SZEGEDI TUDOMÁNYEGYETEM
UNIVERSITAS SCIENTIARUM SZEGEDIENSIS

Medical Physics I. (1st semester)

Physics of hearing

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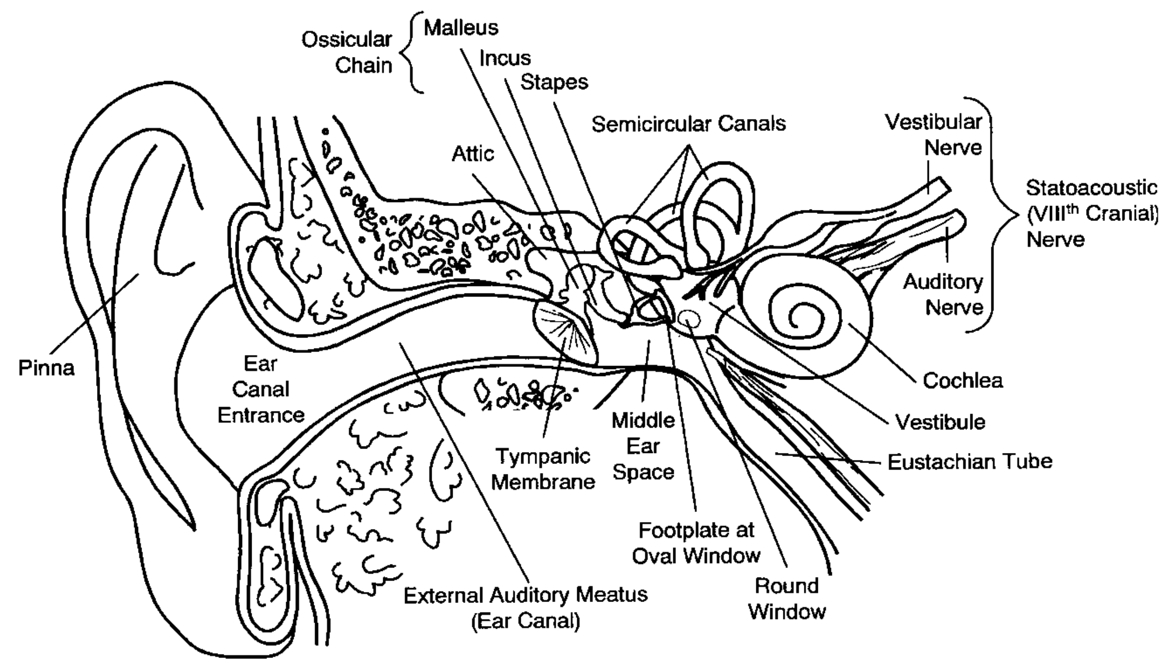
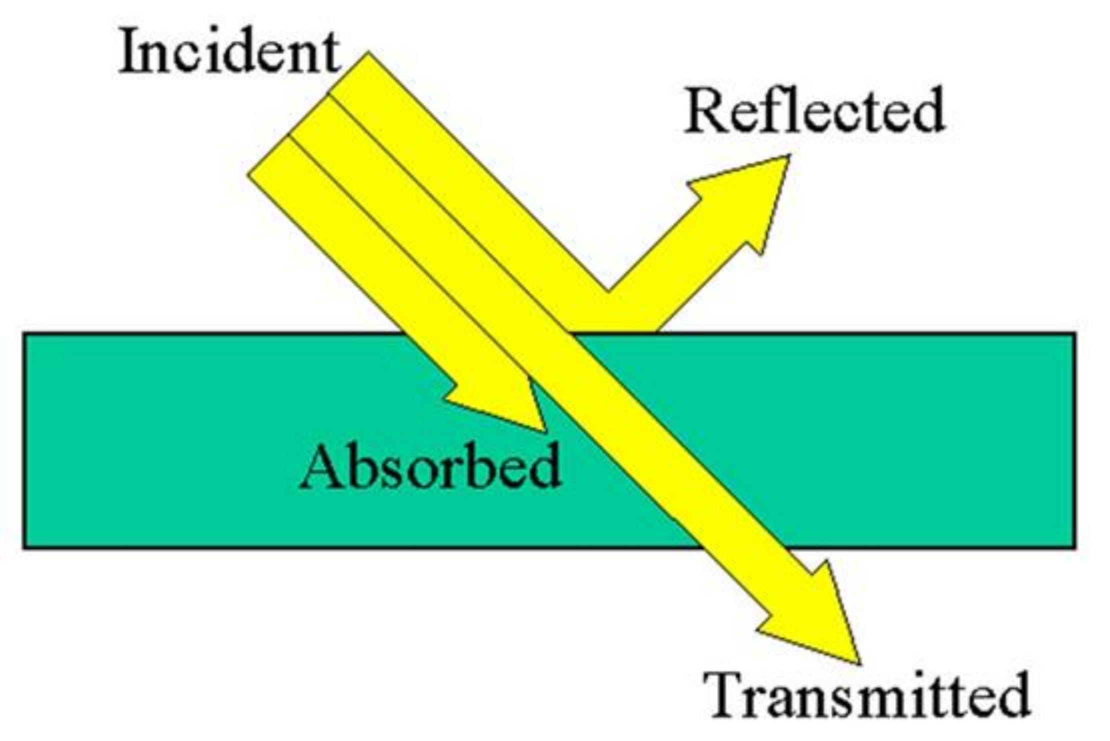
Department of Medical Physics & Informatics

Szeged, October 8, 2015

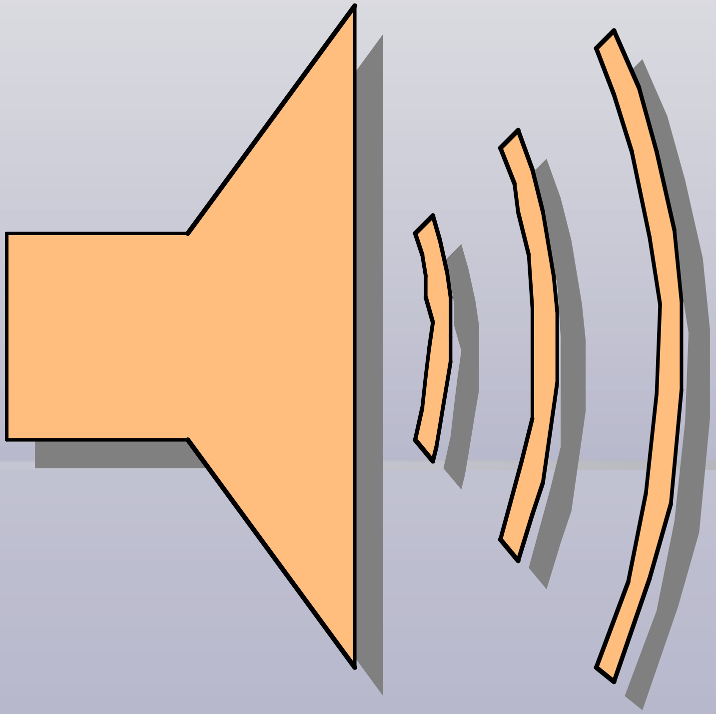
The hearing system –physics of hearing



Basic schematic diagram of the entire auditory system


Incident
Reflected
Absorbed
Transmitted

Sound System



Source

- Any vibrating object

Medium

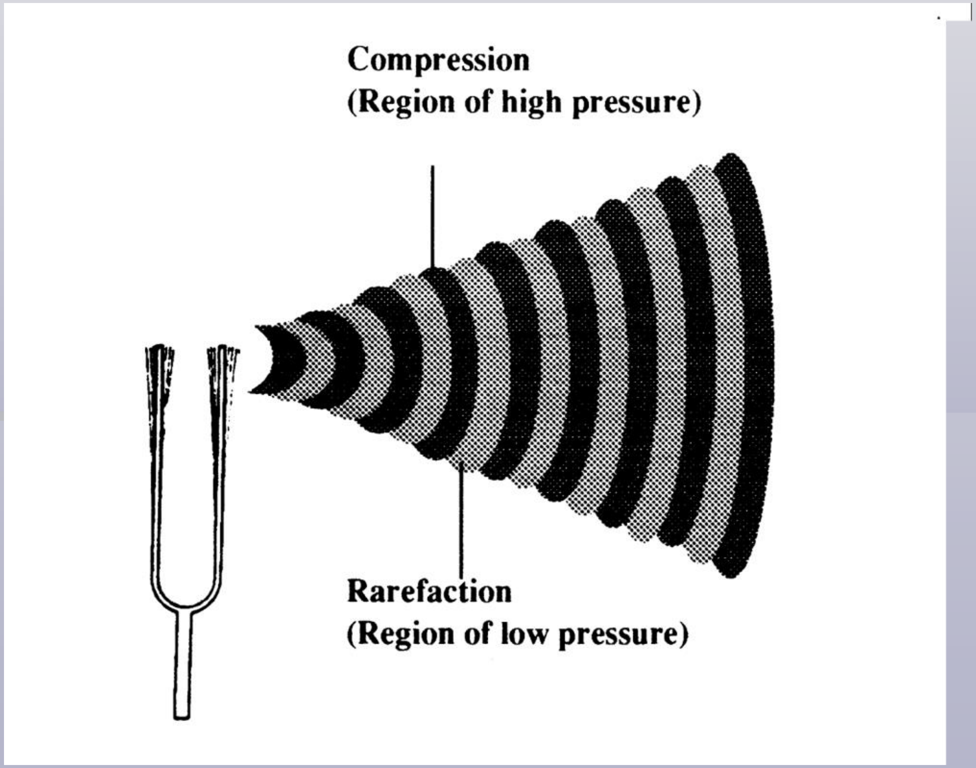
- Any gas, liquid or solid

Receiver

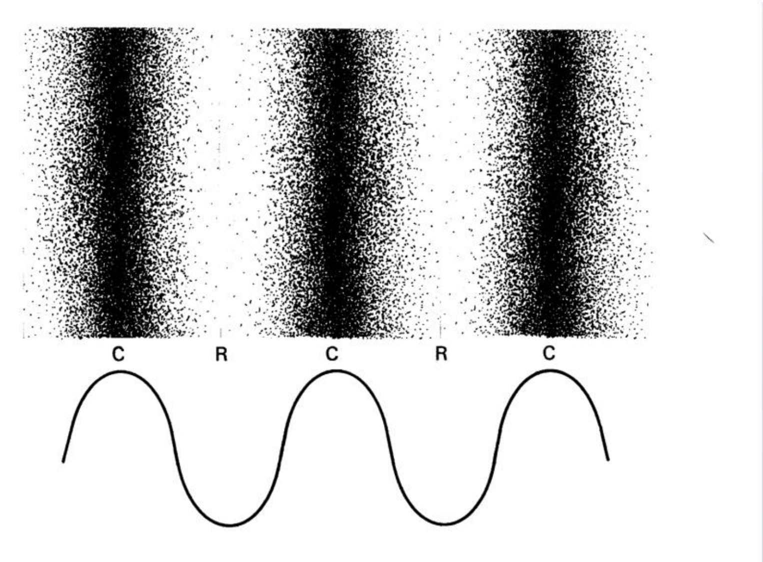
- anything designed to detect the vibrations within the medium originating from the source

A Common Sound System

Illustration of the distribution of molecules surrounding a source in an instant in time



