- Hearing
  - 100 times greater dynamic range than vision.
  - Wide frequency range (20 ~ 20,000 Hz).
- Sense of hearing
  - Mechanical system that stimulates the hair cells in the cochlea.
  - Sensors that produce action potentials in the auditory nerves.
  - Auditory cortex in the brain.
- Ear: conversion of weak mechanical waves in air into electrical pulses in the auditory nerve (Fig.1).
  - Outer ear: ear canal and eardrum (tympanic membrane).
  - Middle ear: three small bones (ossicles) and Eustachian tube.
  - Inner ear: cochlea (hair cells in the organ of Corti in the cochlea).
- Medical specialists
  - Otologist, MD: disease of the ear and ear surgery.
  - Otorhinolaryngologist or ENT specialist, MD: disease of the ear, nose, and Throat
  - Audiologist, non-MD: measuring hearing response, diagnosing hearing disorders, hearing aids.

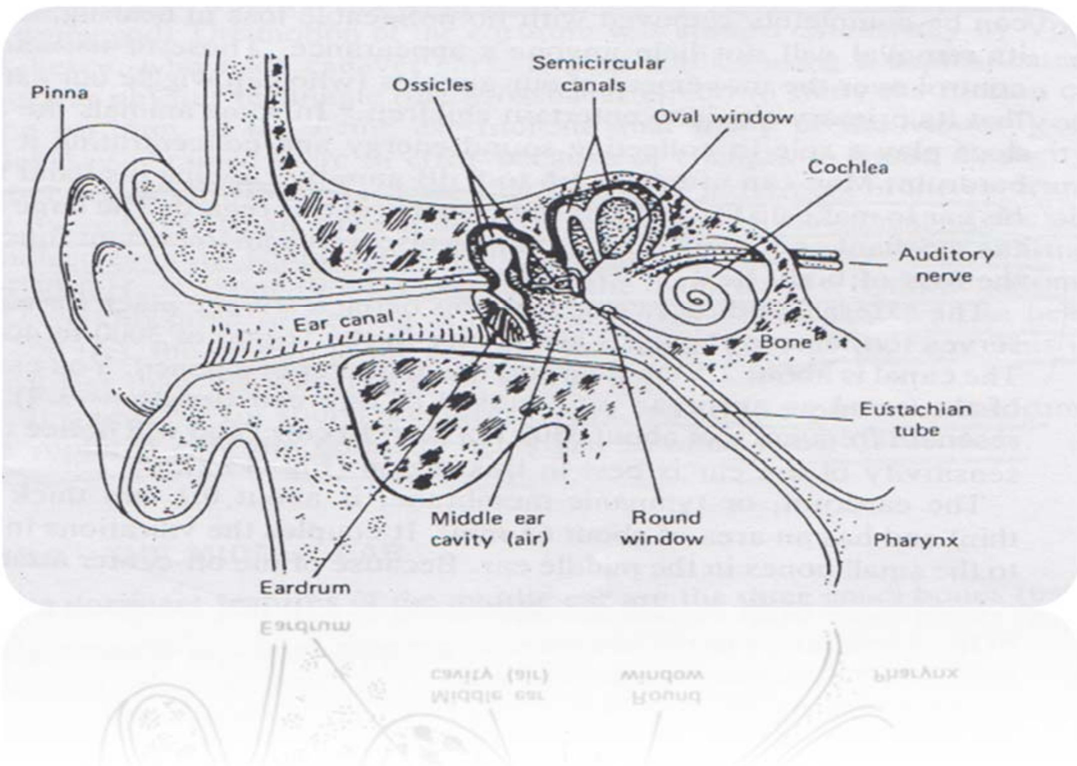

Figure 1: cross section of the ear.

1. The Outer Ear

- External auricle or pinna: not a part of the outer ear.

  Negligible effect on hearing, man can often get a 6 to 8 dB gain by cupping his hand behind his ear.

