MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

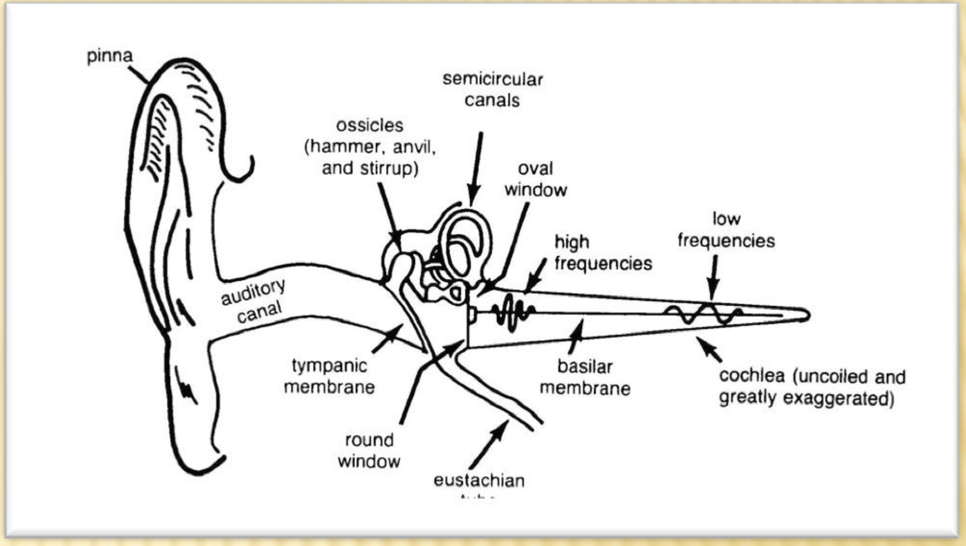
DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 11

THE PHYSICS OF HEARING

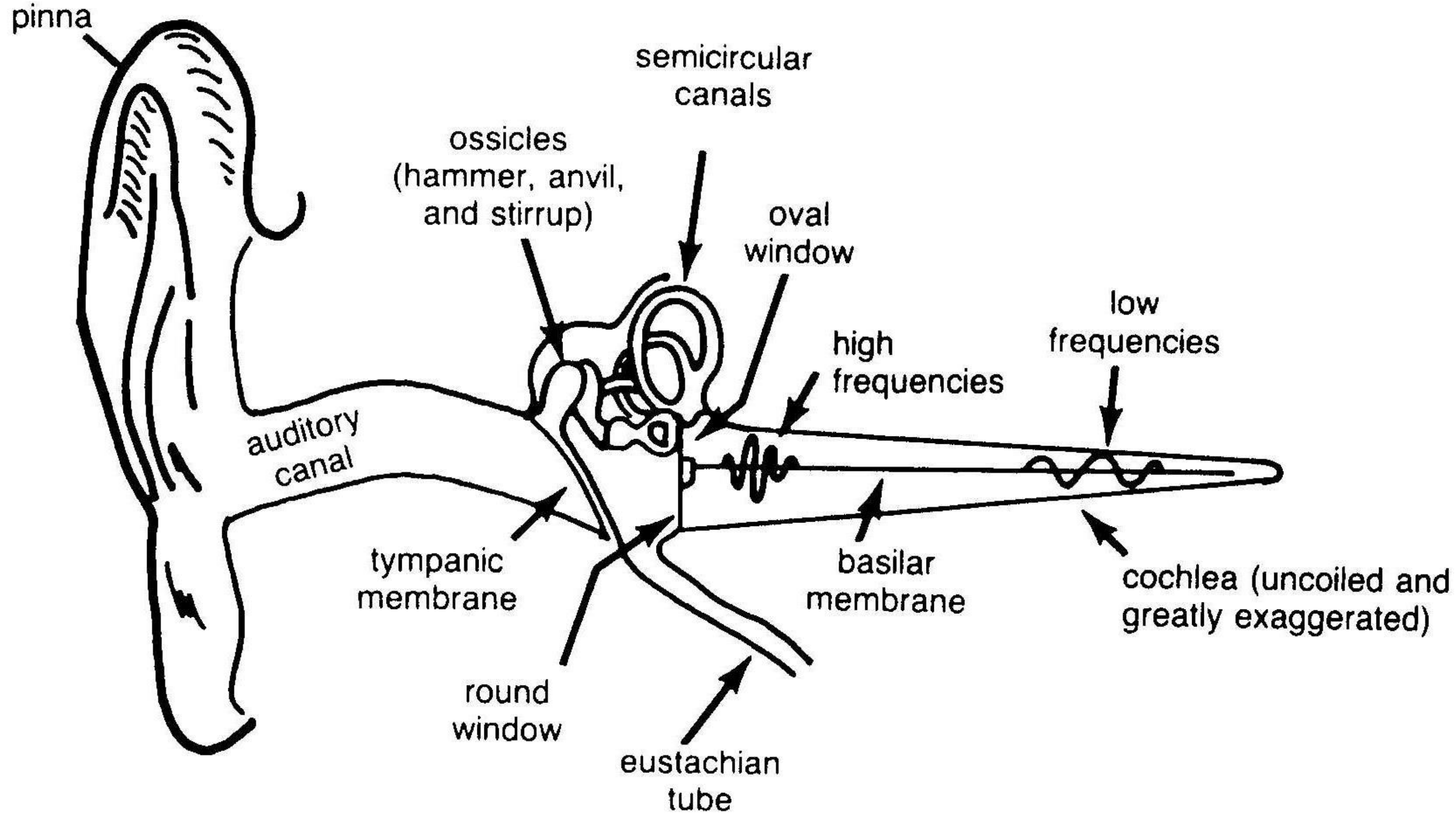
The mechanism of the ear. The range and sensitivity of human hearing. The decibel scale. The distinction between loudness and intensity. Hearing tests. The measurement of environmental sound

The acoustical function of the pinna is based upon the fact that the sound energy received is proportional to the area of the wave front intercepted.



