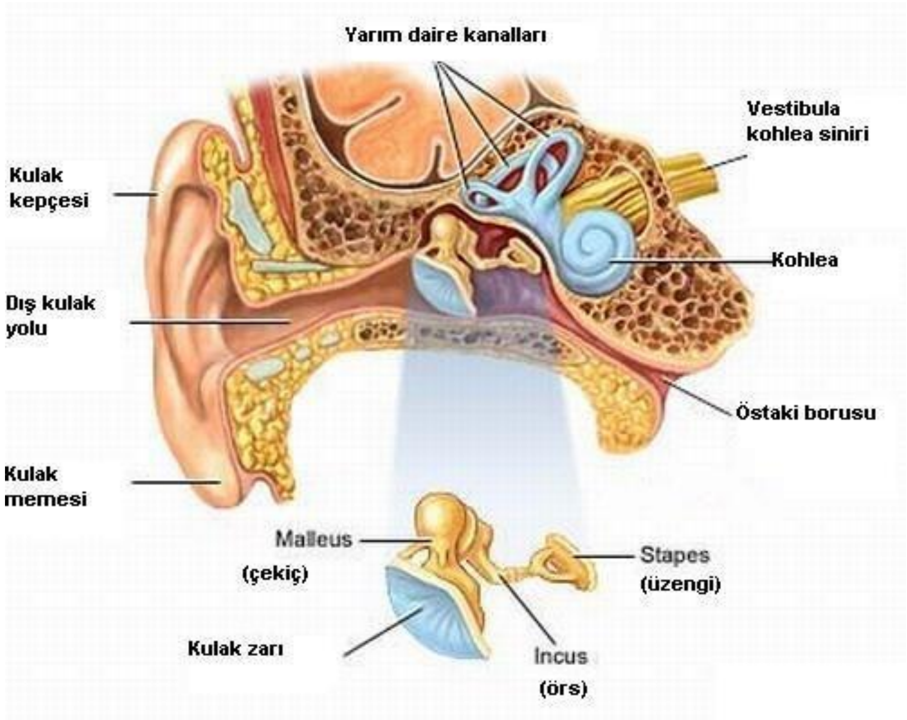




$$F_1 d_1 = F_2 d_2$$

Amplification of the sound in the middle ear

The pressure variation $\mathbf{P_m}$ induce a force $\mathbf{F_m = P_m \times A_m}$ at the eardrum with area A_m which causes a torque at the incus. This torque in turn transmits a force F_0 and pressure P_0 on to the oval window with Area A_0



$\mathbf{F_{mal} = 55 \ X \ P_t}$

$\mathbf{F_{st} = 1.3 \ X \ Fmal}$ → $\mathbf{F_{st} = 1.3 \ X \ 55 \ X \ P_z}$

$\mathbf{F_{st} = 3.2 \ X \ Po}$ → $\mathbf{1.3 \ X \ 55 \ X \ P_z = 3.2 \ X \ P_o}$

$$\frac{P_o}{P_t} = \frac{1.3 \ X \ 55}{3.2}$$

→ **Po/Pt = 22.3**

where p is the pressure, F is the force and A is the area

Amplification of the sound in the middle ear

$$A_{tim} = 55\ mm^2$$

$$A_{oval} = 3.2\ mm^2$$

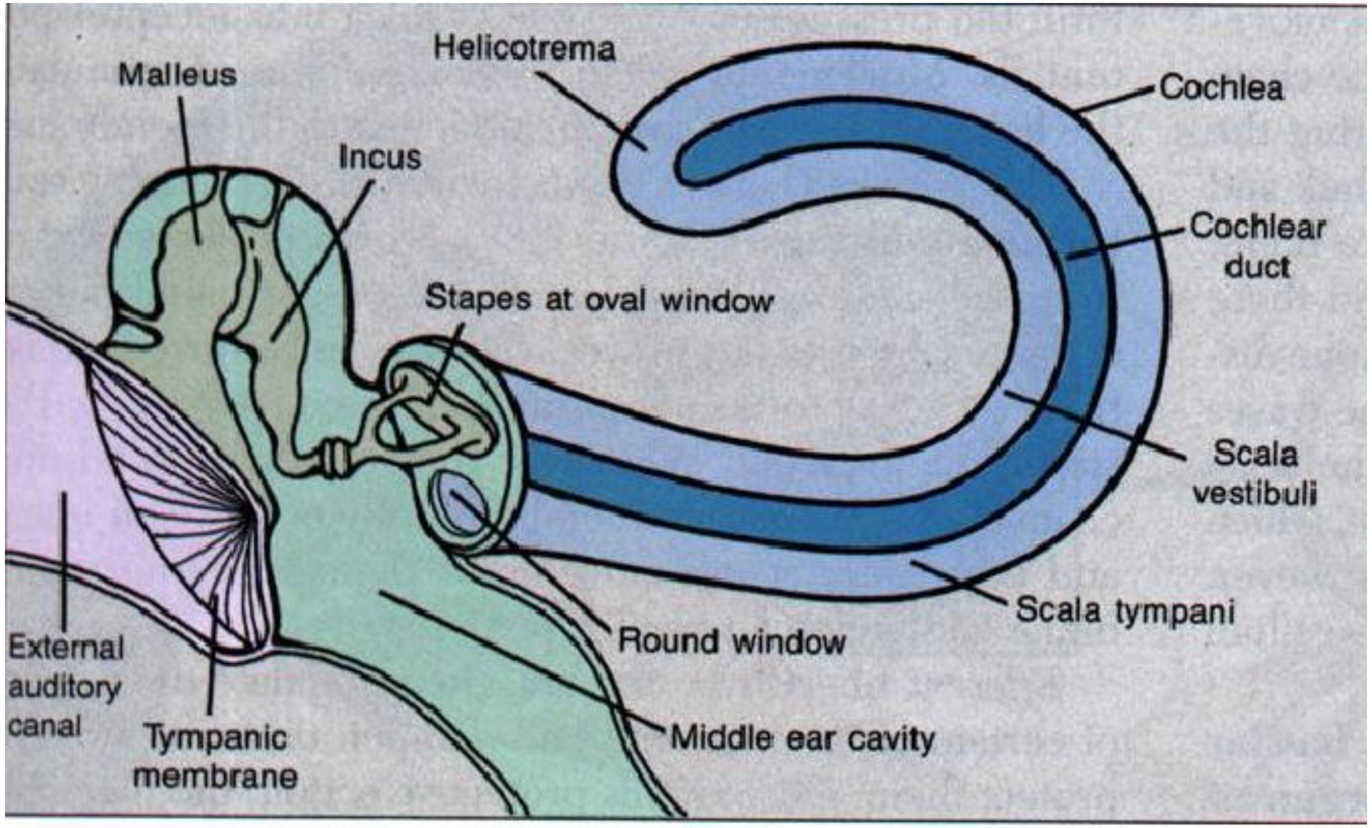
$$\rightarrow \frac{P_{oval}}{P_{tim}} = \frac{A_{tim}}{A_{oval}} \rightarrow \frac{55}{3.2} = 17.2$$

Amp 17.2

How does sound travel through the ear?

Inner ear

- Mechanical energy converts to the electrical energy
- Main conversion side is the cochlea



How does sound travel through the ear?

Inner ear

- If the scala tympani membrane potential is choosen as a reference vestibuli scala will be +5mV and endolymph will be +80mV.