- External auditory canal
  - Storage of ear wax.
  - 2.5 cm long with the diameter of a pencil (λ/4 =length).
  - Increase the sensitivity of the ear in the region of 3000 ~ 4000 Hz.
  - Resonant frequency of 3300 Hz (λ = 10 cm): Fig.2.

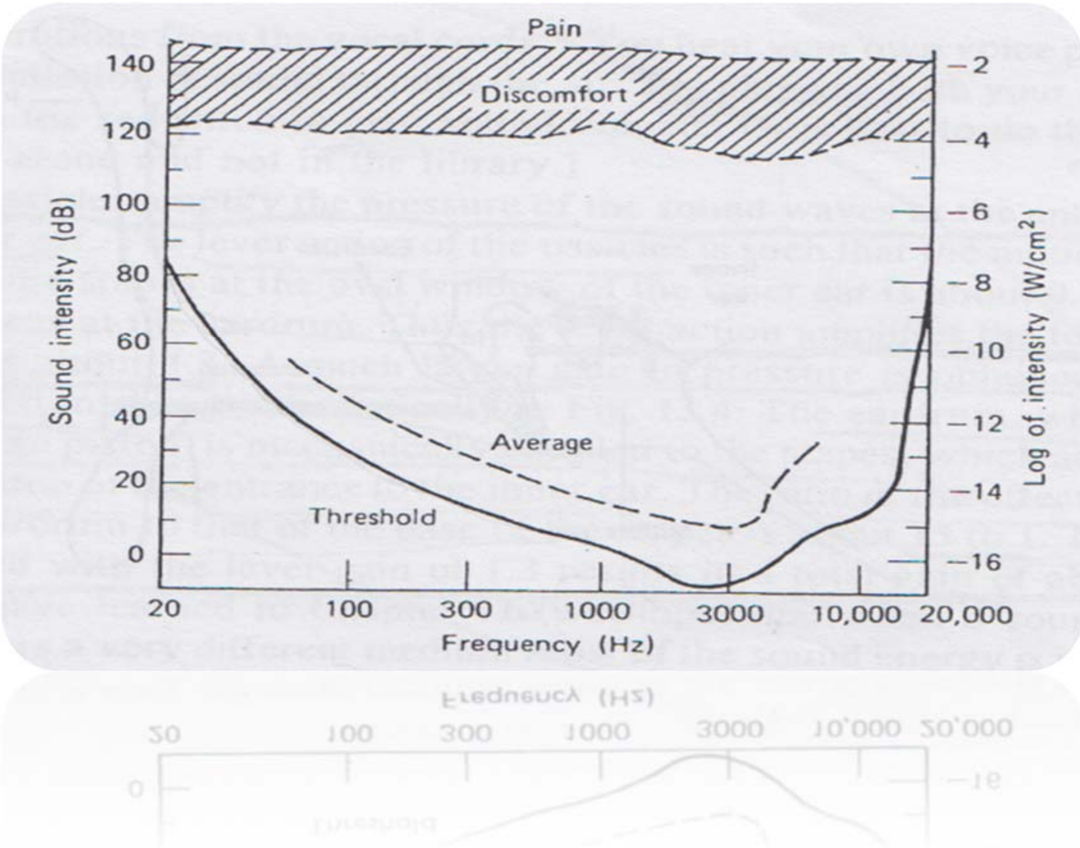

Figure 2: The sensitivity of the ear. The solid curve is the threshold of hearing for a young person with good hearing. Zero decibels occurs at 1000 Hz. The average curve is the average threshold for all people, young and old .Both axes –horizontal and vertical-are logarithmic scales.

- Eardrum or tympanic membrane

-0.1 mm thick (paper-thin) and has an area of about 65 mm^2.
-Couples the vibrations in the air to ossicles.
- The eardrum does not vibrate symmetrically like a drumhead (Fig.1).
-It is clear that the actual movement of the eardrum is exceedingly small since it must be less than the movement of the air molecules in the sound wave. This movement at the threshold of hearing at 3000Hz is about10^{-9}cm less than the diameter of a hydrogen atom. At the threshold of hearing at the lowest frequencies that we can hear 20 Hz, the motion of the eardrum may be as large as 10^{-5}cm. This is still less than the wavelength of visible light.
- Sound pressure over 160 dB rupture the eardrum.
- Ruptured eardrum normally heals like other living tissues.