Condensation and Rarefaction



Bands of condensation and rarefaction emanating from a sound source

Important Physical Characteristics of Sound

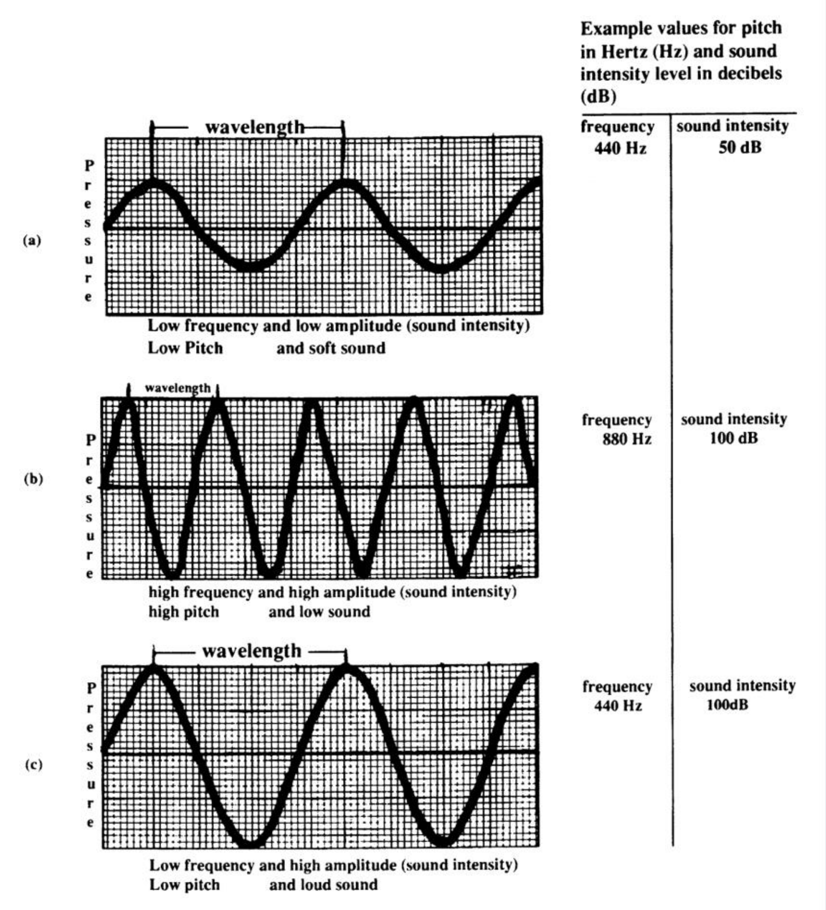
Frequency

- Rate of pressure change as a function of time
- Measured as cycles/sec or Hertz
- The primary determiner of pitch

Intensity

- Magnitude of the pressure change
- Measured as the decibel (dB)
- The primary determiner of loudness

Frequency and Intensity



Sounds a and c share the same frequency and sounds b and c share the same intensity

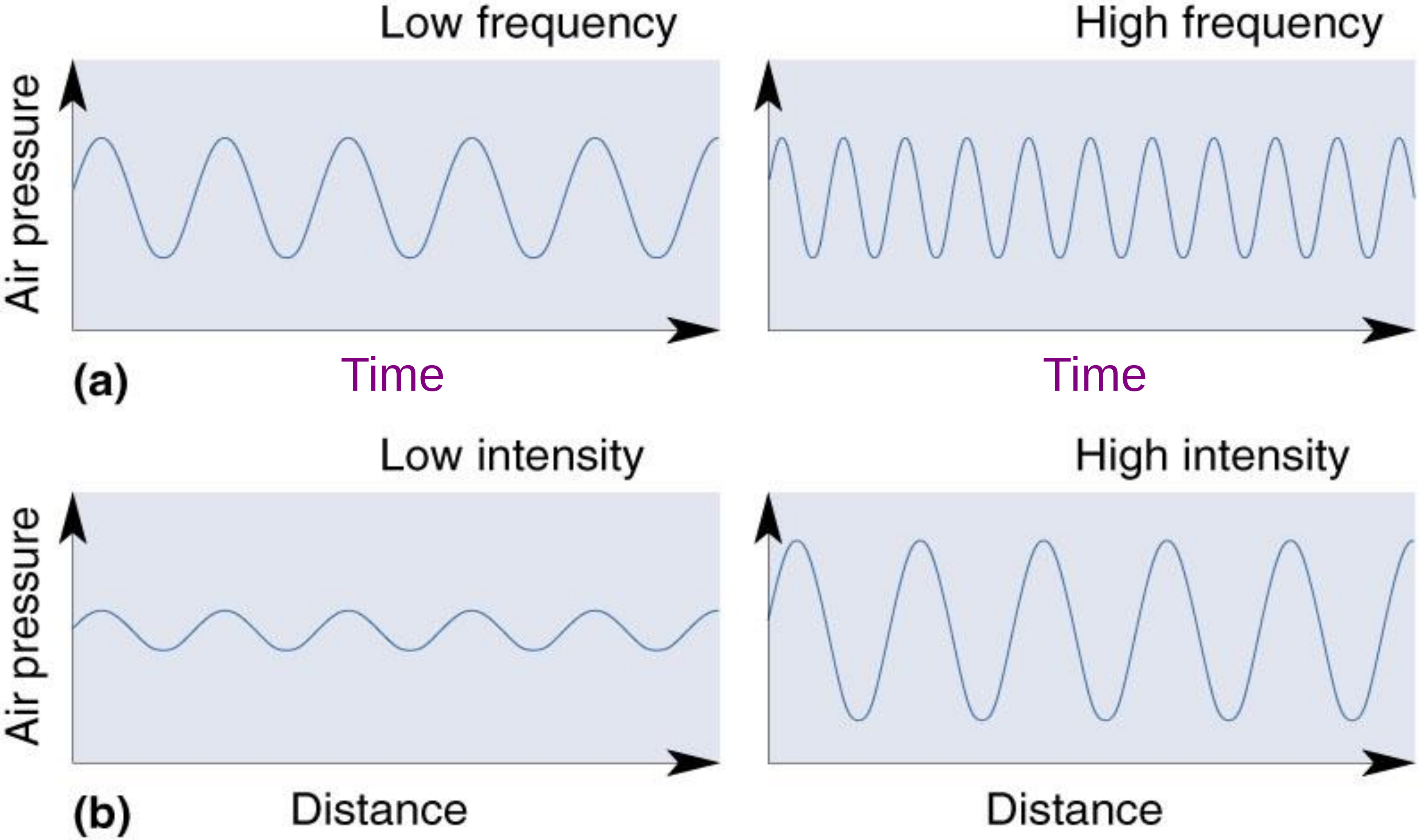
How to quantify loudness: What is a decibel?

- **20 log (p2/p1) dB Sound Pressure Level (SPL)**
- (p2: sound of interest, p1: threshold of human hearing at 1kHz)
- hearing protection: longer exposure of levels above 85 dB

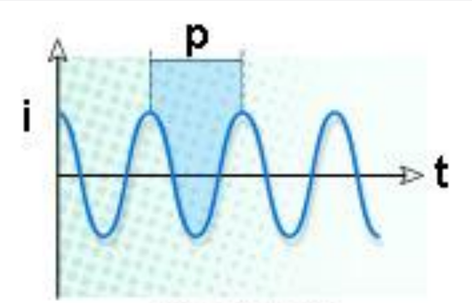
- 80 dB=20 log (p_2/p_1) $p_2=10^4/ p_1$
- P1= hearing threshold (10^{-5} Pa)

Figure 11.2

The frequency and intensity of sound waves. (a) We perceive high-frequency waves as having a high pitch. (b) We perceive high-intensity waves as loud.

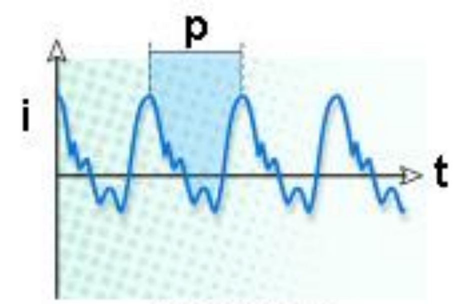


Pure Tones, Musical Sounds, and Noise



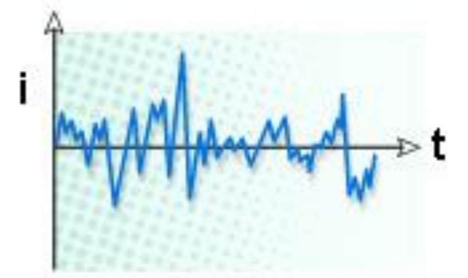
Pure tone

Pure tones: regular wave of a single frequency. i = intensity, p = period, t = time



Music tone

Musical sound: the wave is made up of a fundamental frequency (pitch) and harmonic characteristics of the timbre. Upgrading a sound by one octave means increasing the fundamental frequency twofold.



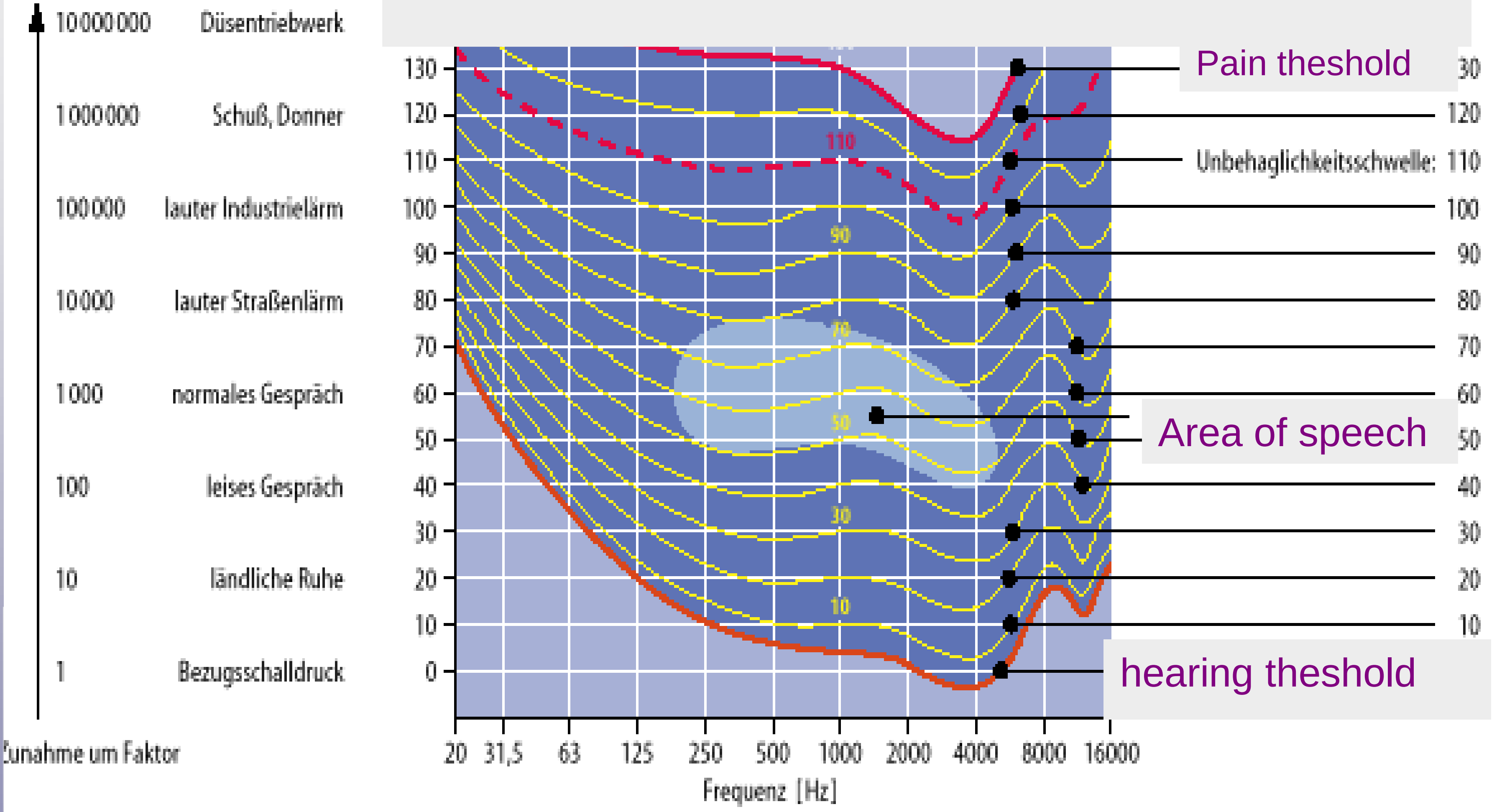
Noise

Noise: no characteristic frequency.