Although the effectiveness of the human pinna is minimal, it tends to concentrate more sound energy into the auditory canal.

In the optimum frequency range (2 - 5.5 kHz), this focusing effect plus the resonance of the auditory canal achieves an amplification of about two.


pinna
semicircular canals
ossicles (hammer, anvil, and stirrup)
oval window
low frequencies
high frequencies
auditory canal
tympanic membrane
basilar membrane
cochlea (uncoiled and greatly exaggerated)
round window
eustachian tube

The oval window could receive sound energy directly in the absence of the other structures, but the tympanic membrane and ossicles act as amplifiers to increase the effectiveness of reception.

Primary function of the tympanic membrane (eardrum) - to increase the effective receiving area.

Since the eardrum is 15 to 30 times as large as the oval window, it receives 15 to 30 times as much sound as would the oval window alone.

This high amplification can be reduced to protect the ear against very loud sounds. A sound of sufficient loudness will trigger a set of muscles that tighten the eardrum and lessen its responsiveness to the sound.

A large fraction of the energy received by the eardrum is passed to the oval window by the set of three small bones known as the ossicles (hammer, anvil, and stirrup).

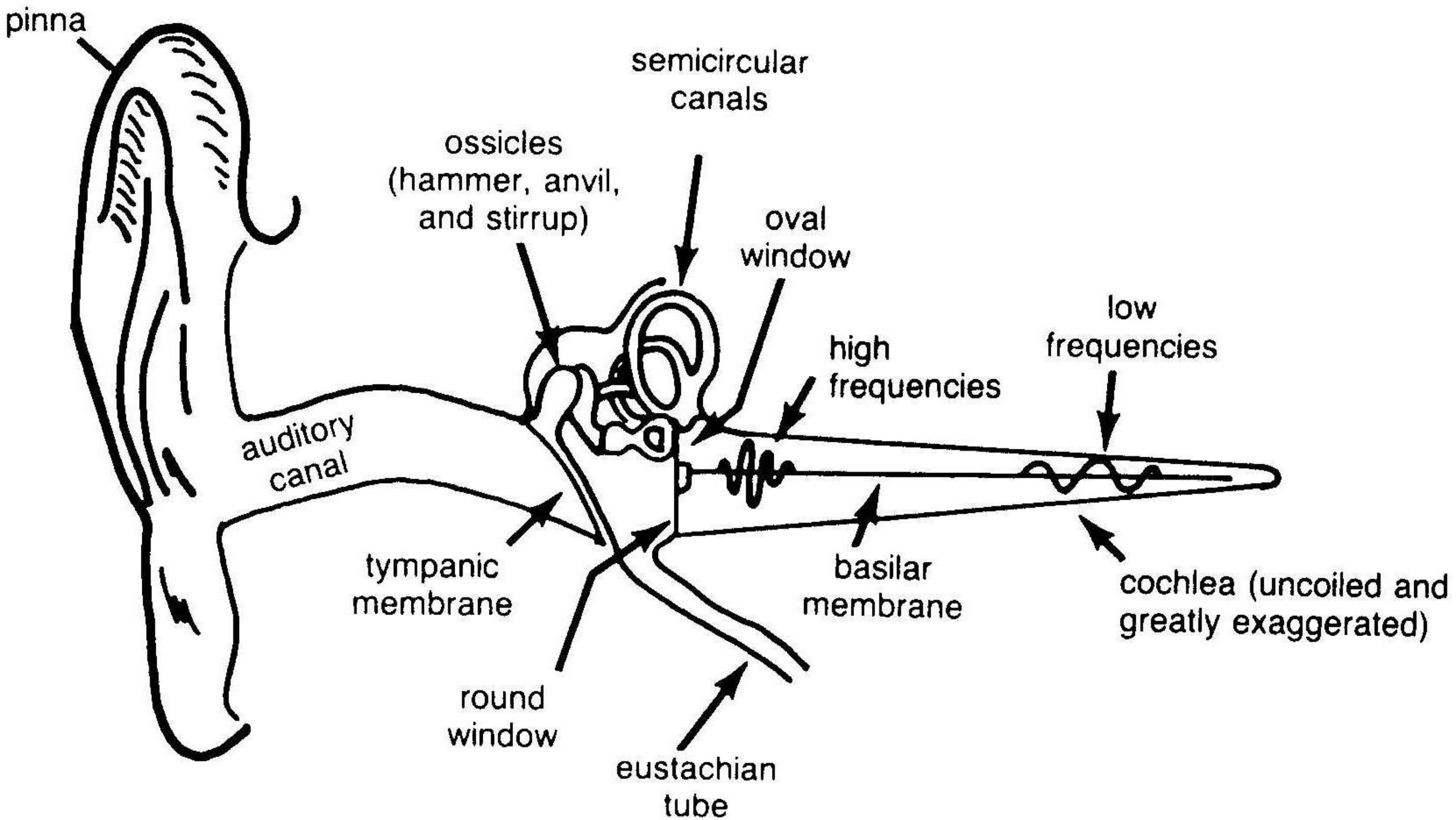
These three bones constitute a lever system, which multiplies the sound force exerted on the oval window.

When very soft sounds are received, this lever system provides up to a threefold enhancement of our hearing sensitivity.

On the other hand, the same system acts to protect us against extremely loud sounds. If the sound is loud enough, the stirrup may actually pull away and break contact with the oval window.

Unfortunately, the ossicle protection mechanism against very loud sounds is not fast-acting enough to protect our ears against sudden loud sounds such as gunshots. Permanent hearing damage from sudden loud sounds is relatively common.