2. The Middle Ear

Three small bones or ossicles (Fig.1): full adult size before birth, fetus can hear in the womb.

- Ossicles

-The ossicles play an important role in matching the impedance of the sound waves at the eardrum to the liquid-filled chamber of the inner ear.
- Malleus (hammer), incus (anvil), stapes (stirrup).

The ossicles amplify the pressure of the sound waves at the entrance to the inner ear. The lever action amplifies the force by a factor of about 1.3. A much larger gain in pressure is obtained by the piston action. The eardrum, which acts like a large piston, is mechanically coupled to the stapes, which acts like a small piston at the entrance to the inner ear. The ratio of the effective area of the eardrum to that of the base of the stapes is about 15 to 1. This gain combined with the lever gain of 1.3 results in a total gain of about 20.
The ossicles and their sensory ligaments play an important role in protecting the ear against loud sounds. A decrease of 15 dB is possible by this means.it takes about 15msec or longer for these muscles to react and damage may be done in this brief period. Persons living or working in an environment of loud sounds permanently lose some of their hearing sensitivity. Noise pollution can result in permanent physiological damage to the hearing mechanism.

- Eustachian tube

It plays a protective role, which leads down toward the mouth. It is normally closed. The middle ear contains air, and it is important for the air pressures on both sides of the thin eardrum to be essentially the same, The Eustachian tube serves to equalize the pressure. The movement of the muscles in the face during swallowing, yawning, or chewing will usually cause a momentary opening of the Eustachian tube that equalizes the pressure in the middle ear with the atmospheric pressure. Rapid pressure change causes pressure difference across the eardrum in a short period, such as when flying, riding in hilly country, or riding in the elevator of a tall building. when for some reason the Eustachian tube does not open , the resulting pressure difference deflects the eardrum inward and decreases the sensitivity of the ear, at about 60 mm Hg across the eardrum , The pressure difference causes pain. Common reasons for the failure of this equalizing system are the blockage of the Eustachian tube by the viscous fluids from a head cold and the swelling of tissues around the entrance to the tube.

3. The Inner Ear

The inner ear, hidden deep within the hard bone of the skull. Is man's best-protected sense organ. The inner ear consists of a small spiral shaped, fluid filled structure called the ***cochlea***. The ossicles of the middle ear communicate with the cochlea via a flexible membrane the ***oval window***; the stapes transmits its pressure variations of incoming sound waves across this membrane to the cochlea. The cochlea communicates with the brain via the ***auditory nerve***- a bundle of about 8000 conductors that inform the brain via coded electrical pulses which parts of the cochlea are being stimulated by incoming sound waves. The auditory nerve provides information on both the frequency and the intensity of the sounds that we hear.
The cochlea is about the size of the tip of the little finger. If its spiral were straightened out, the cochlea would be about 3 cm (~1.25 in.)Long. It is divided into three small fluid-filled chambers that run its full length. The oval window is on the end of the ***vestibular chamber***, the middle chamber is the ***cochlear duct***, and the third chamber is the ***tympanic chamber*** (fig.3).
The vestibular and tympanic chambers are interconnected at the tip of the spiral. Pressure produced at the oval window by the stapes is transmitted via the vestibular chamber to the end of the spiral and then returns via the tympanic chamber. Since fluid is almost incompressible, the cochlea needs a "relief valve"; the flexible ***round window*** at the end of the tympanic chamber serves this purpose (fig.1).
A sound wave entering at 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. The motions of this membrane are about 10 times smaller in amplitude than the motions of the eardrum. Stimulation of nerves in the cochlear duct near the oval window indicates high-frequency sounds. Low frequency sounds Cause "large" motions in the basilar membrane and stimulation of nerves in the cochlear duct near the tip of the spiral.