From: Prominade ‘Round the Cochlea
www.iurc.montp.inserm.fr/cric/audition/english/index.htm

Psychophysical Measurement

dB



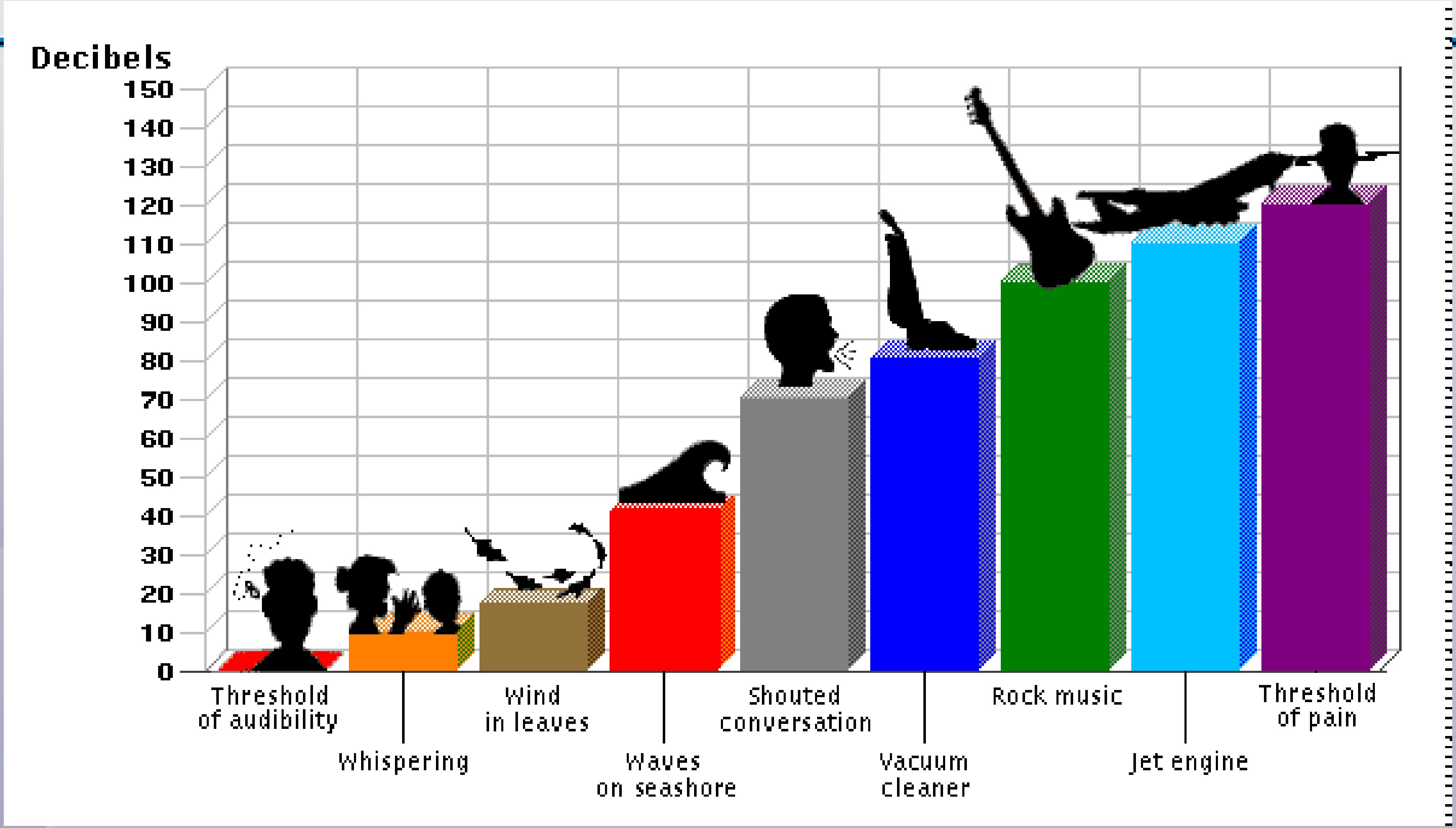
Pain theshold

Area of speech

hearing theshold

Equal loudness curves, unit (phons)

Sound Intensity



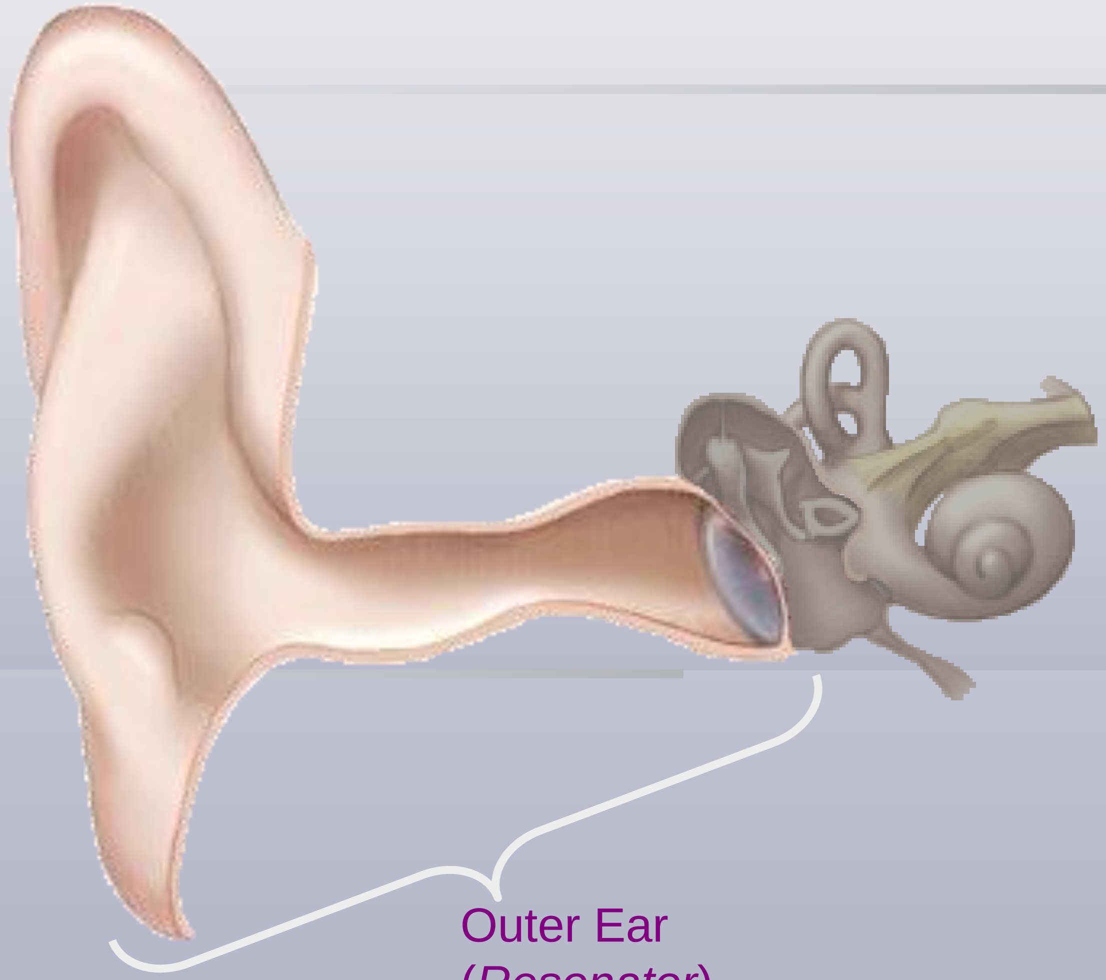
Divisions of the Ear

- Outer ear – pinna and auditory canal down to the tympanic membrane – directs sound waves to the hearing apparatus – highly developed in different species or not developed or modified in others
- Middle ear – 3 ossicles in an air-filled cavity connected to the oropharynx by the auditory tube – impedance matching between air and cochlear fluids – amplifies pressure by a factor of 20
- Inner ear – 3 fluid-filled coiled tubes in the petrous portion of the temporal bone (cochlea [Latin for snail])

Path of Sound

- External canal
- Vibrates eardrum
- Vibration moves though ossicles
  - Malleus, incus, stapes
- Stapes vibrates oval window of cochlea
- Creates pressure wave in the fluid inside

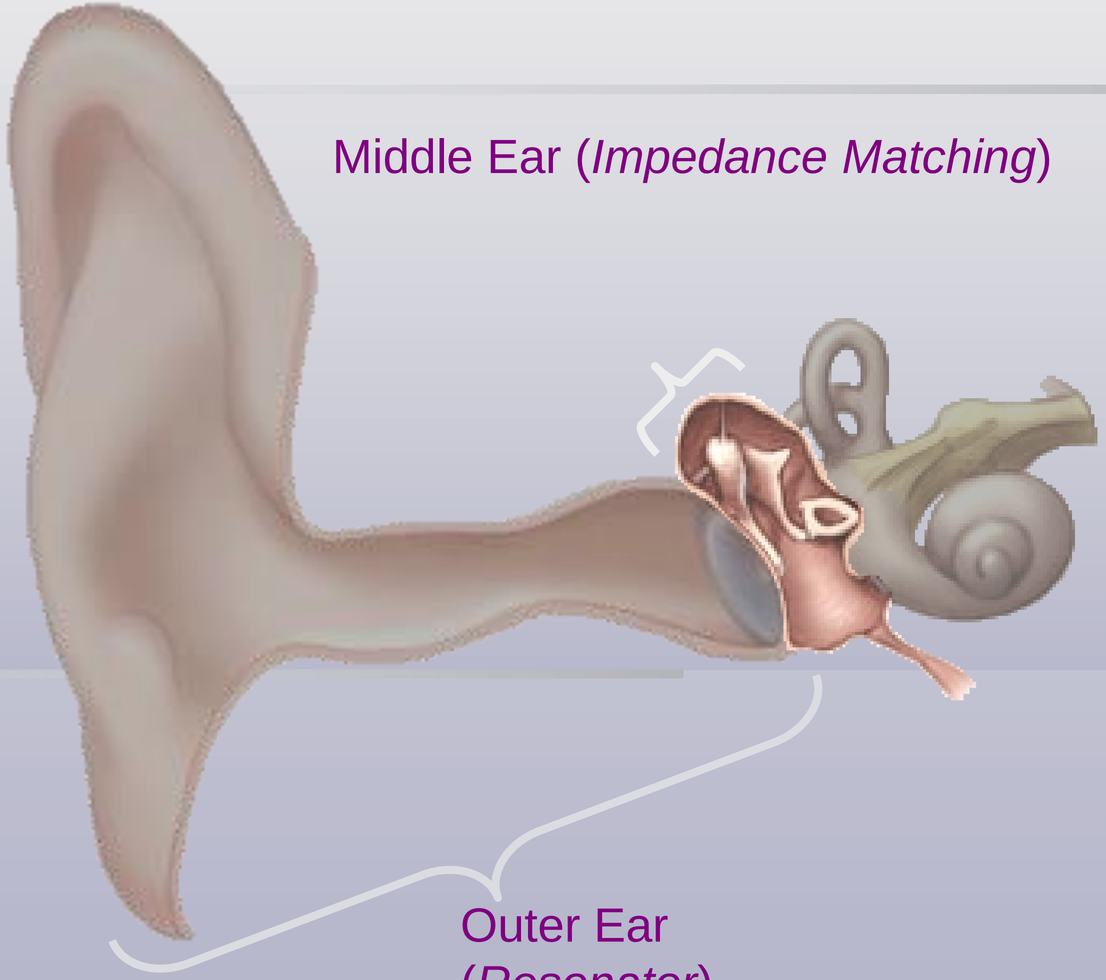
Ear anatomy and basic physics 1.



Outer Ear
(*Resonator*)

http://www.nidcd.nih.gov/StaticResources/health/hearing/images/normal_ear.asp

Ear anatomy and basic physics 2.