Acting together under optimal conditions, the three amplification mechanisms may produce an effective amplification of around 180
(a factor of 2 from the pinna and auditory canal, a factor of 30 from the eardrum, and a factor of 3 from the ossicles).


pinna
semicircular canals
ossicles (hammer, anvil, and stirrup)
oval window
low frequencies
high frequencies
auditory canal
tympanic membrane
basilar membrane
cochlea (uncoiled and greatly exaggerated)
round window
eustachian tube

The amplified mechanical force transmitted to the oval window by the ossicles results in a hydraulic pressure in the cochlear fluid, creating a wavelike ripple in the basilar membrane.

The behavior of this wave as it travels through the cochlea is the key to our ability to distinguish different frequencies (pitches) of sound.

A high frequency wave will peak near the oval window and excite the basilar membrane in that area. When nerve cells in that area of the basilar membrane relay a signal to the brain, it is perceived as a high pitch. A low frequency wave will peak near the end of the cochlea and signals are perceived as low pitches.

THE RANGE AND SENSITIVITY OF HUMAN HEARING

The threshold of human hearing occurs at

$I_0 = 10^{-12}$ W/m^2 ($I_0 = 10^{-16}$ W/cm^2) at 10^3 Hz.

Sound intensities up to $10^{13}\ I_0$ W/m^2 will not damage the hearing mechanism if onset is gradual and exposure is brief.

The frequency range for human hearing – 20 to 20 000 Hz.

The upper frequency limit for hearing depends upon the intensity of the sound. At a given intensity the upper frequency limit is usually higher for women than for men and decreases with increasing age.

The human ear is sensitive to frequency differences between two sounds when sounded together or separately. When the tones are sounded simultaneously, the frequency difference is detected by means of the beats caused by interference between the sound waves.

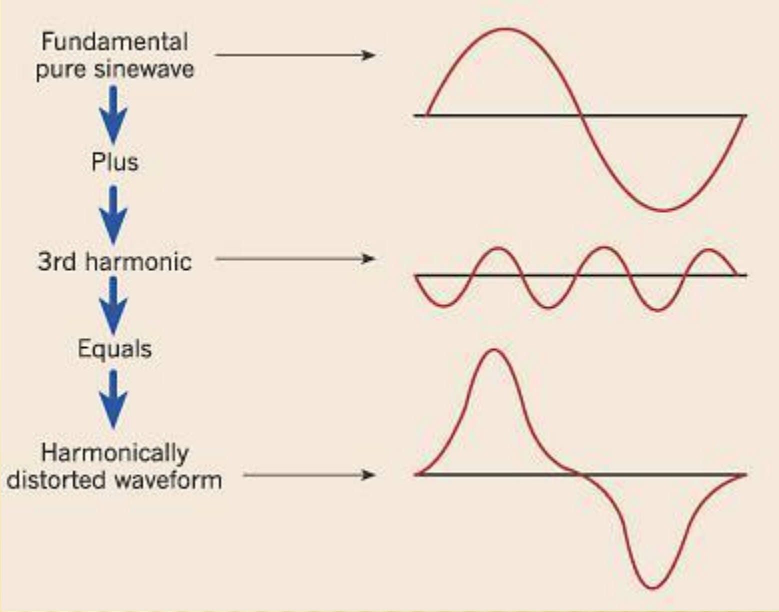
The ability to discriminate between different frequencies depends upon the fact that they excite different areas on the basilar membrane.

At 10^3 Hz a frequency change of 3 Hz can be perceived by most people. It is thought that there must be a "sharpening" process involved in the production of the nerve impulses and their transmission to the brain which enhances the frequency sensitivity.

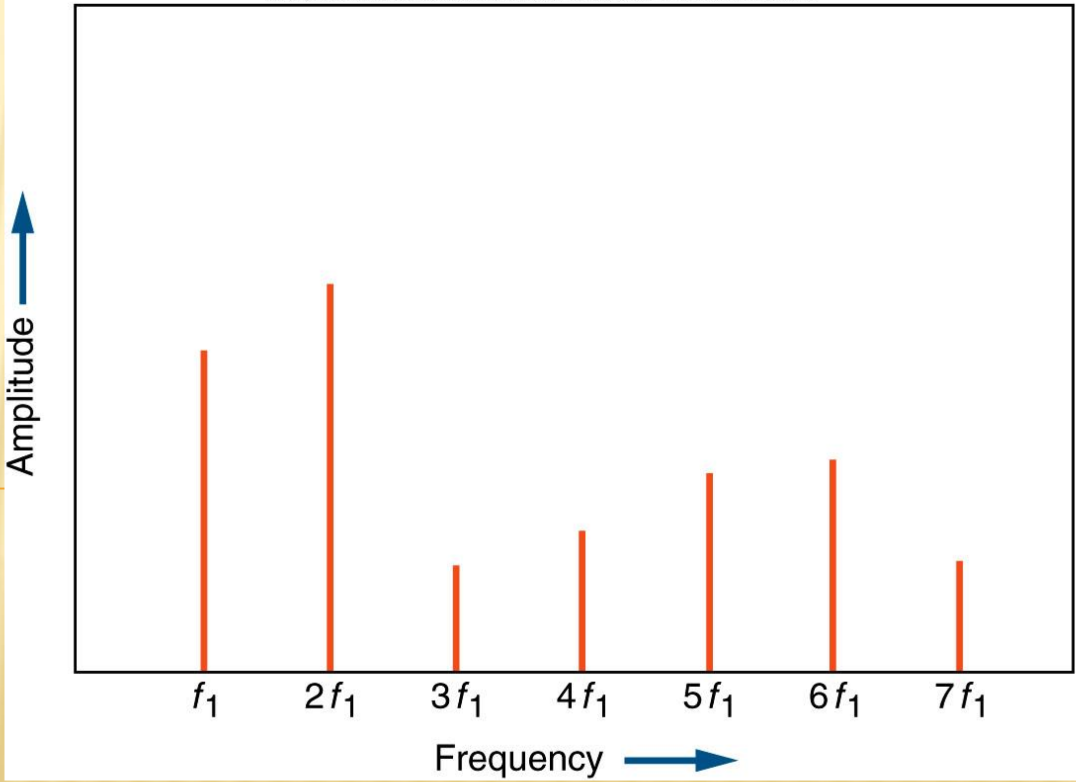
The ear is sensitive to frequency ratios rather than to absolute frequency changes. If it takes a 3 Hz change to be heard at 1000 Hz, it takes only about 0.3 Hz to be heard at 100 Hz.