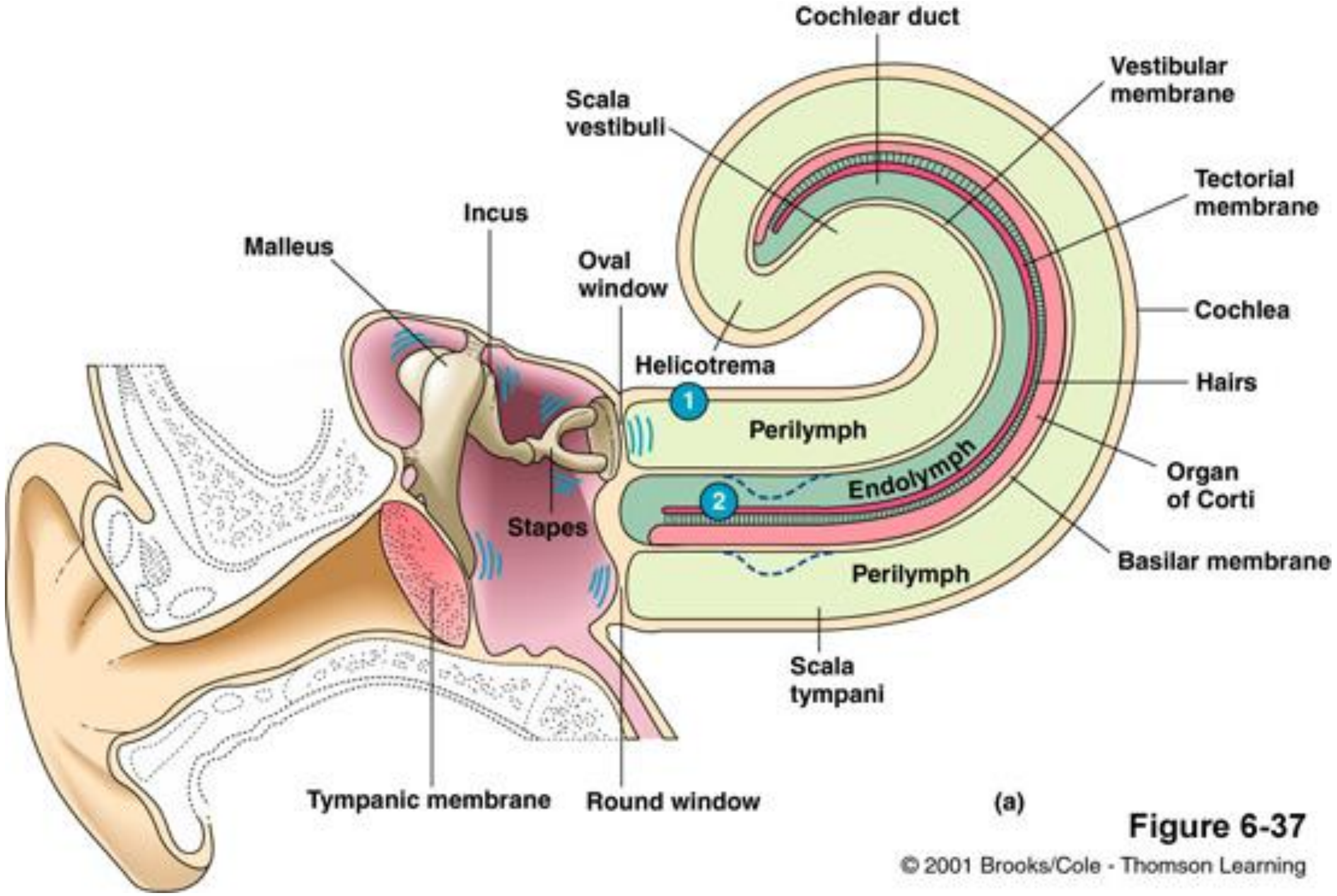
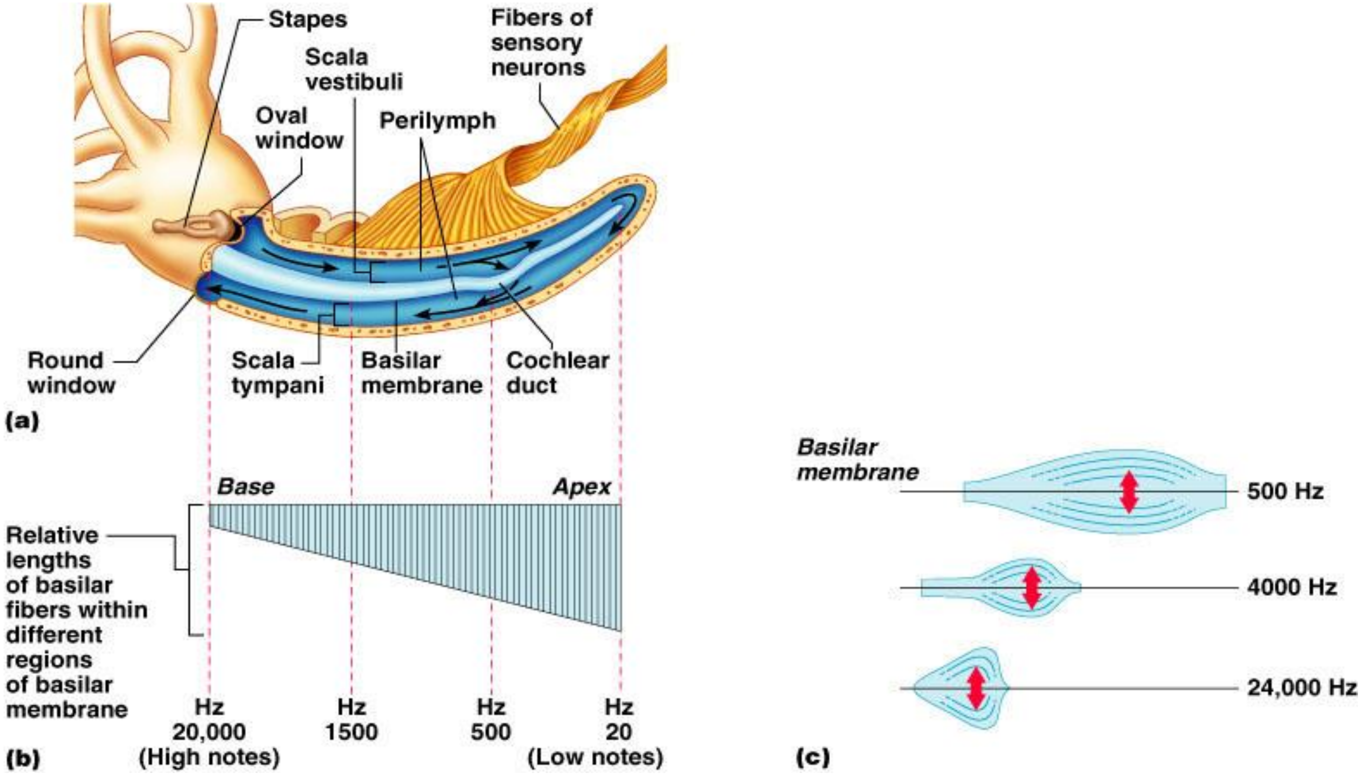
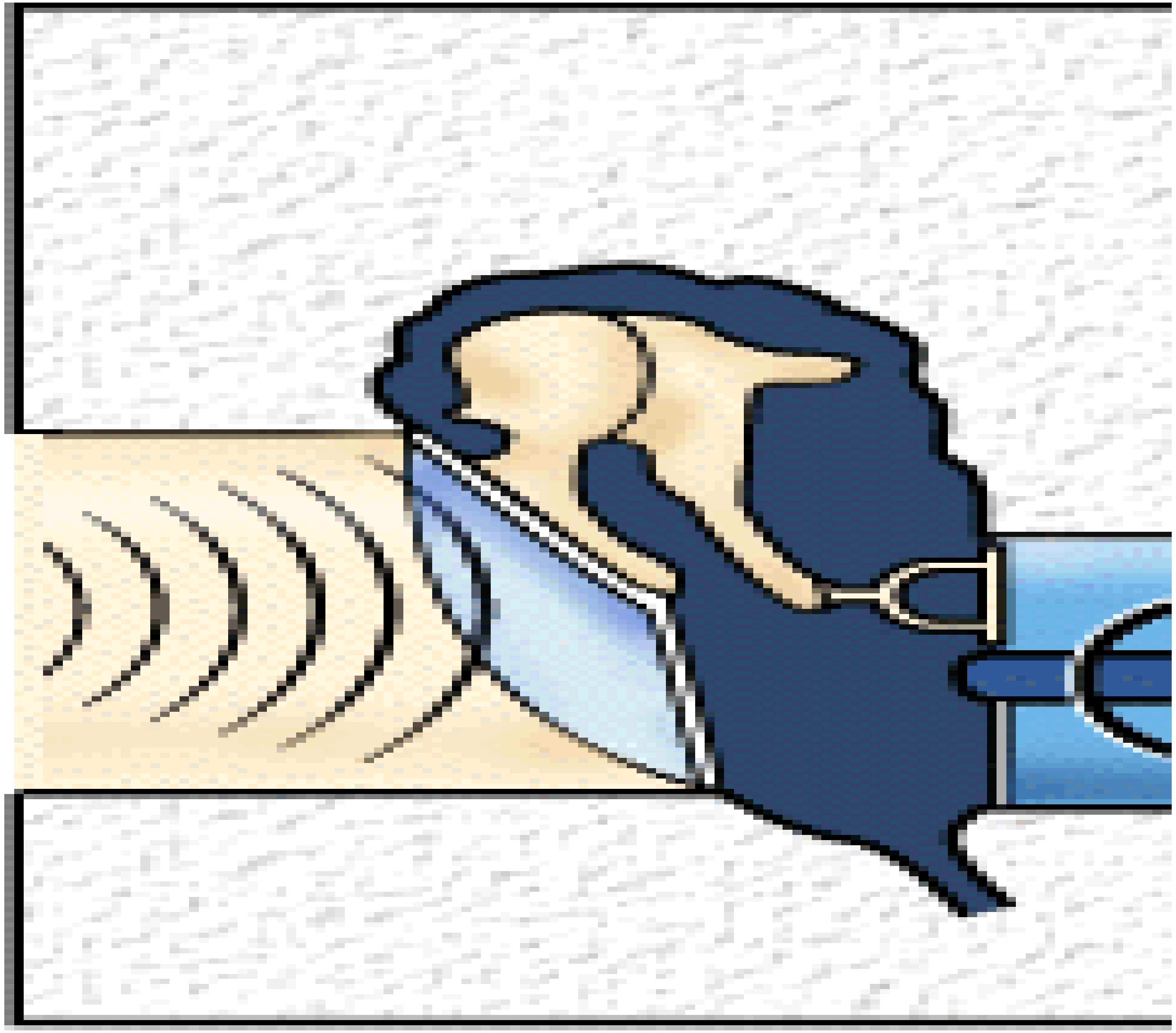