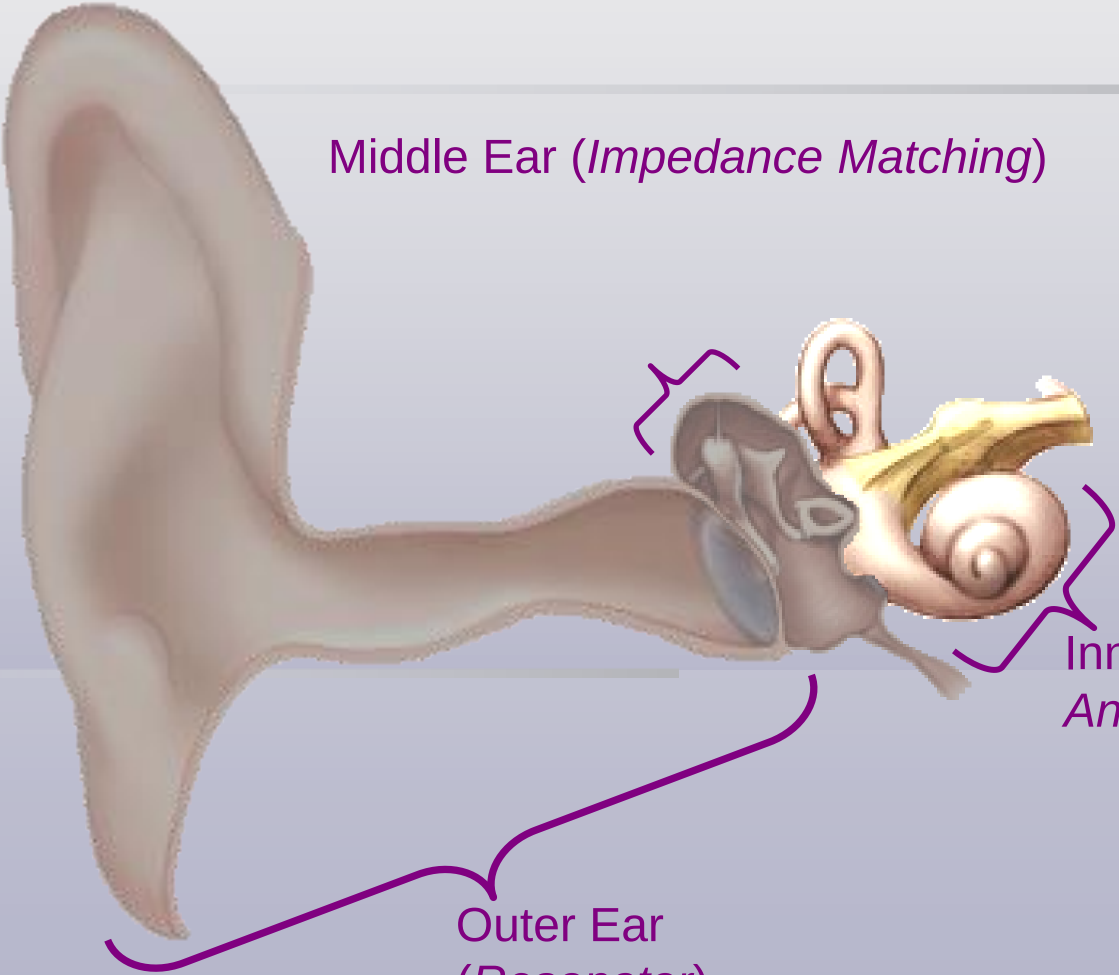


Middle Ear (*Impedance Matching*)

Outer Ear
(*Resonator*)

http://www.nidcd.nih.gov/StaticResources/health/hearing/images/normal_ear.asp

Ear anatomy and basic physics 3.



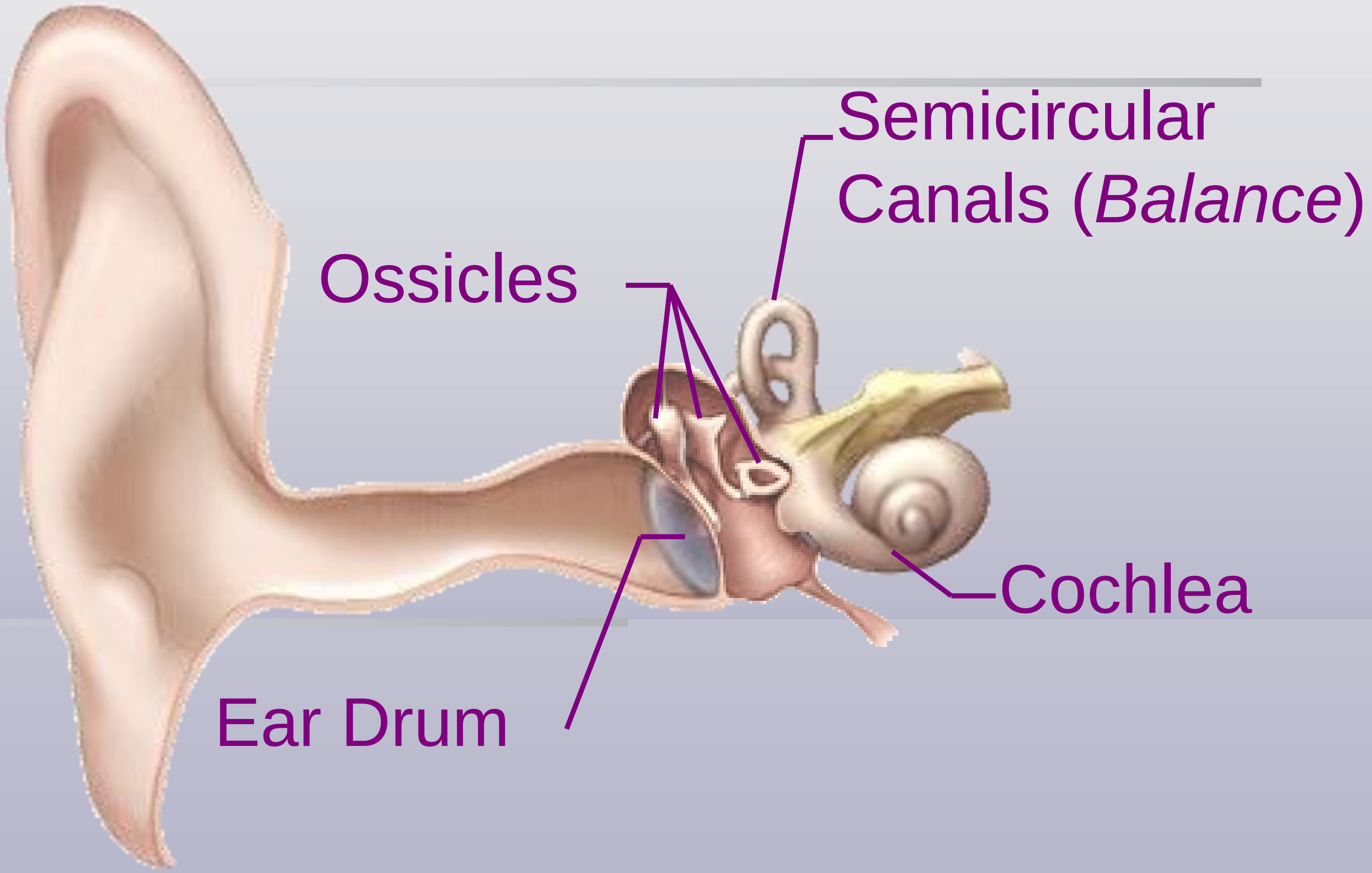
Middle Ear (*Impedance Matching*)

Inner Ear (*Fourier Analyzer*)

Outer Ear (*Resonator*)