Besides the ability to distinguish between sounds of different frequency and intensity, the ear can distinguish between sounds of different "quality" even though they may have the same frequency and intensity.

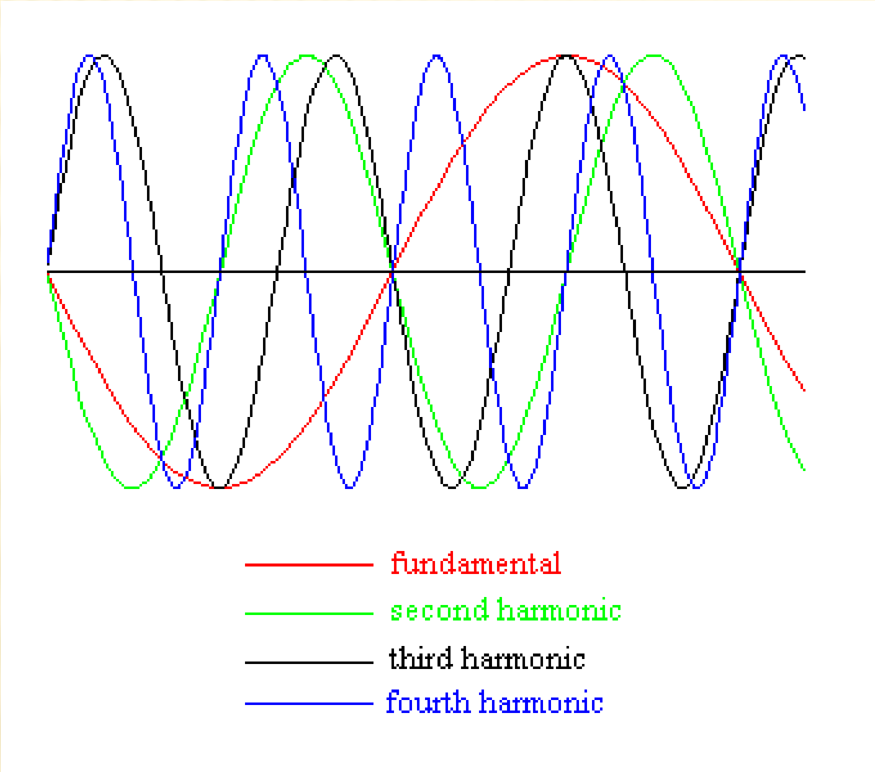
The ear has no trouble distinguishing between a trumpet and a clarinet, even though they may be playing the same note at the same loudness.

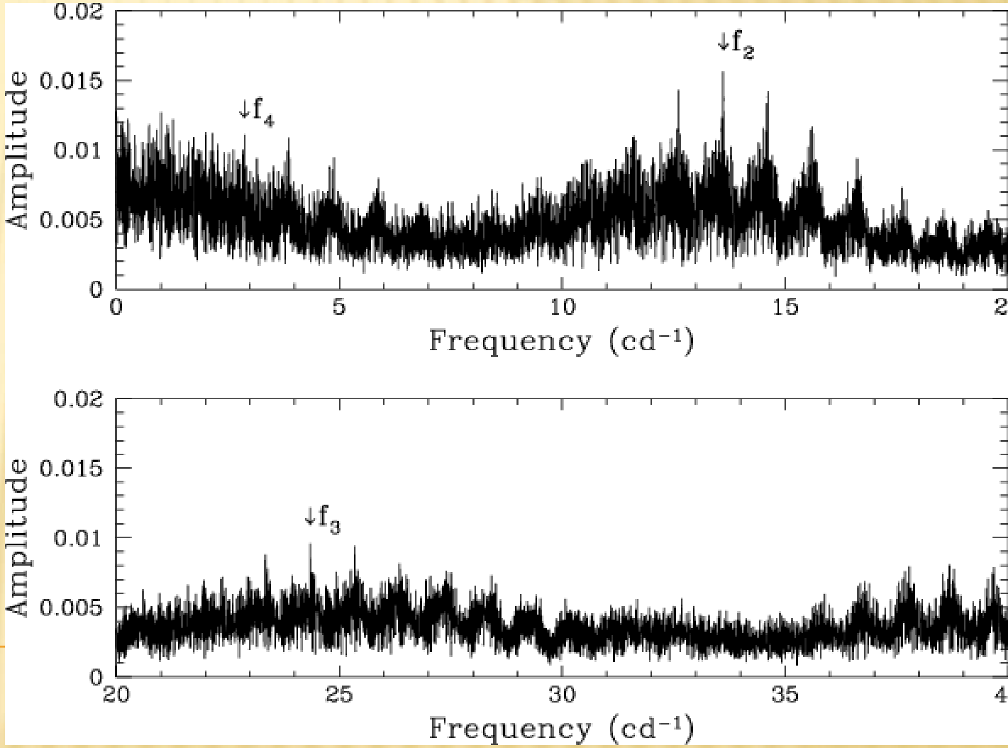


Different types of vibrating objects will produce different "overtones" or higher frequencies above the fundamental frequency.