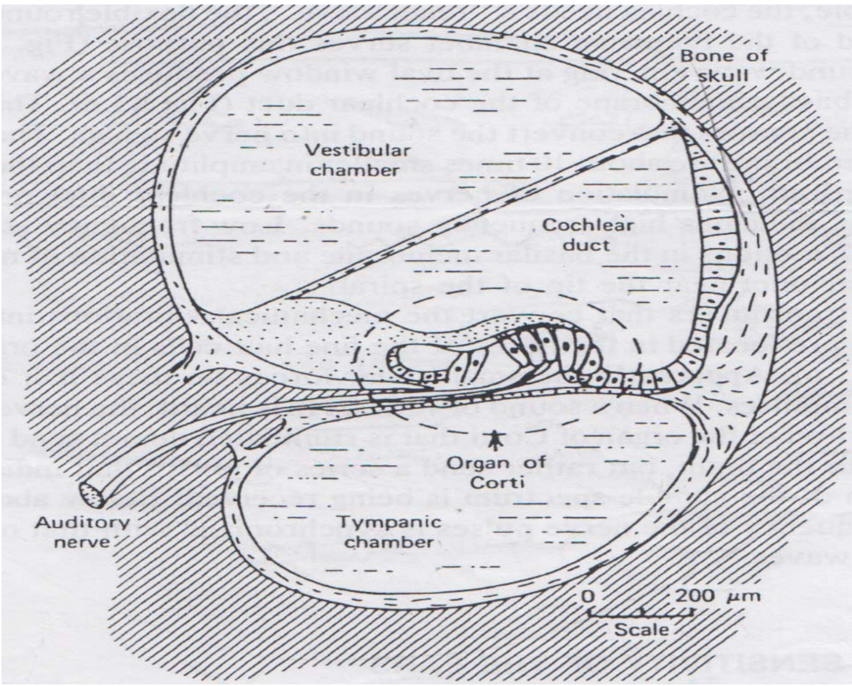

Figure 3 : The chambers of the cochlea.

The transducers that convert the mechanical vibrations into electrical signals are located in the bases of the fine hair cells in the organ of Corti.
Apparently the small shear forces on these hair cells induce nerve impulses. When a sound of 10,000 Hz is heard, the nerves located in the portion of the organ of Corti that is stimulated do not send a 10,000 Hz signal to the brain, but rather send a series of pulses that indicates which portion of the audible spectrum is being received. Below about 1000 Hz, the frequency of the nerve pulses is synchronized with that of sinusoidal sound waves.

4. Sensitivity of the Ear

-The ear is not uniform over 20 ~ 20,000 Hz**.**

-Most sensitive range: 2 ~ 5 kHz (Fig.2).

The ***average*** line shows the levels at which half the people tested will detect the sounds. Notice that even a good ear needs about 30 dB more intensity to detect a sound at 100 Hz than to detect one at 1000 Hz.
Sensitivity changes with age. The highest frequency you can hear will decrease as you get older. A person 45 years old typically cannot hear frequencies above 12 kHz and needs about 10 dB more intensity than he did at age 20 to be able

to hear a 4000 Hz note. A 25 dB loss in sensitivity in the frequencies above 2000 Hz usually has occurred by age 65. Hearing deteriorates more rapidly if the ears are subjected to continuous loud sounds.
Such as: [People who play in rock bands, Factory workers] measurable losses in hearing.
The property of sound we call ***loudness*** is a mental response to the physical property called ***intensity***. The loudness of a sound is roughly proportional to the logarithm of its intensity and this effectively compresses the huge range of sound intensities to which the ear responds ($\sim 10^{-12}:1$).In addition, and the loudness of a sound depends strongly on its frequency. A sound of 30 Hz that is barely audible has the same loudness as a barely audible sound of 4000 Hz, even though their intensities differ by a factor of about 1,000,000, or 60 dB. The unit of loudness the ***phone.*** One phon is the loudness of a 1 dB, 1000Hz sound; 10 phones is the loudness of a 10 dB, 1000 Hz sound.

H.W: **How does the normal ear respond to different frequencies?**