http://www.nidcd.nih.gov/StaticResources/health/hearing/images/normal_ear.asp

Ear anatomy substructures

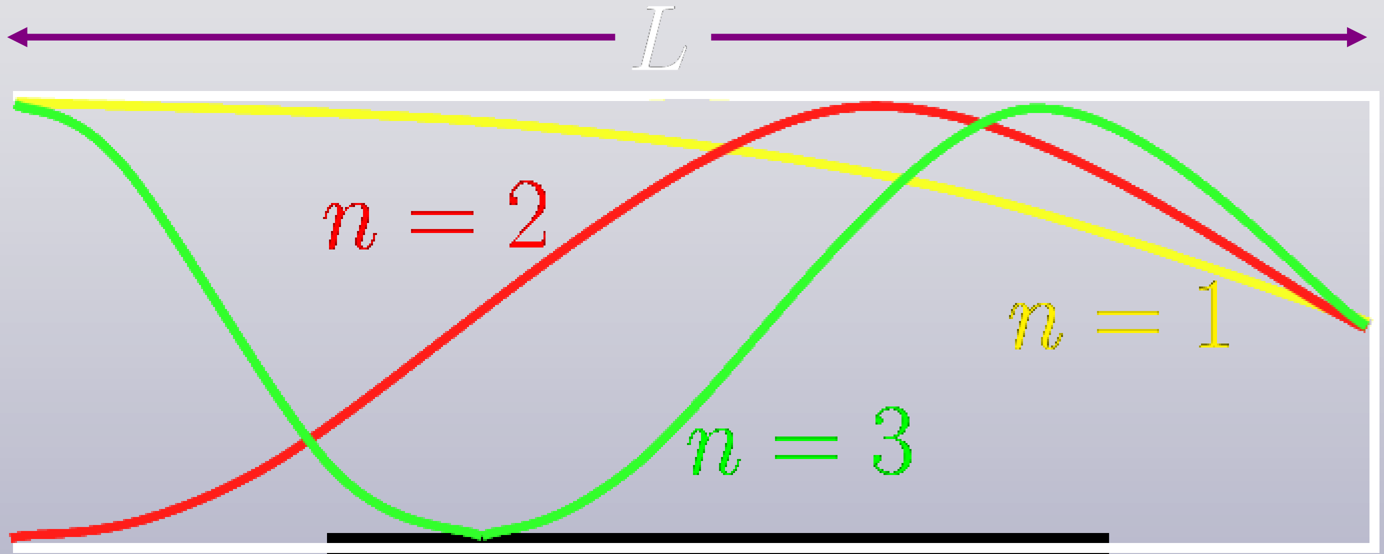


The outer ear

The human ear is most
responsive at about 3,000 Hz

Most speech occurs at
about 3,000 Hz

Partially closed pipe resonator model



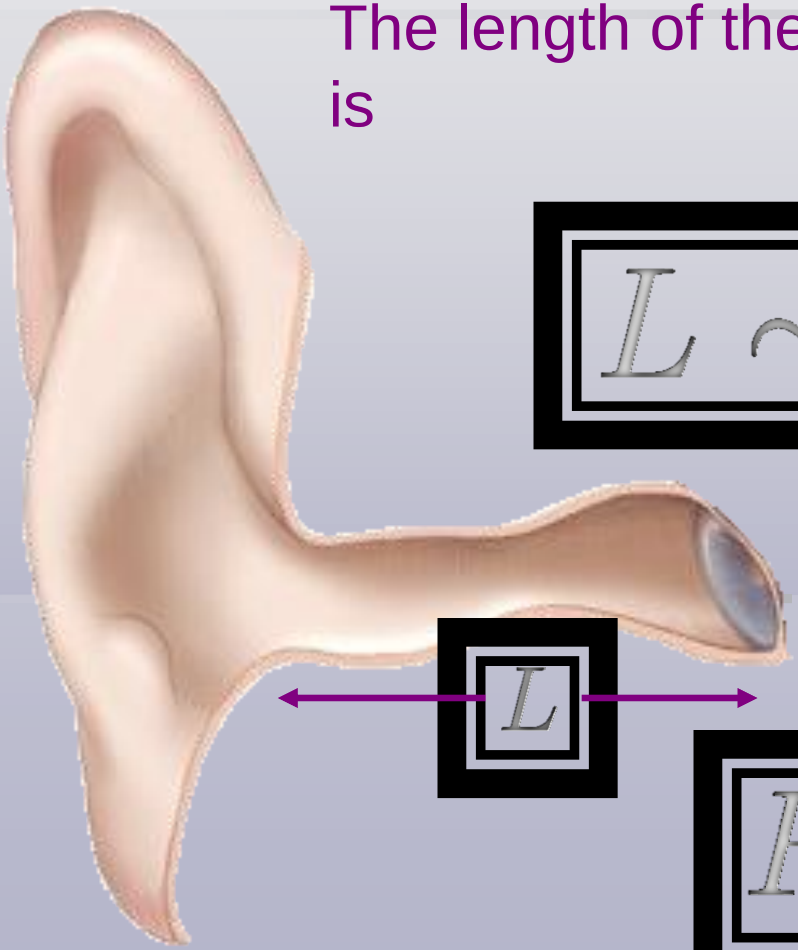
$$\boxed{F_n = \frac{nc}{4L}}$$

frequency

speed of sound

mode

Outer ear resonator



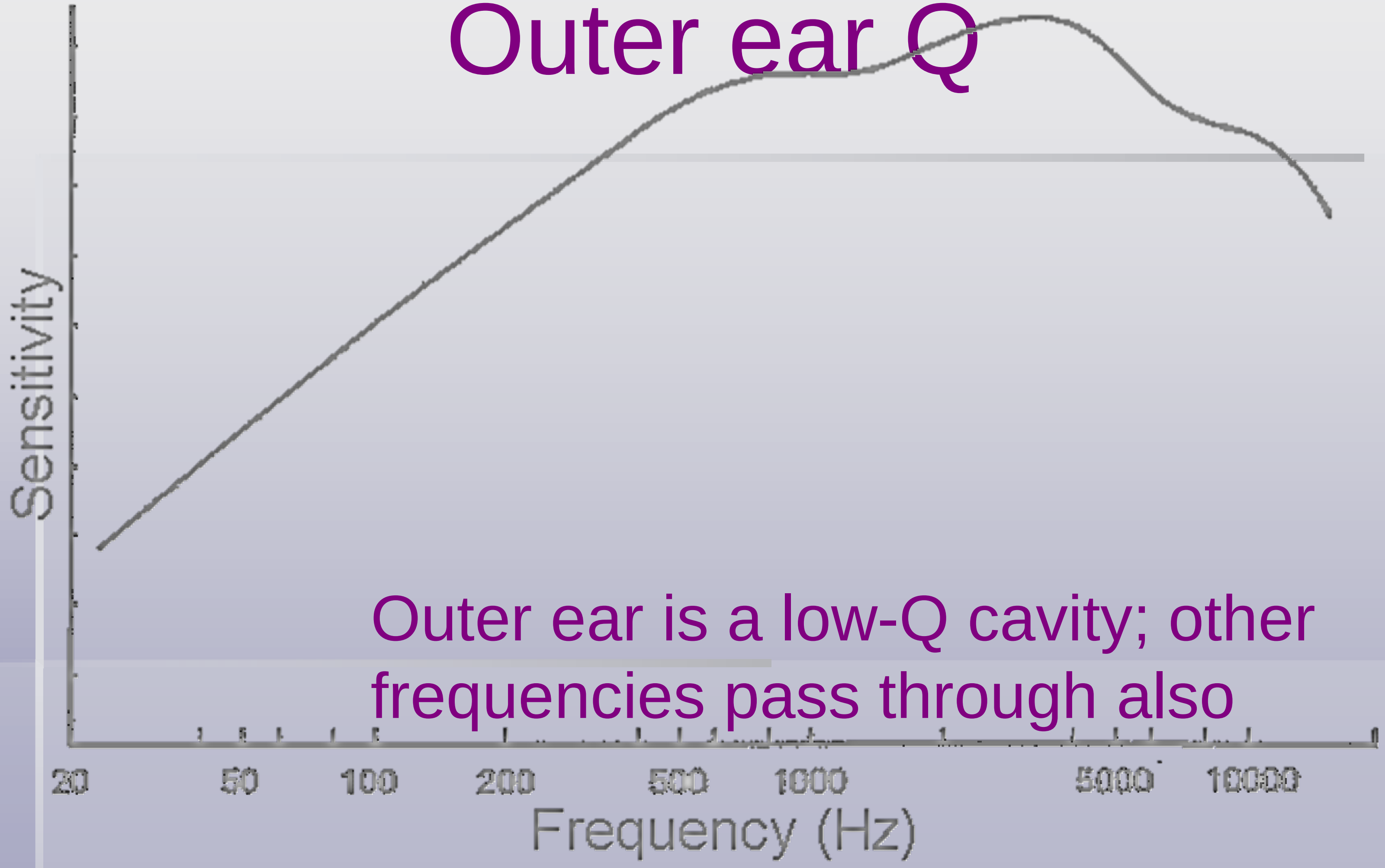
The length of the human auditory canal is

$$\boxed{L \sim 28mm}$$

This gives a fundamental mode of

$$\boxed{F_1 \sim 3000Hz}$$

Outer ear Q

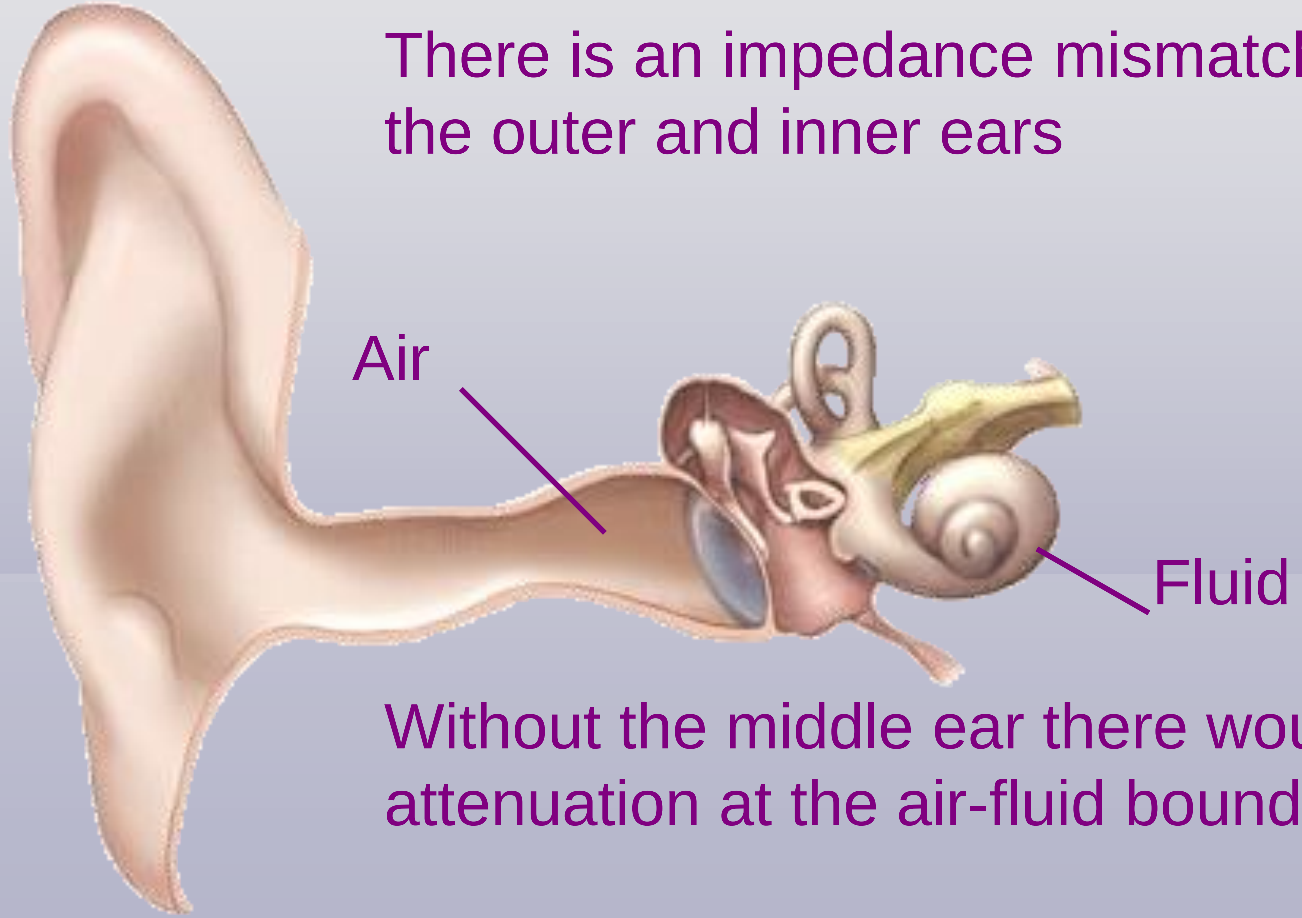


Outer ear is a low-Q cavity; other frequencies pass through also

W. J. Mullin, W. J. George, J. P. Mestre, and S. L. Velleman, *Fundamentals of sound with applications to speech and hearing* (Allyn and Bacon, Boston, 2003)

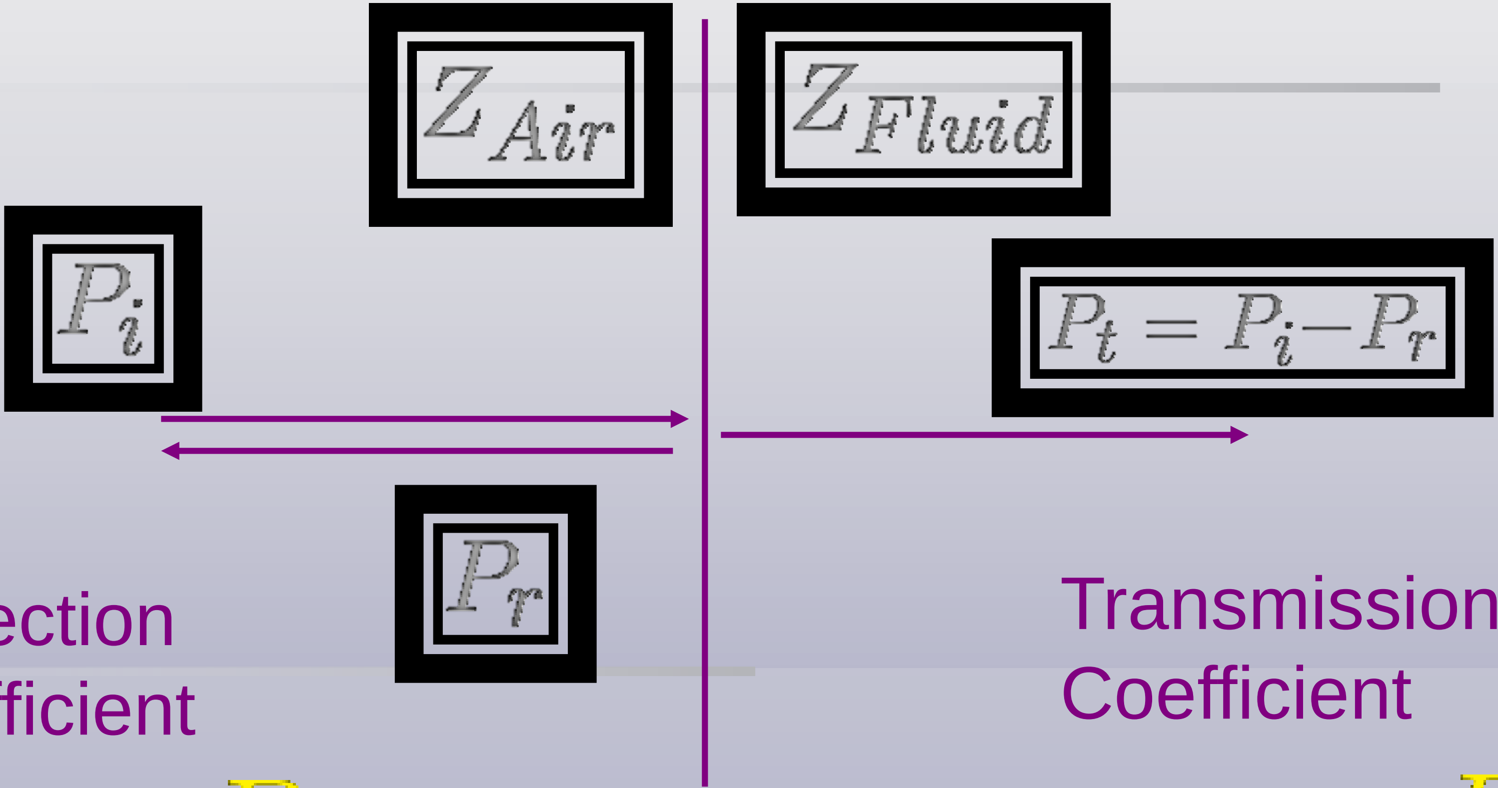
The middle ear

There is an impedance mismatch between the outer and inner ears



Without the middle ear there would be large attenuation at the air-fluid boundary