The varying frequencies and intensities of these overtones is the basic difference between the sound qualities of different sound sources.





The human voice can vary the quality of the sound by changing the configurations of the resonant cavities involved in sound production so that the overtone frequencies and amplitudes are changed.

This is an important factor contributing to the ability to produce distinguishable and reproducible sounds for intelligent speech.

THE DECIBEL SCALE

When direct intensity measurements in W/cm^2 are used, the range of numbers is inconveniently large. The sound intensity at the pain threshold is 10^{12} or 10^{13} times as intense as the threshold of hearing intensity.

To obtain a more manageable set of numbers it is convenient to use a logarithmic scale of intensities, the decibel scale. The intensity in decibels (the so-called relative intensity) is defined as

$$n\,(dB) = 10\log_{10}\left(\frac{I}{I_0}\right)$$

Relative intensity

where I - intensity of sound in W/m^2 and $I_0 = 10^{-12}\ W/m^2$ (the threshold of hearing intensity at 10^3 Hz).

Two sounds A and B with intensities I_A and I_B can be compared by the relationship:

$$n_A - n_B\,(dB) = 10\log_{10}\left(\frac{I_A}{I_B}\right)$$

THE DISTINCTION BETWEEN LOUDNESS AND INTENSITY

Sound *intensity* is defined as the acoustic power per unit area, and it is therefore an objective physical measurement which is independent of the frequency of the sound.

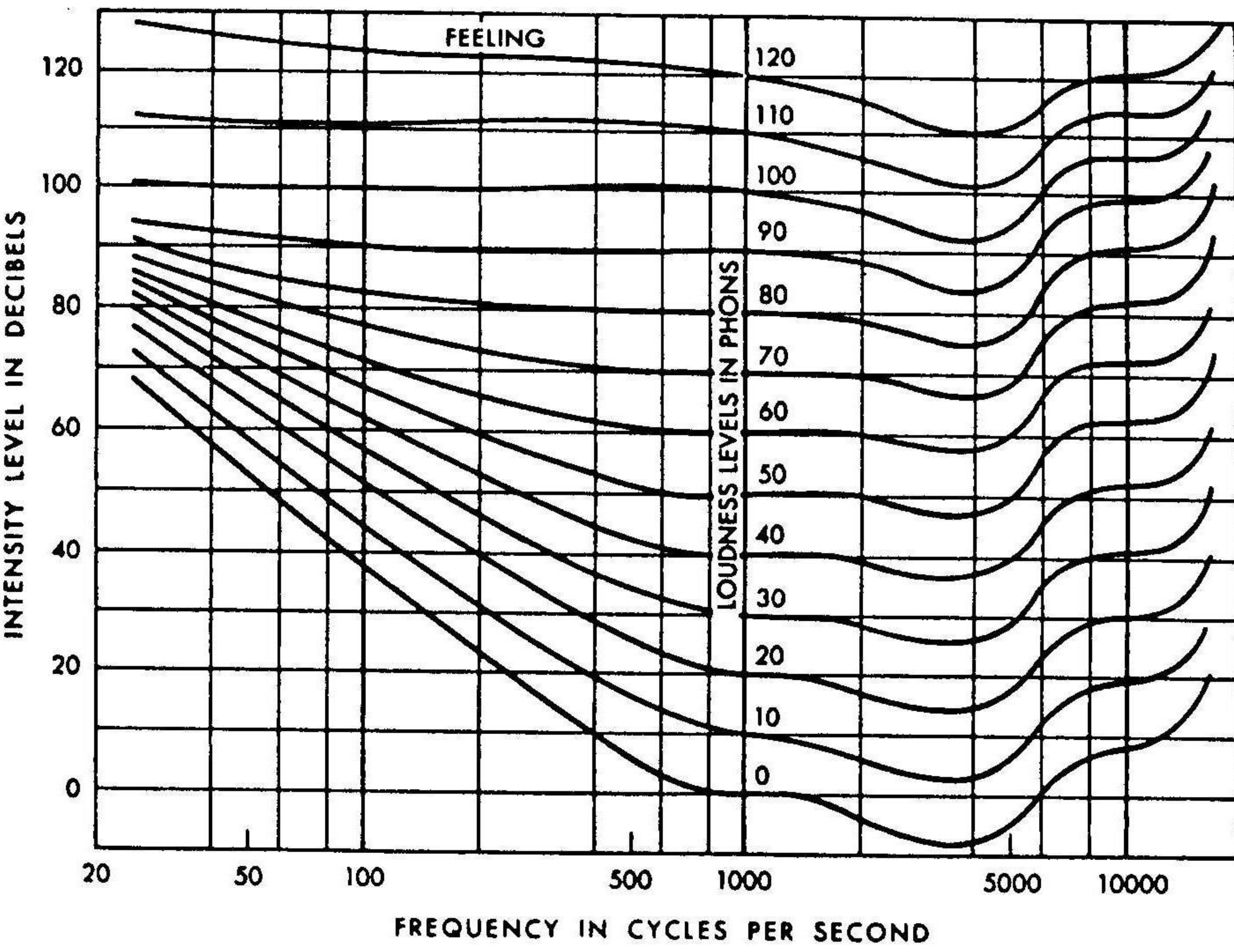
Loudness is not the same as intensity because it involves the perception of the sound by the human ear.

It depends upon the sensitivity of the ear at the particular frequencies contained in the sound. Hence, a very *intense* sound at 40 kHz would not be perceived as *loud*, since the ear does not respond to this frequency.

Since the sensitivity of the human ear varies considerably, even in the 20 to 20 000 Hz range, the study of loudness must be done experimentally and described in relative units.

A collection of **equal-loudness curves** is obtained as a measure of **the average hearing sensitivity** of a large number of persons who were tested.