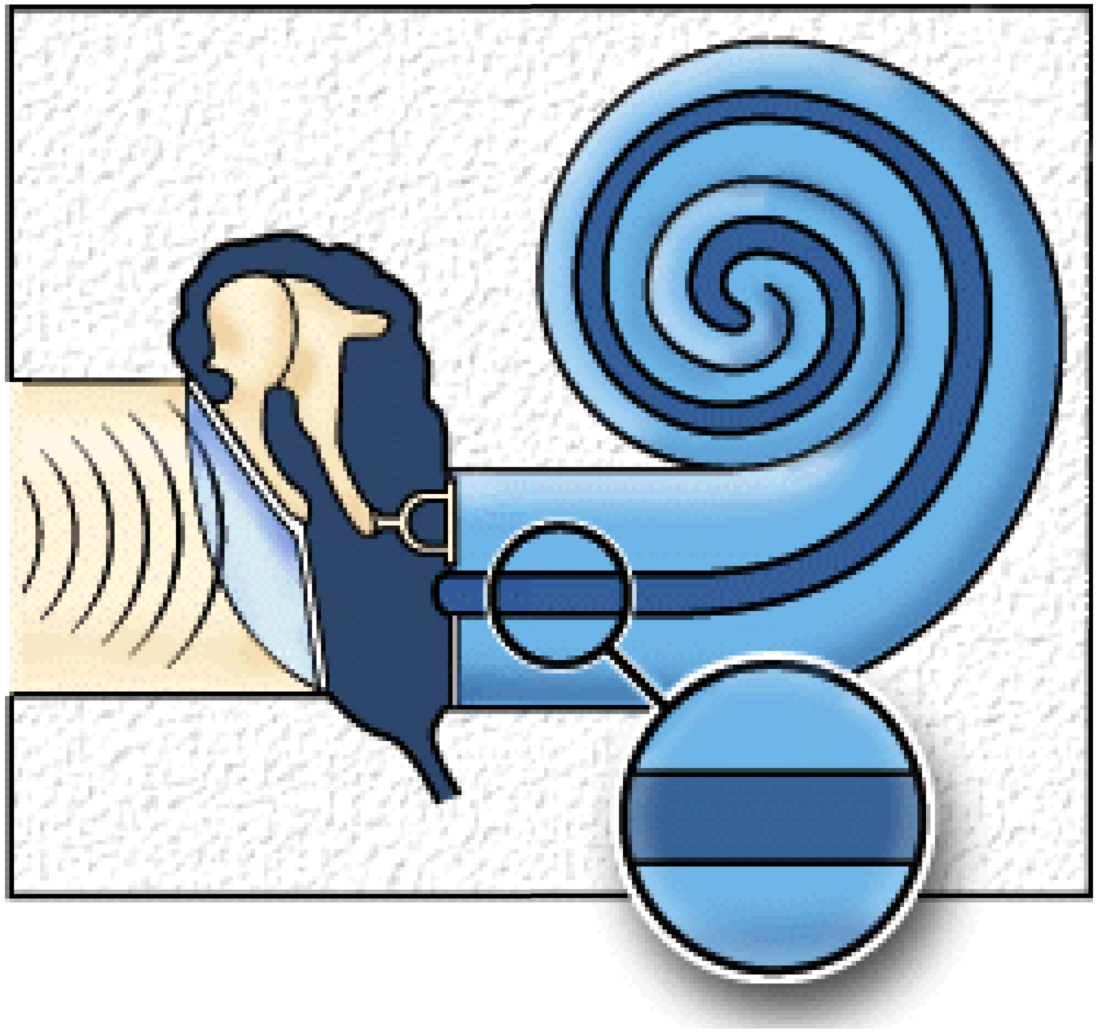
Figure 6-37

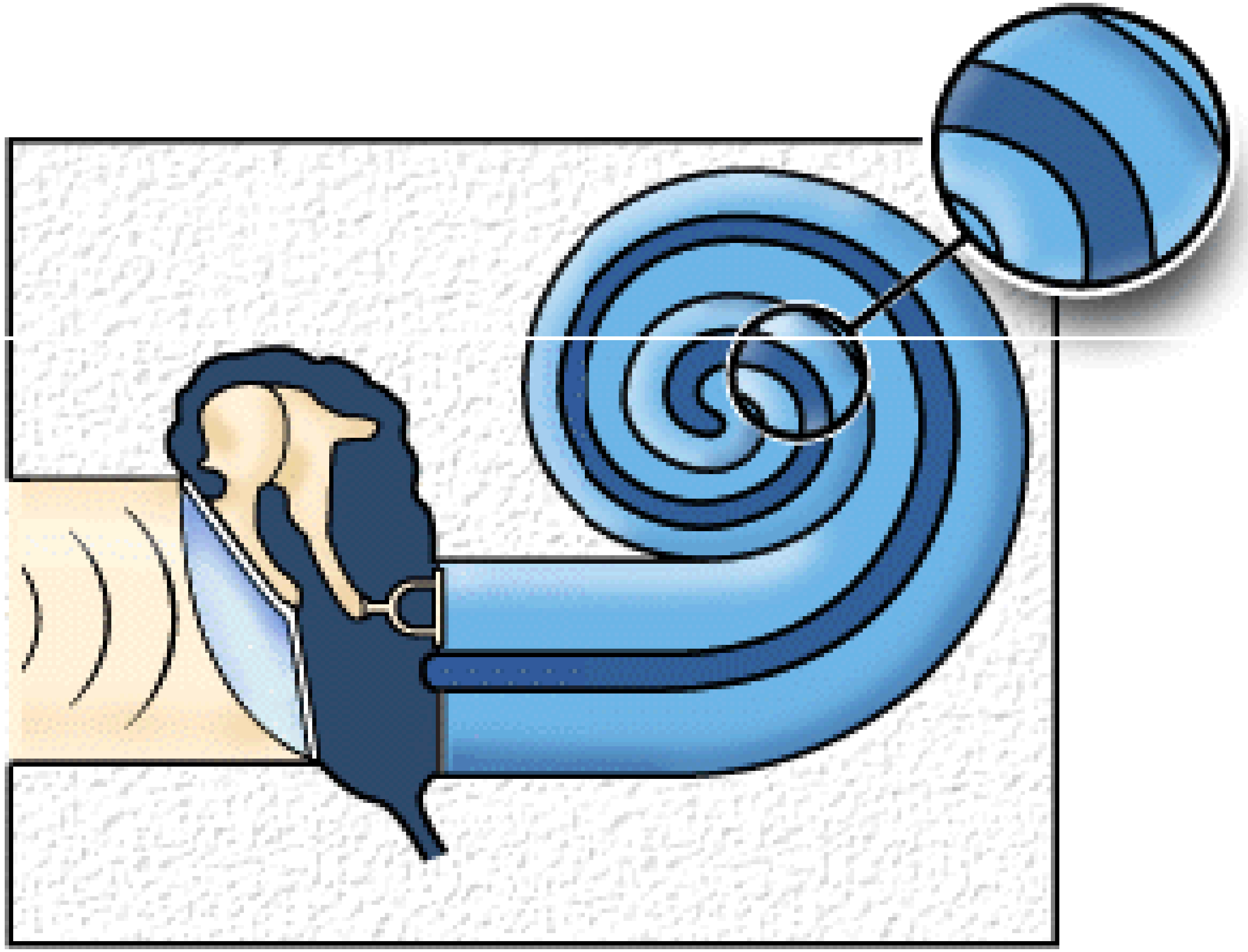
How does sound travel through the ear?

- Basilar membrane is not uniform throughout its length, but rather is relatively wide and thin at the apex of the cochlea, and narrow but thick at the base.
- Because of these properties, a sound wave in the cochlear fluid produces a peak amplitude or height of displacement of the membrane at a certain point along its length.