Transmission and reflection



Reflection Coefficient

$$R = \frac{P_r}{P_i}$$

Transmission Coefficient

$$T = \frac{P_t}{P_i}$$

D. T. Blackstock, *Fundamentals of Physical Acoustics* (Wiley, New York, 2000)

Power transmission

Doing some math gives the power transmission coefficient

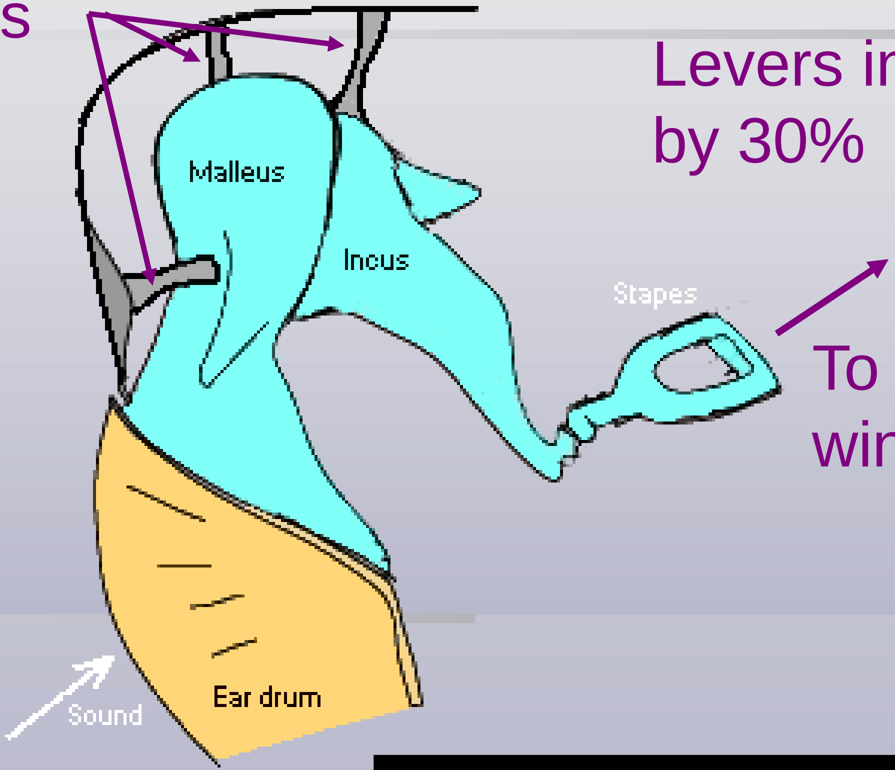
$$\tau = \frac{4Z_{Air}Z_{Fluid}}{(Z_{Fluid}+Z_{Air})^2}$$

Plugging in numbers gives the attenuation

$$\tau = 1\times10^{-3} \rightarrow -30dB$$

W. J. Mullin, W. J. George, J. P. Mestre, and S. L. Velleman, *Fundamentals of sound with applications to speech and hearing* (Allyn and Bacon, Boston, 2003)

Ossicles as levers



Ligaments act as fulcrums

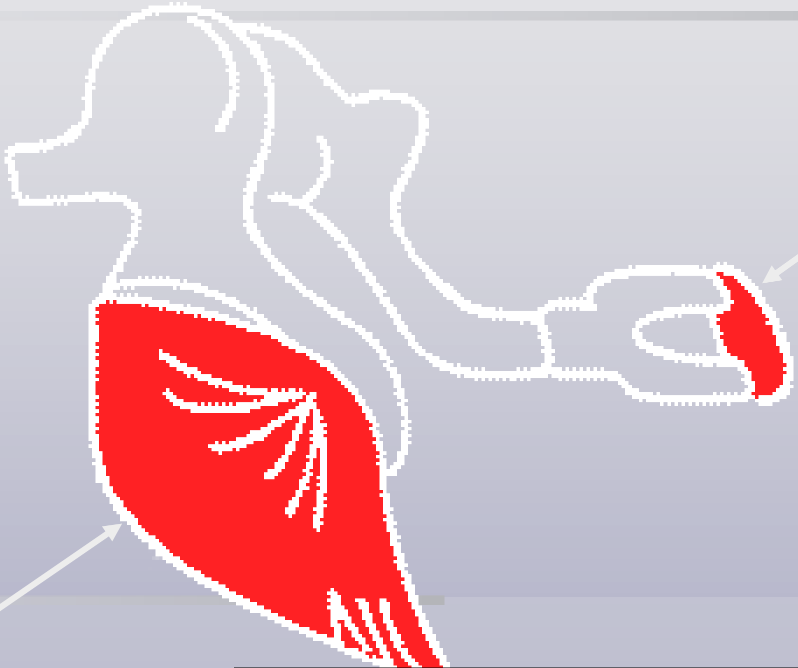
Levers increase force by 30%

To oval window

$$\boxed{F_{Oval} = 1.3 \times F_{Drum}}$$

http://hyperphysics.phy-astr.gsu.edu/hbase/sound/imgsou/oss3.gif

Stapes footprint



Oval window

Ear drum

$$\boxed{A_{Oval} = \frac{1}{19} A_{Drum}}$$

http://www.ssc.education.ed.ac.uk/courses/pictures/hearing8.gif

Impedance match

$$P_{Oval} = \frac{F_{Oval}}{A_{Oval}} = 1.3 \times 19 \frac{F_{Drum}}{A_{Drum}} = 25 P_{Drum}$$