The relative unit of loudness used to label these curves is *the phon.* The equal loudness curves are produced in **controlled tests** in which subjects were asked to compare the loudness of test tones with a standard tone at 10^3 Hz. The curves are plotted in dB as a function of sound frequency in Hz.


FEELING
120
100
80
60
40
20
0
INTENSITY LEVEL IN DECIBELS
LOUDNESS LEVELS IN PHONS
120
110
100
90
80
70
60
50
40
30
20
10
0
20
50
100
500
1000
5000
10000
FREQUENCY IN CYCLES PER SECOND

For example, to plot the curve marked 60 phons, the subjects were exposed to a 1000 Hz tone at an intensity of 60 dB. Then at other frequencies they were asked to raise or lower the sound intensity until it sounded the same *loudness* as the 1000 Hz tone.

At 50 Hz frequency, the intensity must be raised to about 78 dB to sound as loud as the 1000 Hz tone at 60 dB, since the ear is much less sensitive at 50 Hz.

The equal-loudness curve formed by the collection of these results is called a 60 phon curve to signify that every point on the curve represents a sound that is *as loud as* a 60 decibel, 10^3 Hz tone.

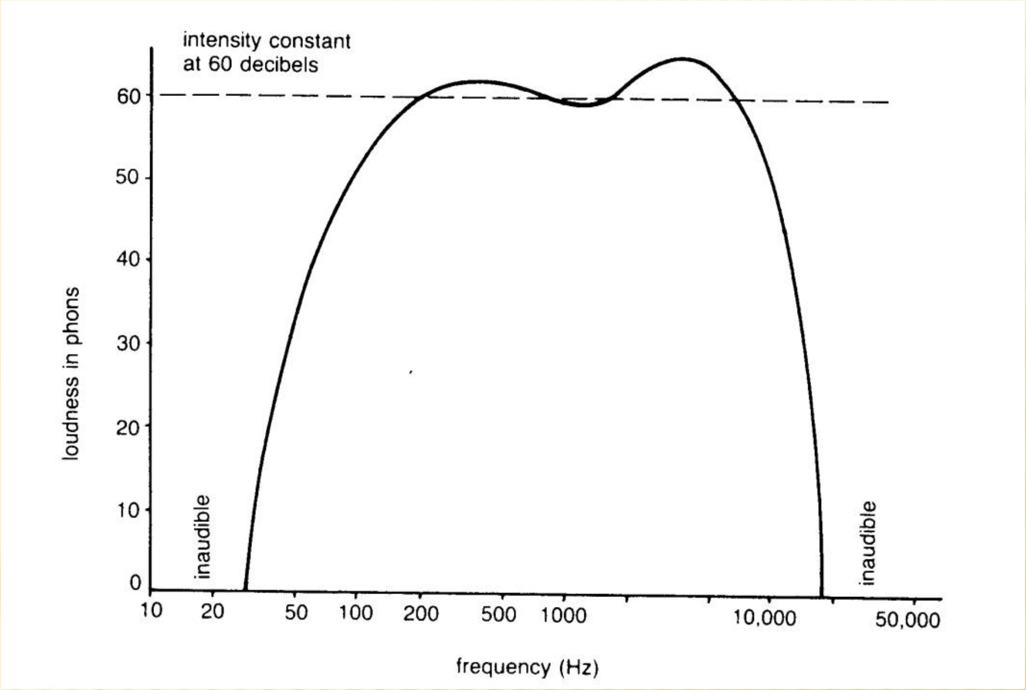
Using the equal loudness designation, phon, the threshold of hearing could be said to be zero phons, regardless of the frequency. It is not correct to refer to zero dB as the threshold of hearing unless the sound has the frequency 1000 Hz.

It can be seen that the threshold of hearing (0 phons) at 60 Hz is at about 48 dB, or almost **100,000 times** as intense as the **zero decibel level**. The hearing sensitivity has dropped by 48 dB at this frequency.

The sensitivity curve is flatter at high intensities. The ear's sensitivity is not so frequency dependent at high sound levels.

If a tone of constant intensity (60 dB in this case) is started at a very low frequency and swept through the audible range, the loudness will vary with the sensitivity of the ear.

The plot of loudness in phons is then a plot of the ear's sensitivity as a function of frequency. Note that the range of maximum sensitivity is the range from 2000 to 6000 Hz.



It is found that this frequency range is the most important for the understanding of speech. The inaudible regions are not indications of the ultimate limits of human hearing, but these sounds are inaudible at an intensity of 60 dB. The range of hearing can be extended by raising the intensity, but practical limits occur when the intensity must be raised to the physical pain threshold in order to be audible.

Analysis

(1) Two sounds of the same intensity but different frequencies will not in general be perceived to have the same loudness;

(2) At a constant frequency, an increase in intensity will increase the perceived loudness;

(3) A lower pitched instrument in the orchestra must produce sounds of greater intensity to match the loudness of mid-range instruments near 1000 Hz;

(4) The ear's sensitivity varies less with frequency when the sound is very loud. Very soft tones will be perceived as deficient in the bass frequencies and the very high frequencies.