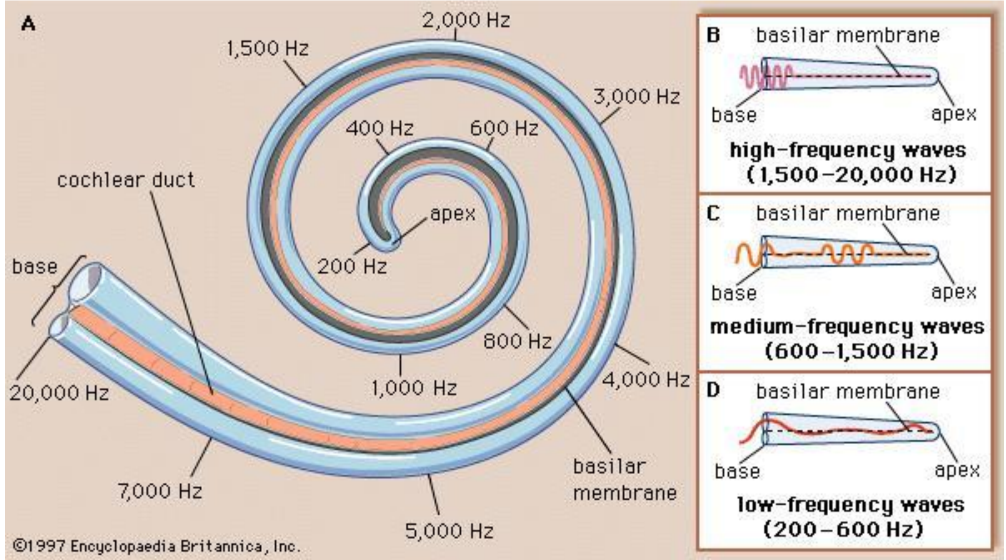




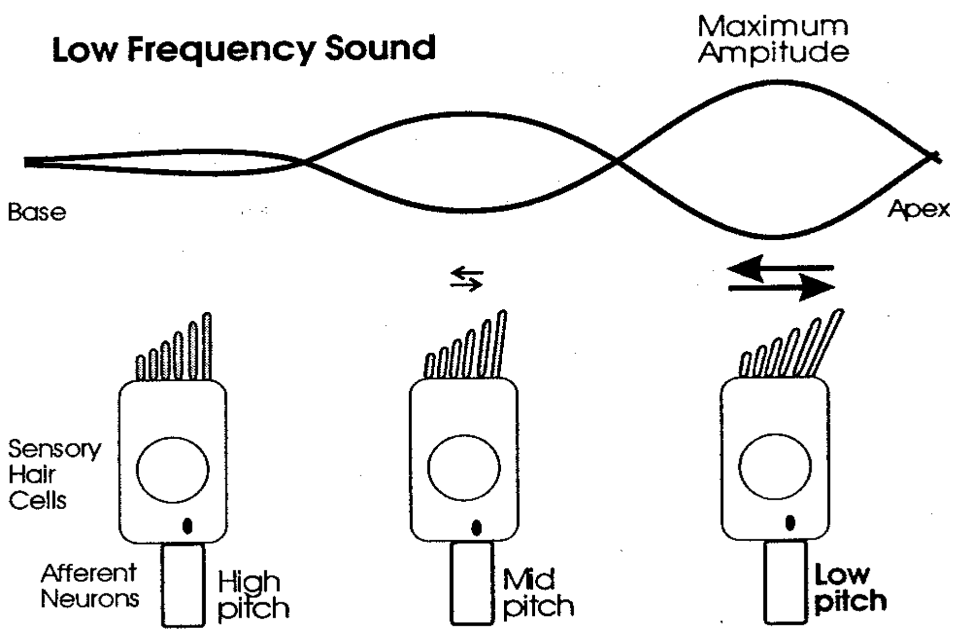


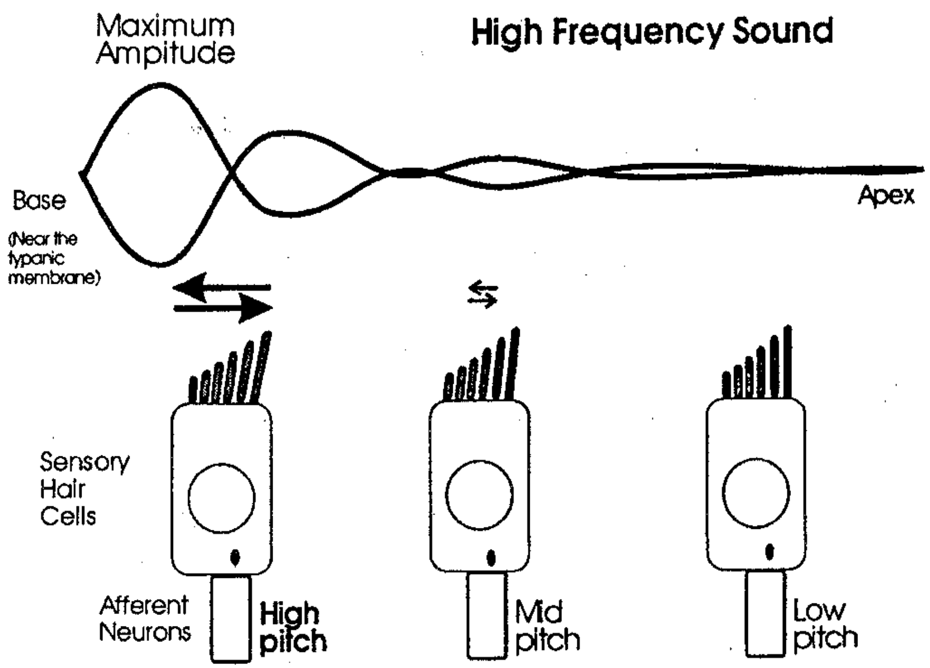
Theories of hearing

- Helmholtz's Resonance Theory (Place Theory): The inner ear serves as a tuned resonator that passes the spectral representation to the brainstem, and then to the auditory cortex via the auditory nerve. The basilar membrane of the ear resonates the sound with a corresponding characteristic frequency.
- VON BÉKÉSY 'S EXPERIMENTS showed the existence of traveling waves in the basilar membrane and that maximal displacement of the traveling wave was determined by the frequency of the sound. The basilar membrane can not explain the hearing alone.
- Other theories: temporal theory, volley theory