Since

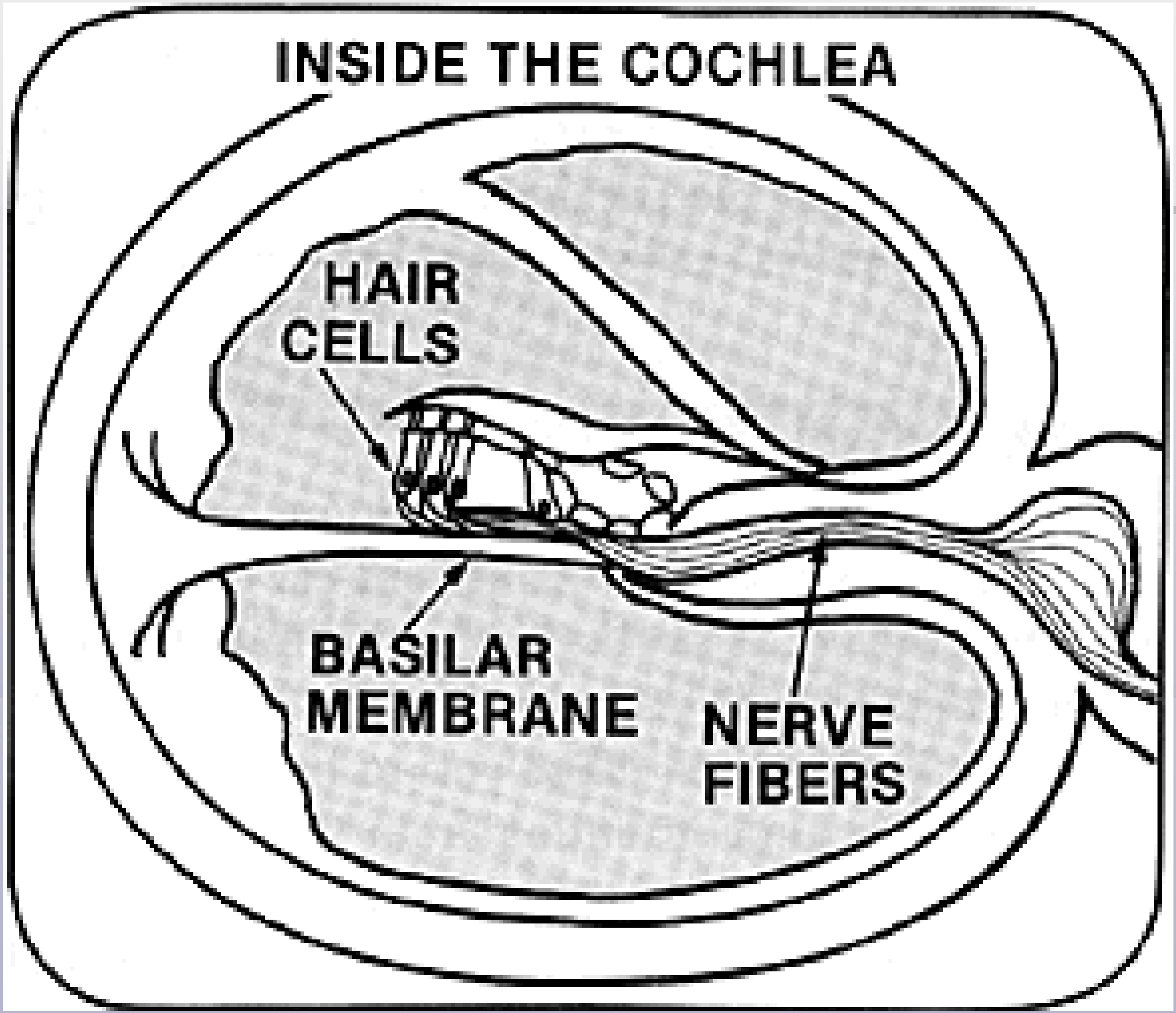
$$I \propto P^2$$

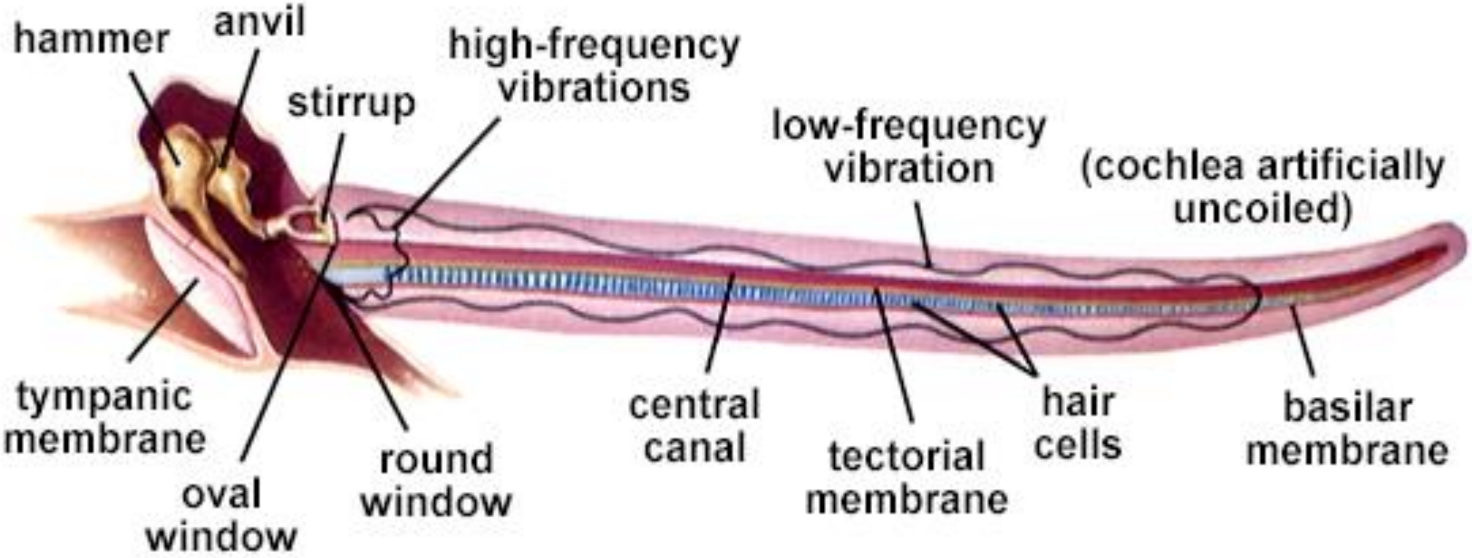
Sound intensity

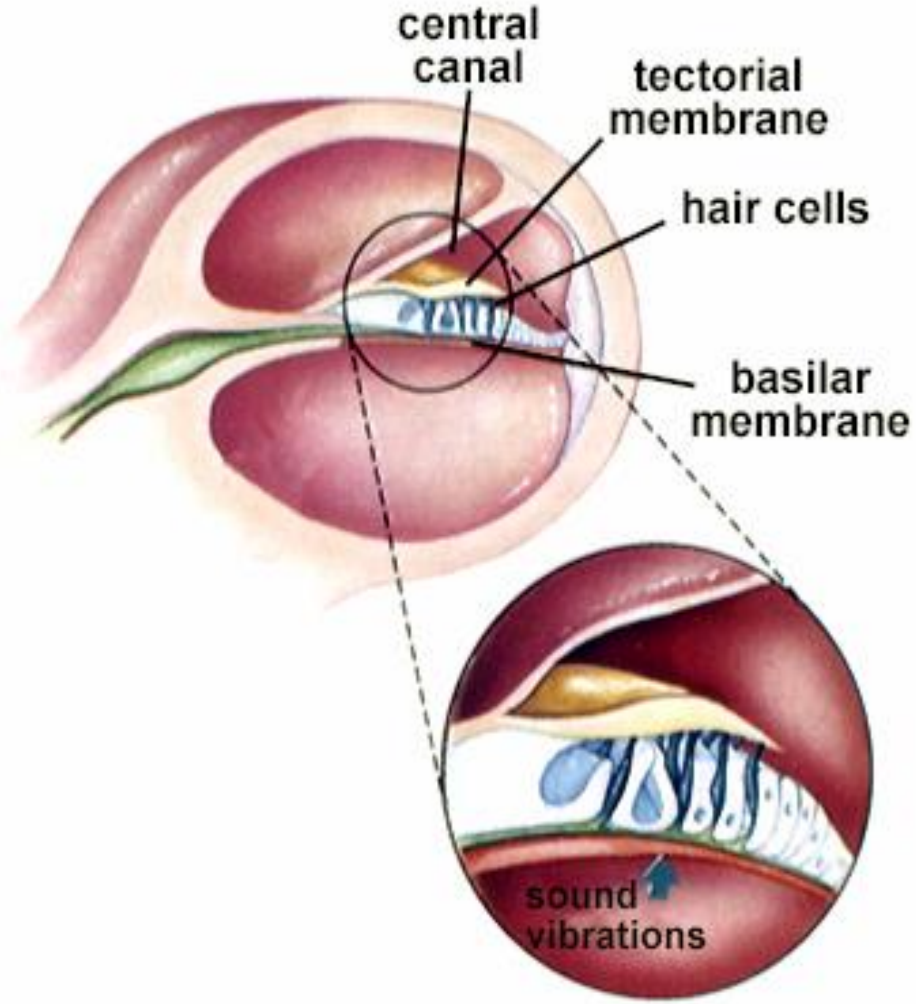
the sound intensity increases 625 times, or $28\ dB$

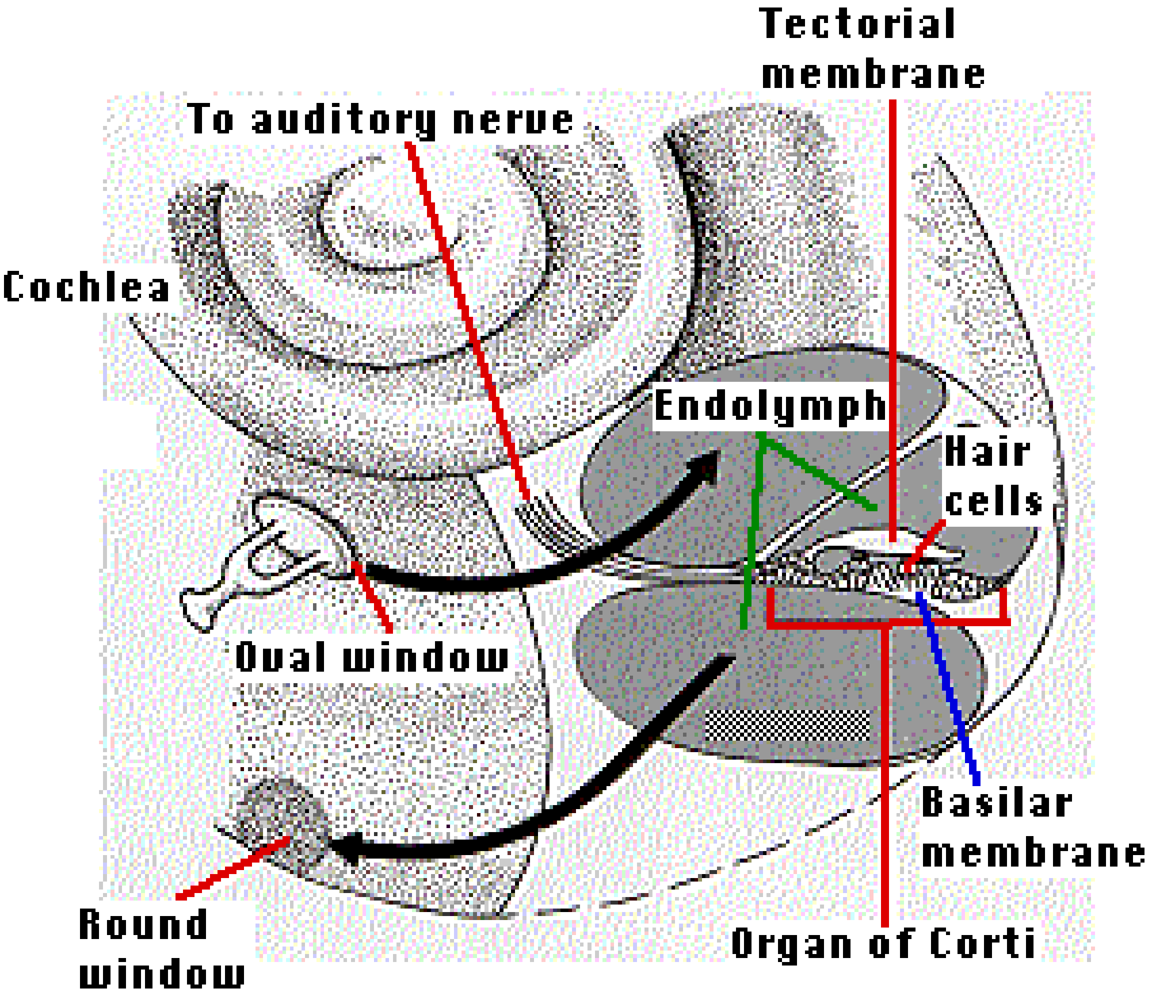
Pressure Transduction Through the Cochlear Fluids

- Vibrations are transmitted from the tympanic membrane to the cochlea by the ossicles
- The foot plate of the stapes deflects the membrane of the oval window (at the vestibule), causing fluid movement in the scala vestibuli
- Pressure changes are transmitted up the scala vestibuli to the apex and then back down the scala tympani to the round window
- The round window membrane deflects 180º out of phase with the oval window


INSIDE THE COCHLEA
HAIR CELLS
BASILAR MEMBRANE
NERVE FIBERS

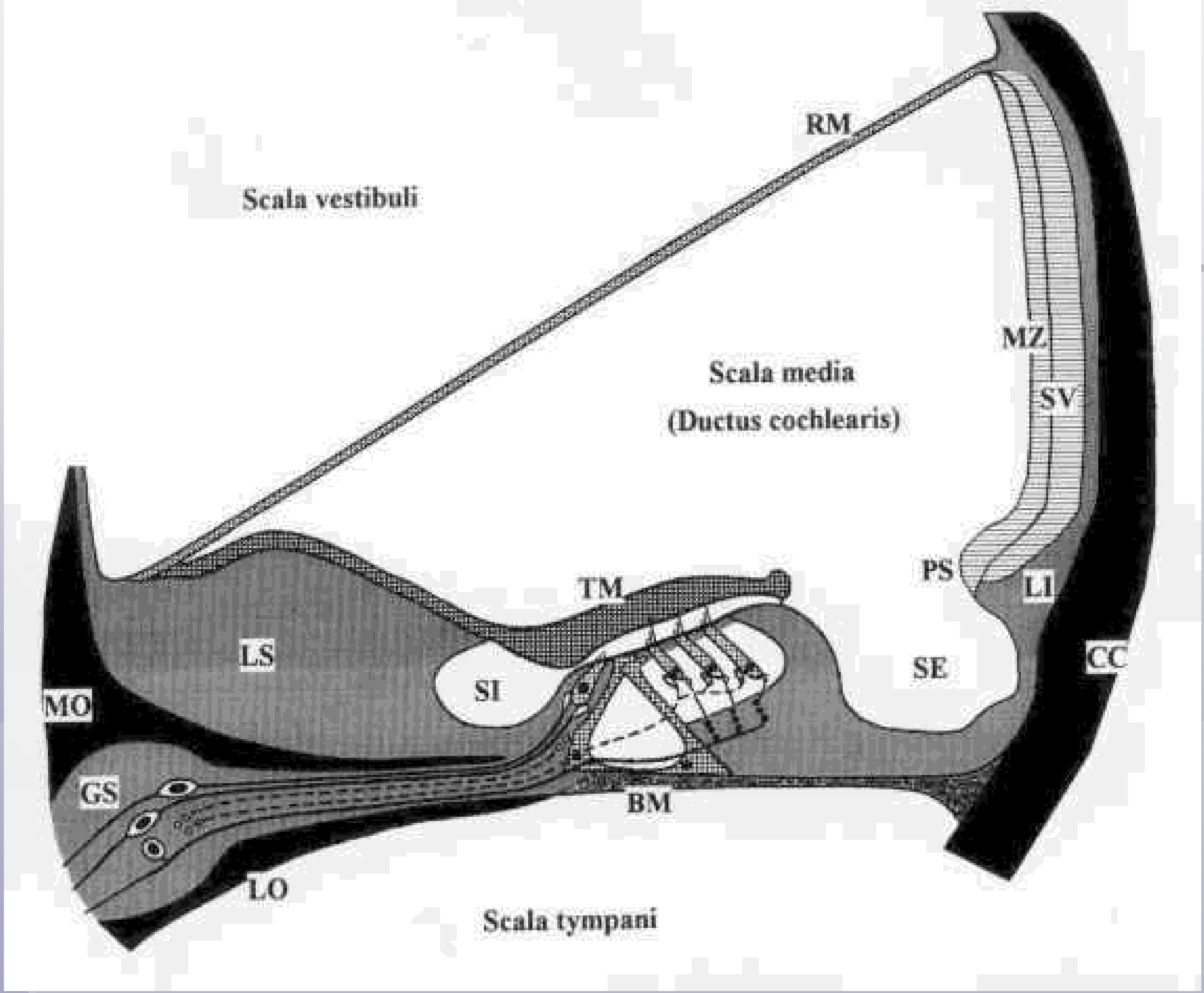

hammer
anvil
stirrup
high-frequency vibrations
low-frequency vibration
(cochlea artificially uncoiled)
tympanic membrane
oval window
round window
central canal
tectorial membrane
hair cells
basilar membrane