HEARING TESTS

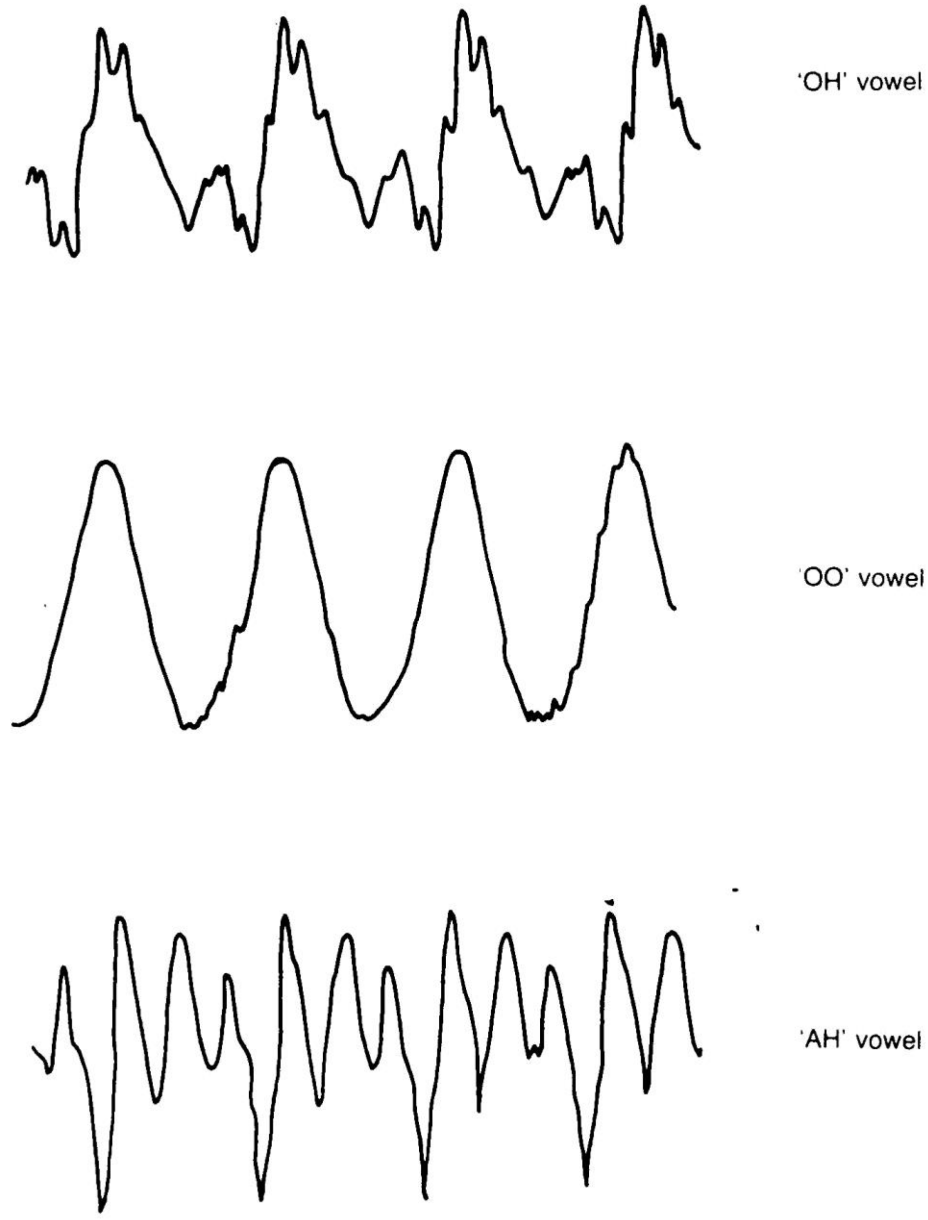
Def. Testing for hearing loss is referred to as audiometry. The two basic approaches to testing are **pure tone** and **speech audiometry**.

Def. A "pure tone" is a tone of single frequency. Pure tone audiometry is the simplest and most common.

Speech audiometry has some advantages since speech sounds are the most important sounds which we must interpret, but the tests are more complex.

The frequency range of human voice: 85 to 1100 Hz.

A person with normal hearing in this range and severe hearing loss above 1100 Hz cannot understand speech sounds at normal levels.



Note: The pitches and intensities of the above sounds are similar.
Differences in harmonic content produce the distinctive sounds.

All of these tones have approximately the same frequency and loudness, but it is important for the ear to be able to distinguish these sounds.

A pure tone would produce a smooth sine wave. The difference in the waveforms is caused by the presence of higher frequencies (overtones) superimposed upon the basic frequency.

It can be shown mathematically that any such repeating, continuous waveform, can be reproduced by the addition of a series of pure tones of successively higher frequencies.

The normal ear can detect the presence of overtones of varying amplitudes and frequencies as differences in the "quality" of the sound.

If the hearing is impaired in such a way that the **fundamental frequency** is heard, but not the **overtone frequencies**, then the differences in quality cannot be heard and understanding suffers.

The presumption of pure tone audiometry is that if a person's hearing is normal at all pure tone frequencies, then the person will have normal hearing in terms of the complex superposition of frequencies which make up speech and music.

This presumption is difficult to prove directly, but the evidence of experience shows that it is reasonably valid.

Hearing tests generally include the evaluation of the threshold of hearing at a series of f.

The instrument used is an *audiometer*, which includes an electronic oscillator to produce pure tones at the specified f, an attenuator to control the loudness, and compatible earphones.