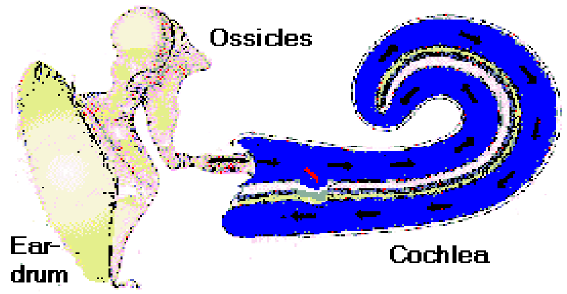


Theories of hearing

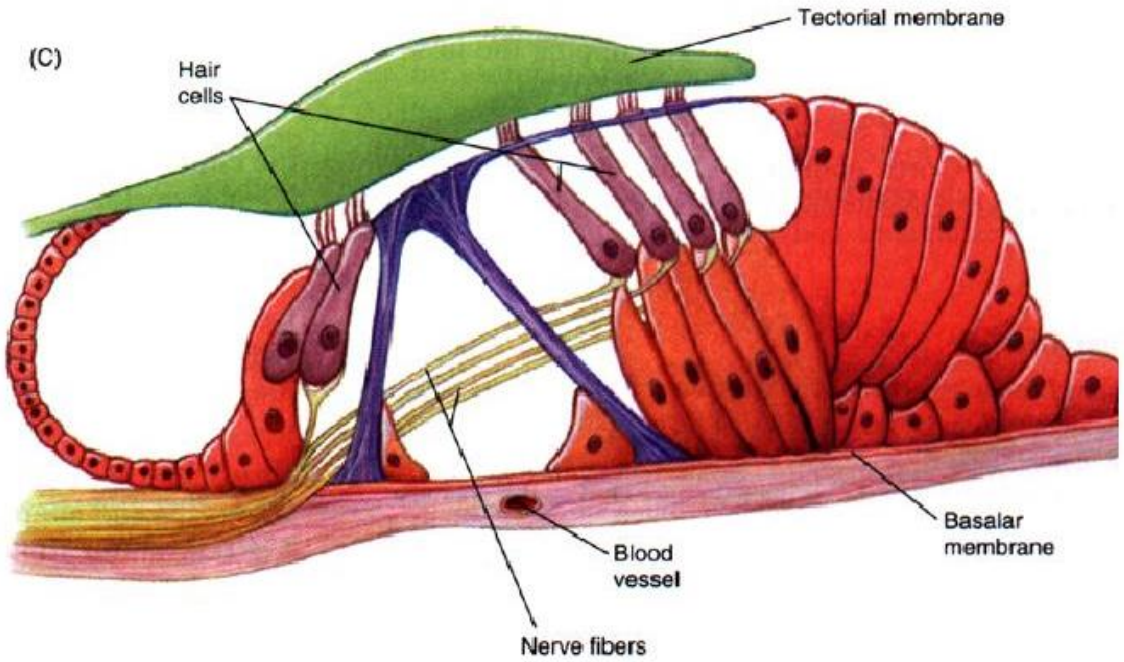




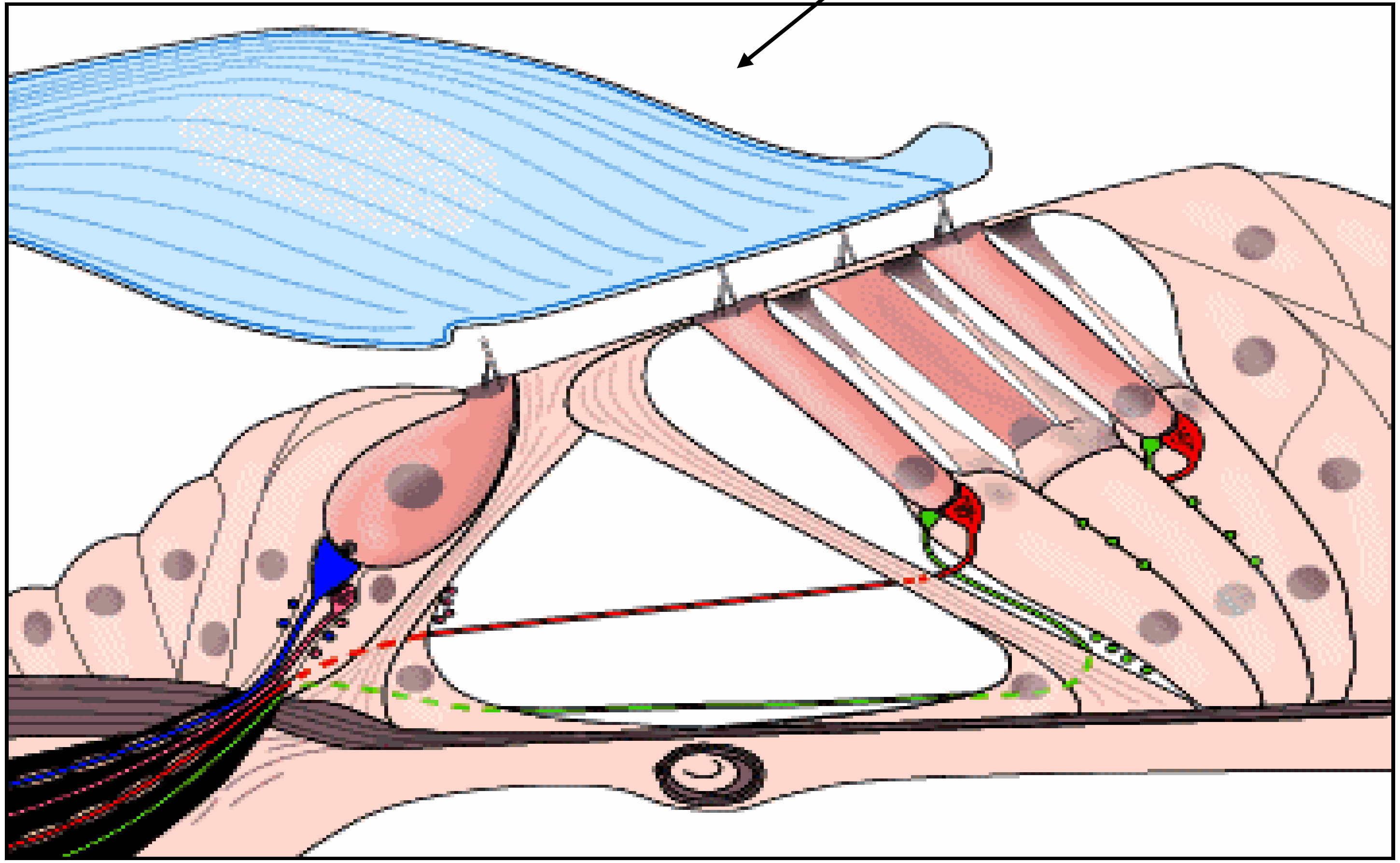
Hair cells

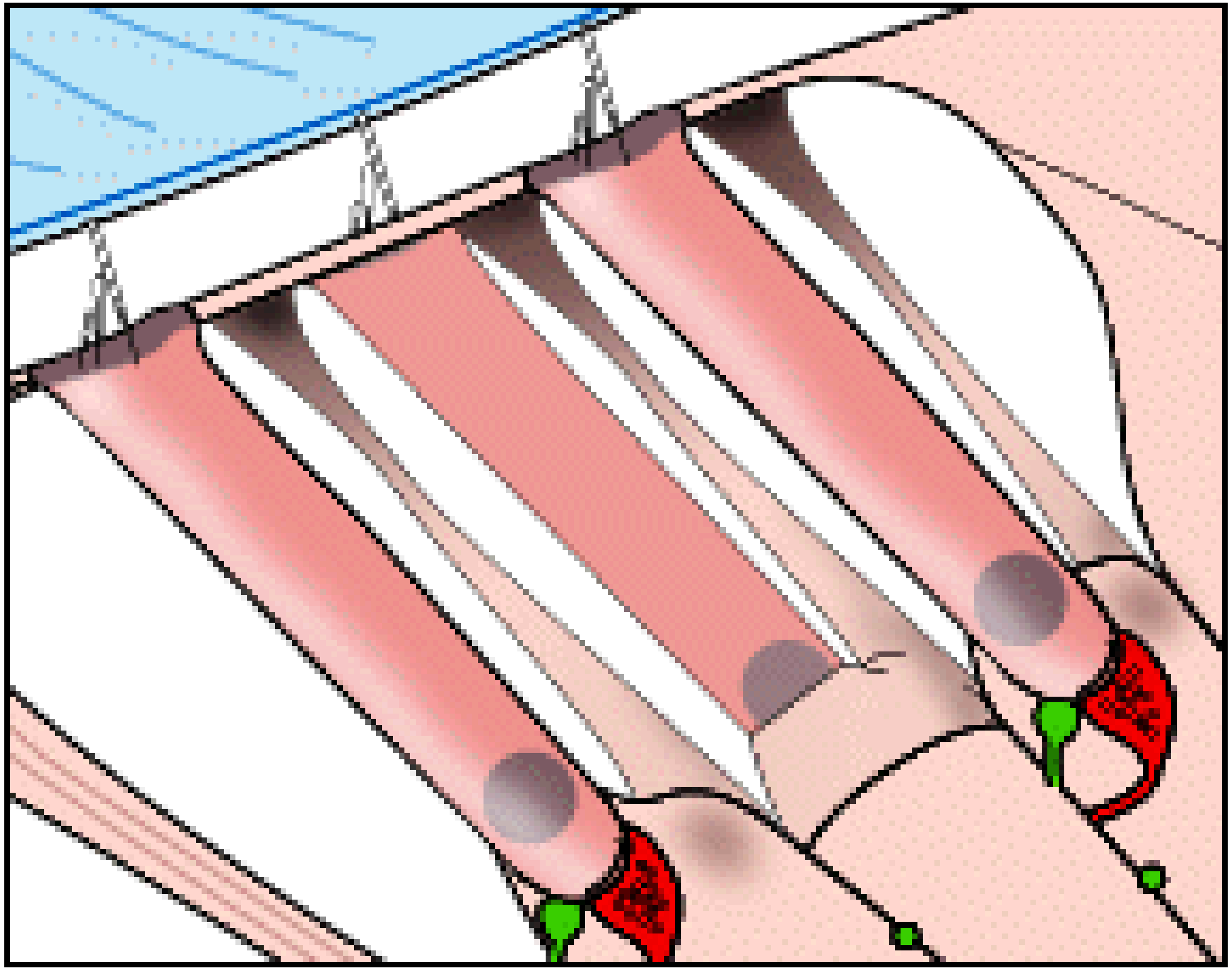


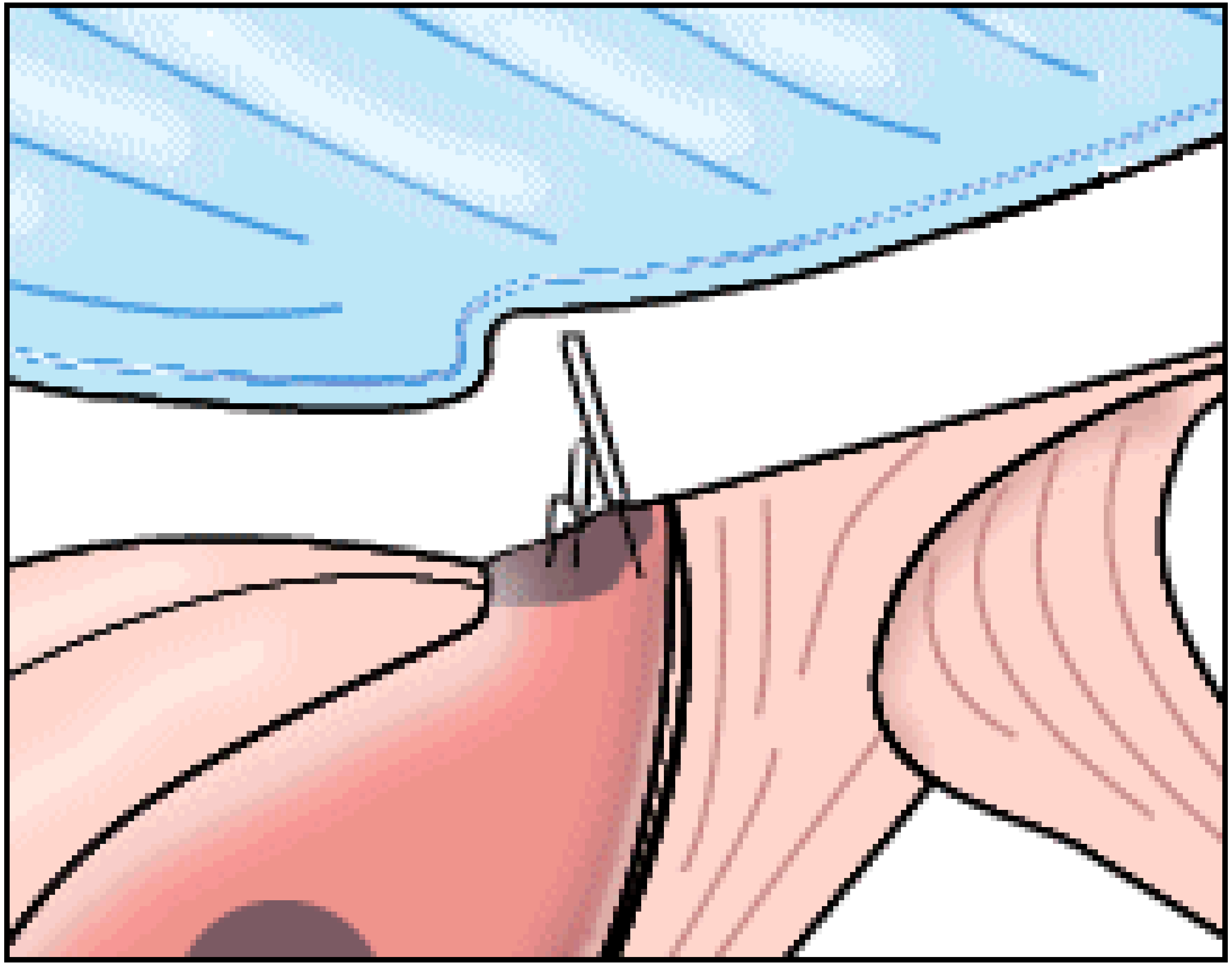
- The auditory receptor cells, called hair cells, lie embedded within the basilar membrane. This membrane divides the spiralled cochlea into upper and lower chambers. Movement of the fluid within the cochlea causes stimulation of the hair cells.