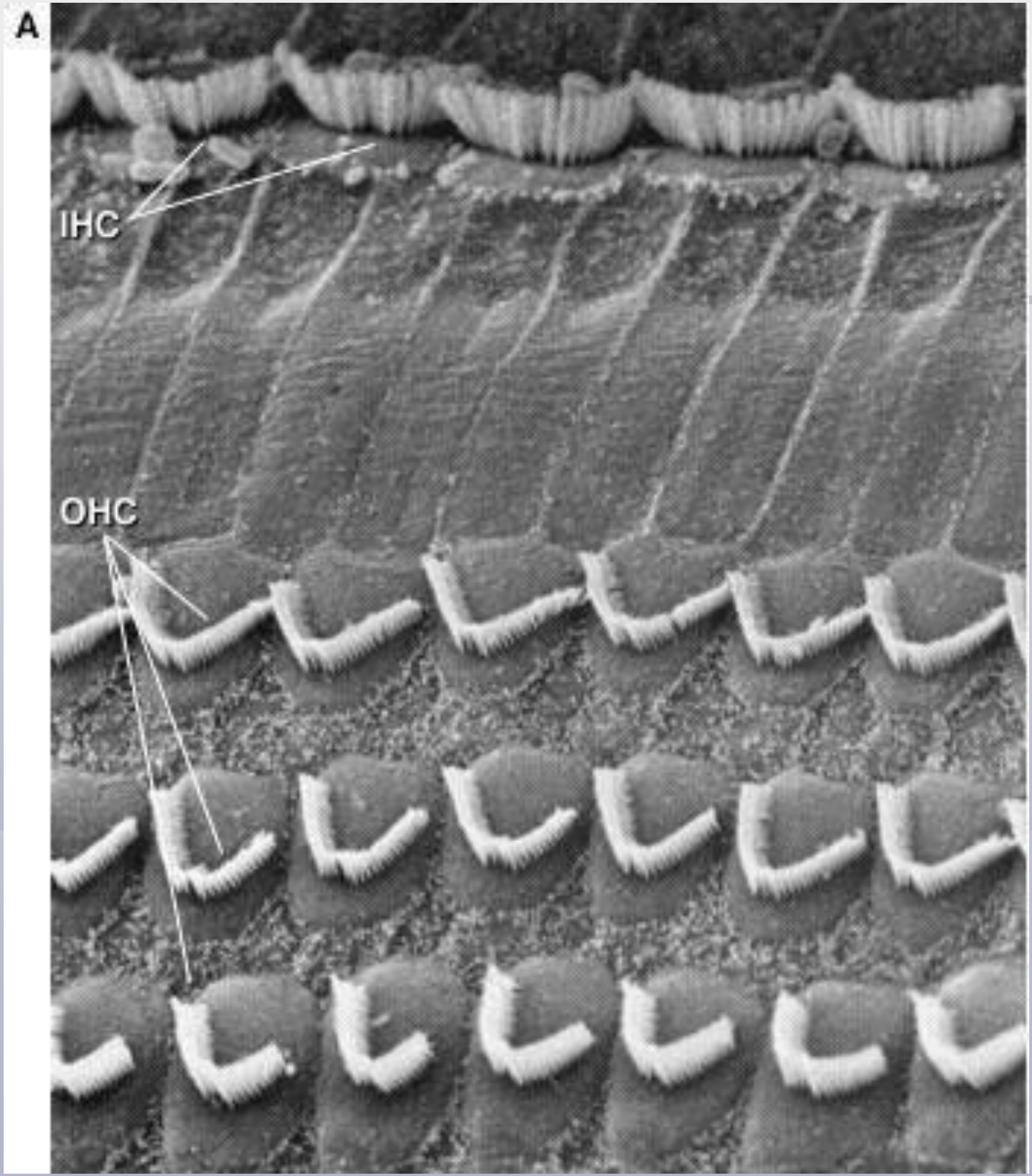

central canal
tectorial membrane
hair cells
basilar membrane
sound vibrations

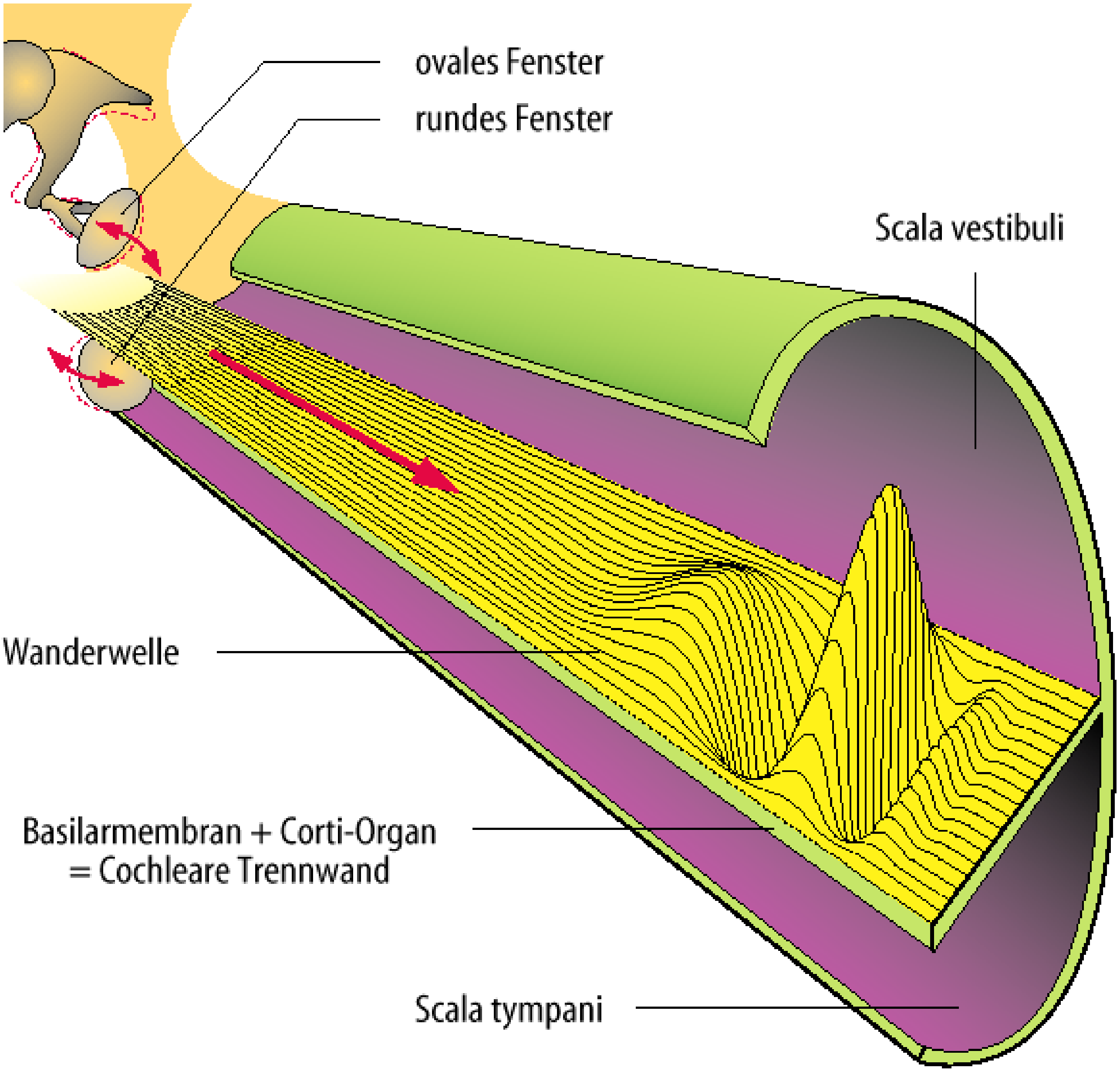

Tectorial membrane
To auditory nerve
Cochlea
Endolymph
Hair cells
Oval window
Basilar membrane
Round window
Organ of Corti

Cochlear Fluids

- **Scala tympani and scala vestibuli – perilymph – similar to CSF and extracellular fluid**
  - **Low K^+ (7mM) and high Na^+ (140mM)**
- **Scala media – endolymph – similar to intracellular fluid**
  - **High K^+ (150mM) and low Na^+ (1mM)**
- **Stria vascularis (on the outer margin of the scala media) actively resorbs sodium and secretes potassium against their concentration gradients; important target for causing deafness**


RM
Scala vestibuli
MZ
Scala media
(Ductus cochlearis)
SV
PS
TM
LI
LS
SE
CC
SI
MO
GS
BM
LO
Scala tympani


A
IHC
OHC



ovales Fenster

rundes Fenster

Scala vestibuli

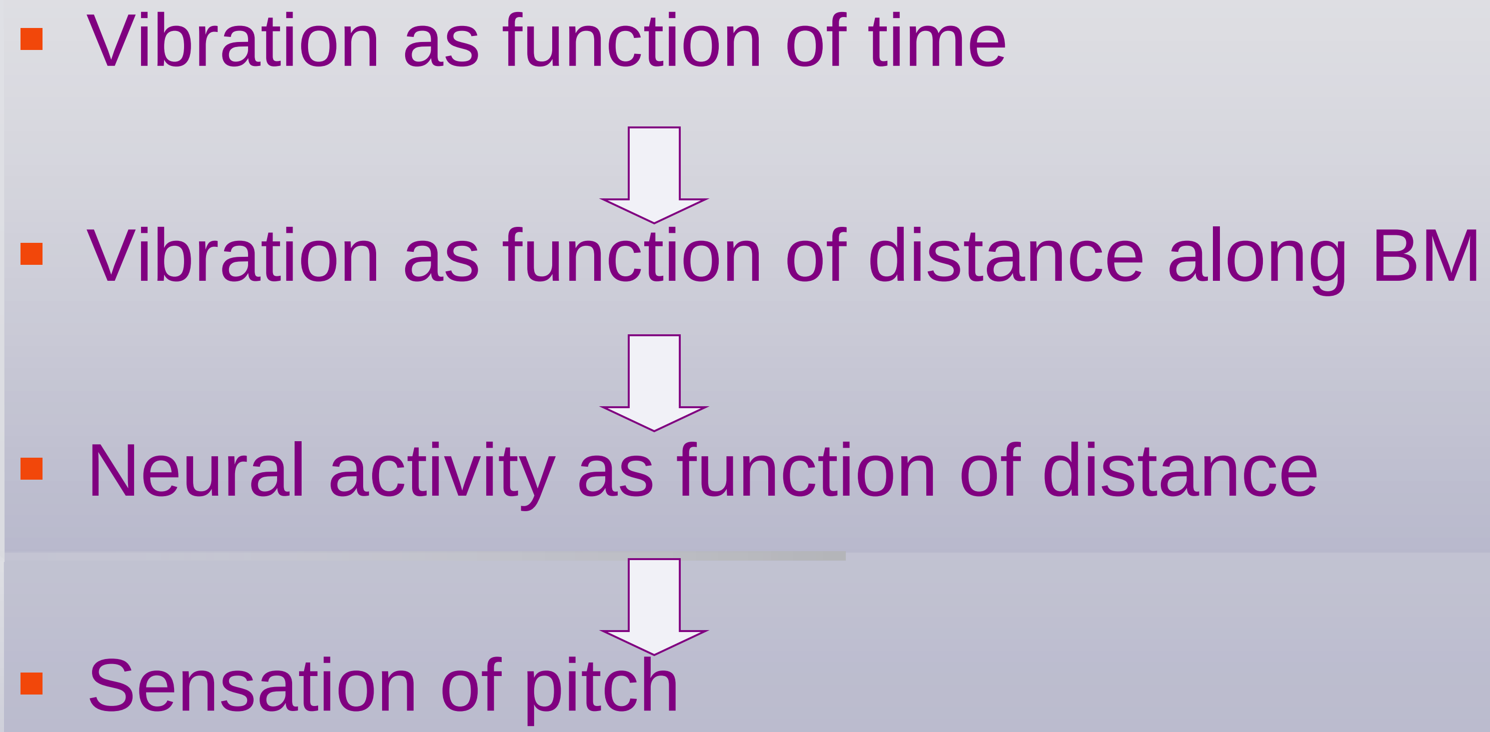
Wanderwelle

Basilarmembran + Corti-Organ
= Cochleare Trennwand

Scala tympani

Abb. 15-14 aus Schmidt/Thews: Physiologie des Menschen 27. Auflage 1997

Place Theory



- Vibration as function of time
- Vibration as function of distance along BM
- Neural activity as function of distance
- Sensation of pitch

The Nobel Prize in Physiology or Medicine 1961

"for his discoveries of the physical mechanism

of stimulation within the cochlea"