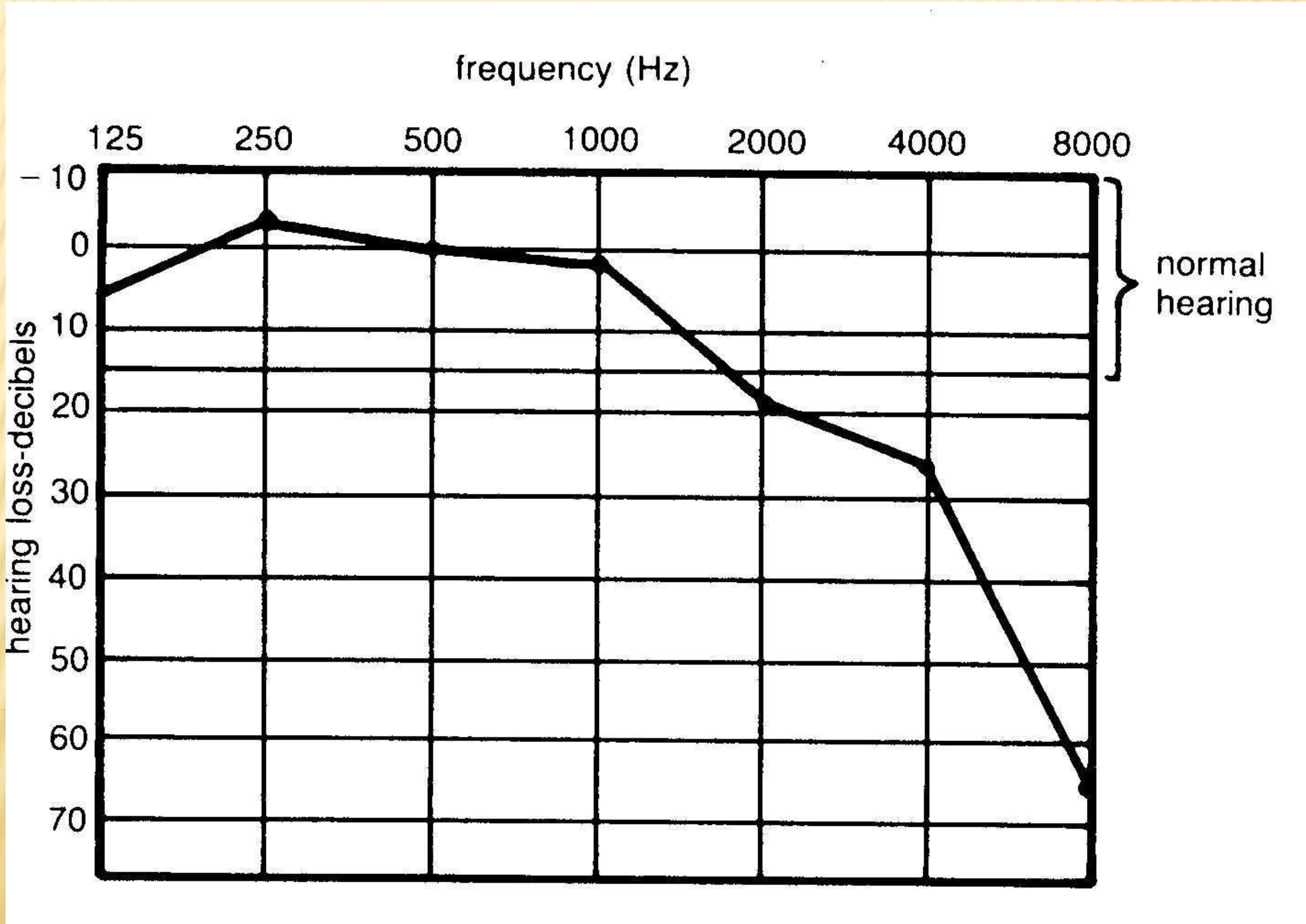
Since the sensitivity of the ear varies widely over frequency, the instrument **must be calibrated according to the normal hearing curve**. Therefore, the threshold of hearing measurement is not an absolute intensity measurement, but a measurement of the ratio of the intensity required for audibility to the normal threshold intensity agreed upon as an international standard.

This ratio is measured in dB, so a 30 dB hearing loss means that the sound intensity had to be increased 30 dB above the standard threshold level for that frequency to be heard.

The zero level represents the normal threshold, which is sometimes labeled zero dB Hearing Level (0 dB HL).

In actual tests there would be two curves for each case to represent the two ears, and bone conduction hearing tests are also included as a part of a complete audio-logical assessment.

Audiogram showing presbycusis — the loss of high frequency sensitivity.



THE MEASUREMENT OF ENVIRONMENTAL SOUND

It is misleading to measure environmental sounds on a strict decibel intensity scale since that gives **equal weighting to all sounds** in the audible frequency range, and the ear is not equally sensitive to all frequencies.

The ear discriminates against both very low and very high audible frequencies.

The usual approach is to use **a sound-level meter** with a standard contour filter which discriminates against low and high frequency sounds in a way that approximates the human ear's response.

There are three internationally accepted standard contour filters, known as the A, B, and C contours.

The A contour discriminates most strongly against very low and very high frequencies and is the best approximation to the human ear for sounds of soft and medium intensities.

If a meter with such a contour gives a reading of 80, it is recorded as 80 dBA to indicate the contour. For routine sound surveys the dBA readings are generally preferred.

Straight decibel readings can be very misleading in buildings where the meter may pick up a lot of low frequency sound from air circulation units that may be nearly inaudible to the ear.

The B and C contours (recorded **dBB** and **dBC**) discriminate against low and high frequencies by lesser amounts and thus have "flatter" response curves.

The B and C contours are sometimes useful for surveys of **loud traffic noise** and **industrial noise** levels.

It has been recommended that no worker be exposed to a continuous sound level of 85 dB for more than 5 hours a day without protective devices.

REVIEW QUESTIONS

1. Define sound.
2. Describe the mechanisms in the ear which amplify the sound which reaches the ear. Does the amount of amplification depend upon the intensity of the sound?
3. Describe the basic pitch sensing mechanism of the ear.
4. Why must sound loudness be distinguished from sound intensity?
5. What are the advantages of expressing sound intensities in decibels rather than in W/cm^2?

6. Under what conditions could you have very intense sounds which strike a normal ear but cannot be heard?
7. In hearing tests the sequence of frequencies chosen (125, 250, 500 Hz, and so on) is such that the frequency is doubled between test points. Why is this more desirable than regular sets of frequencies separated by a constant number of Hz (e.g., 500, 1000, 1500)?
8. If hearing by bone conduction in a given patient was found to be nearly normal but severe hearing loss was indicated with airborne sounds, what types of causes are indicated for the hearing loss?