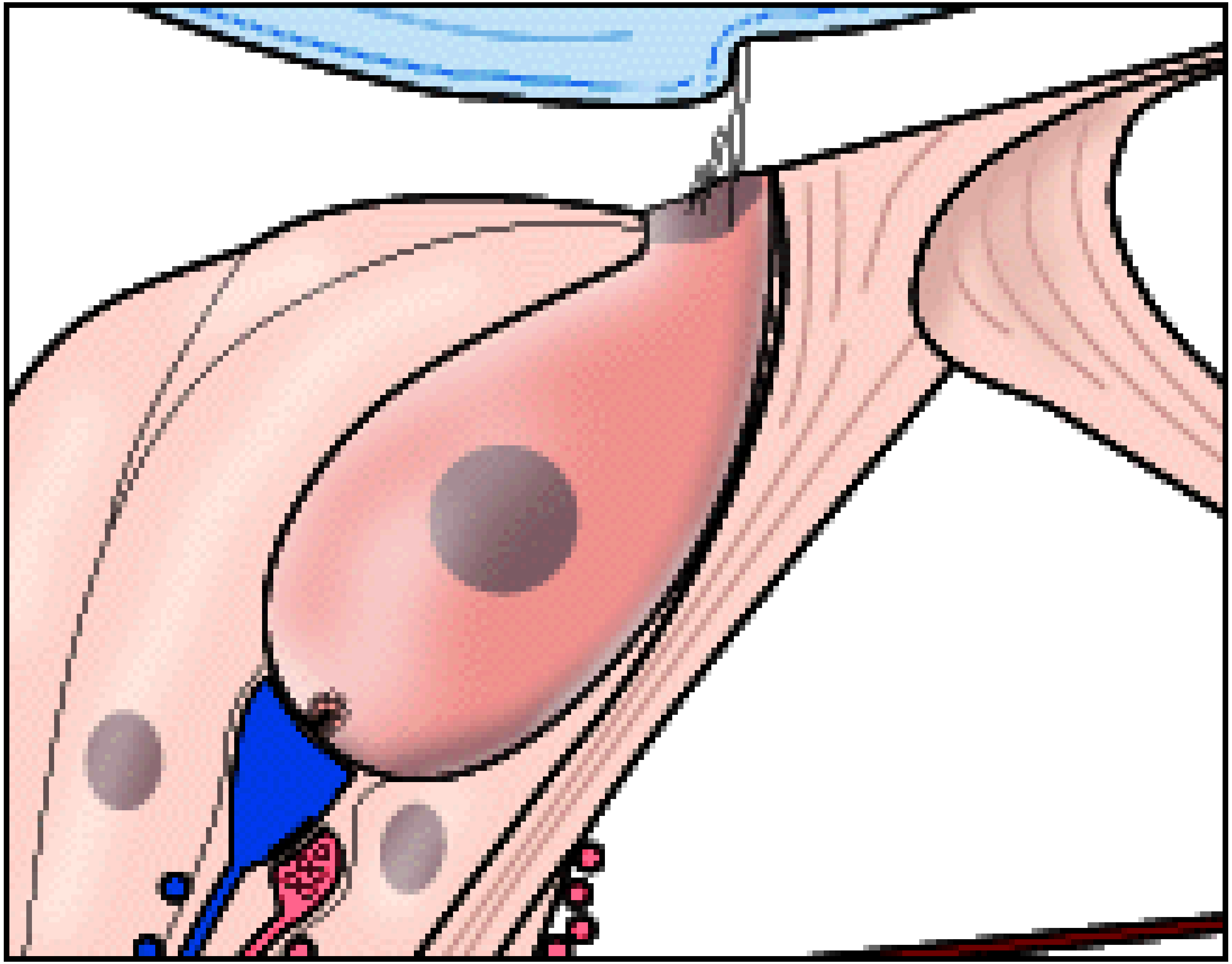


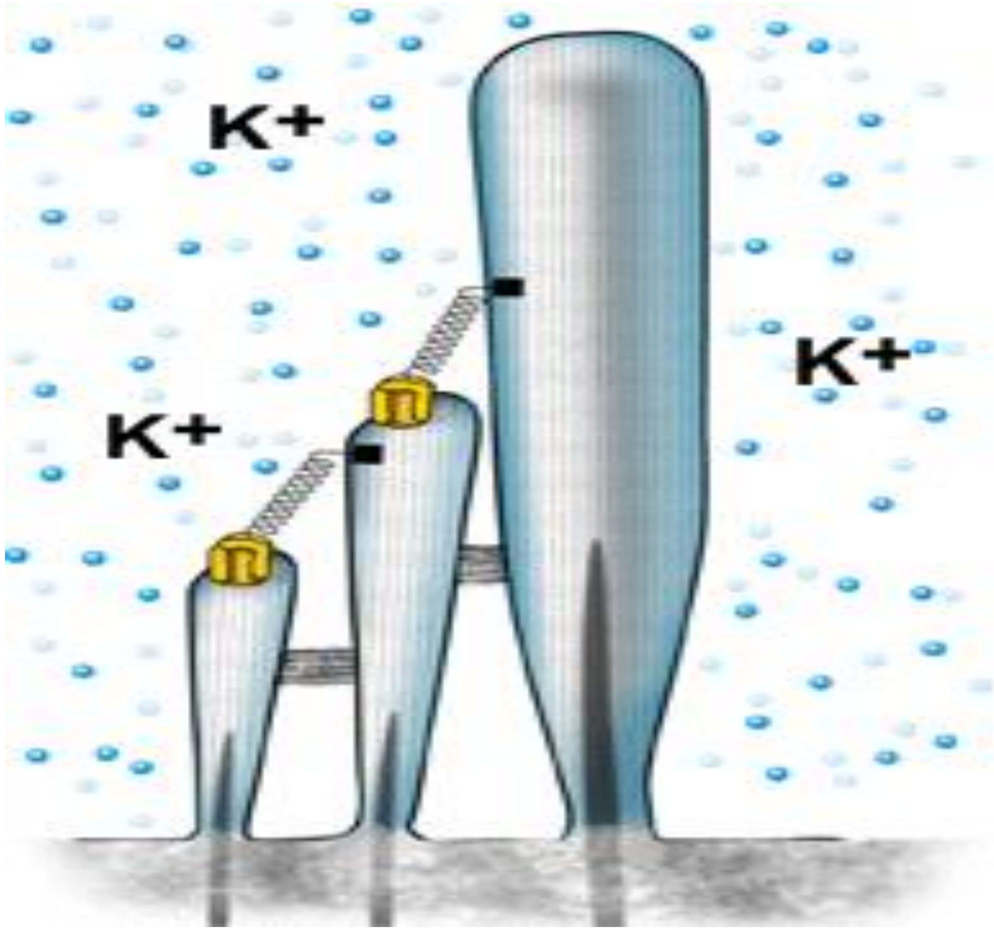
Tectorial membrane

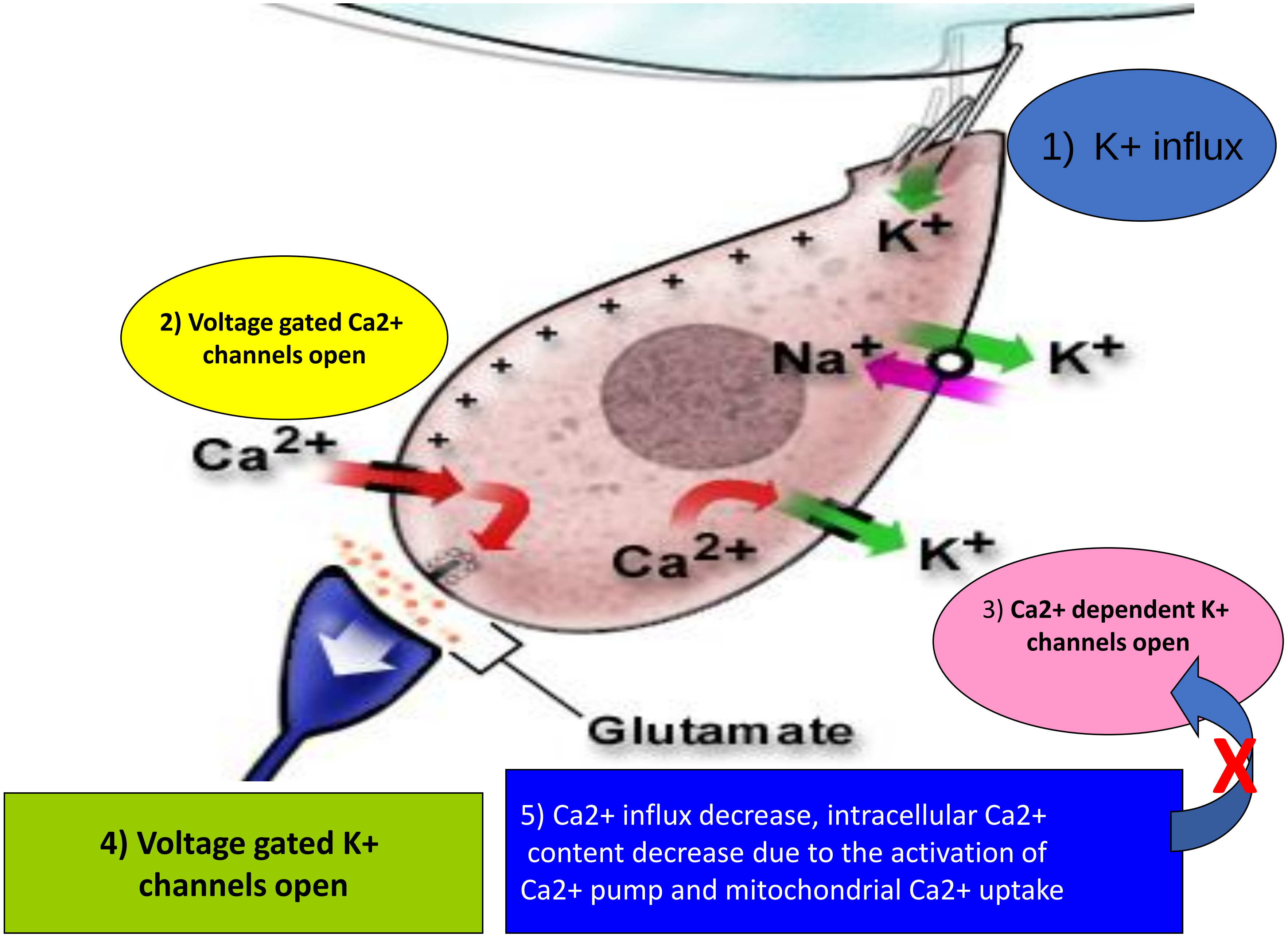









K+
K+
K+



1) K+ influx
K+
2) Voltage gated Ca2+ channels open
Na+
K+
Ca2+
Ca2+
K+
3) Ca2+ dependent K+ channels open
Glutamate
X
4) Voltage gated K+ channels open
5) Ca2+ influx decrease, intracellular Ca2+ content decrease due to the activation of Ca2+ pump and mitochondrial Ca2+ uptake

Summarize the workings of the ear:

- The pinna captures sound waves and channels them through the ear canal to the eardrum.
- Vibrations of the eardrum pass along the three bones of the middle ear, with the base of the stapes then rocking the oval window in and out.
- The membranous oval window acts something like a piston in a hydraulic system: it pushes and pulls on the enclosed fluid of the cochlea.
- The fluid vibrations move the basilar membrane, and this motion activates auditory receptor cells (hair cells) sitting on the membrane, which send signals to the brain.