8.3.2 SOUND[M30]

8.3.2.1 Sound Waves

Sound waves, like any other waves, are the result of disturbances caused by vibrating objects. In the case of sound waves, the vibrating object could be the vocal cords of a human being, the vibrating string and sound board of a guitar or violin, the vibrating tines of a tuning fork, or the vibrating diaphragm of a radio speaker.

The **kinetic energy of the vibration** is carried forward by **compression waves,** which are by nature both **mechanical** and **longitudinal**.

These waves:

- consist of regions of **high and low pressure**;
- undergo **reflection** and **refraction**;
- show **interference effects**;
- travel most easily through solids:
  less easily through liquids;
  less easily through gases;
  not at all through a vacuum.

8.3.2.2 Frequency and Pitch

As we have already seen, the frequency of a sound wave is a measure of the number of times individual particles of the transmission medium vibrate in a particular time interval, typically one second. This, of course, is the frequency at which the source of the sound wave is vibrating.

Sound waves are invariably defined by their frequency. Unlike electromagnetic radiation, for which frequency and wavelength definitions are used interchangeably[1], the speed of sound waves varies considerably with the medium in which the waves are travelling. The human ear is sensitive to changes in pitch, and it is changes in the frequency of sound waves that manifest themselves as changes in pitch. Thus, regardless of the speed of a sound wave, or its wavelength, it is the frequency that is detected by the human ear. Regardless of their wavelength:

High frequency waves are heard as **high pitch sounds**.

Low frequency waves are heard as **low pitch sounds**.

Certain sound waves when generated simultaneously will sound particularly pleasant to the ear—these are said to be **consonant.** Sound waves that do not produce a pleasing effect when played together are said to be **dissonant**. Consonant sound waves, or notes, form the basis of intervals in music. For example, any two notes whose frequencies make a 2:1 ratio are said to be separated by an octave and interact in a pleasing fashion—*i.e.* two notes have a pleasant sound, when played together, if one is twice the frequency of the other. Similarly, two notes with a frequency ratio of 5:4 are separated by an interval of a third, and are also pleasing to the ear when played together. Examples of other note intervals and their respective frequency ratios are listed in the table on the following page.

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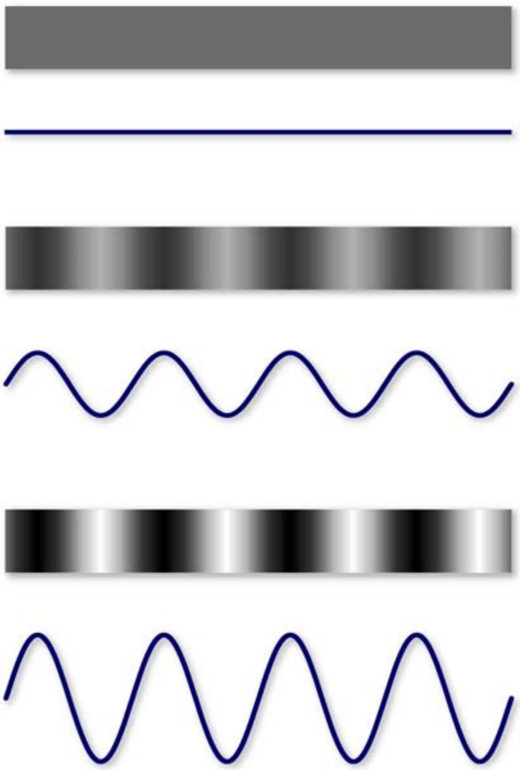
[1] This is only possible because, for all intents and purposes in the present context, electromagnetic waves travel at a constant speed, the speed of light.

Interval	Frequency Ratio	Examples	
Octave	2:1	512 Hz and 256 Hz	C_5 & C_4
Third	5:4	320 Hz and 256 Hz	E_5 & C_4
Fourth	4:3	342 Hz and 256 Hz	F_5 & C_4
Fifth	3:2	384 Hz and 256 Hz	G_5 & C_4

In general, two notes, when played together, produce a pleasing sound if the frequency of one is a small integer multiple of the other.

The range of human hearing is about 20–20,000 Hz. Sound above the human hearing range is generally known as **ultrasound**, and that below the hearing range as **infrasound**. But not all animals are sensitive to the same range of frequencies. The hearing range for dogs is around 50–45,000 Hz, and for cats is around 45–85,000 Hz. Bats, being essentially blind, rely on sound echolocation for navigation and feeding, and can detect frequencies as high as 120,000 Hz. Dolphins can detect frequencies as high as 200,000 Hz. While dogs, cats, bats, and dolphins have an unusual ability to detect ultrasound, elephant possesses the unusual ability to detect infrasound, having an audible range of around 5–10,000 Hz.

8.3.2.3 Amplitude and Intensity



As with any wave, the amplitude of a sound wave is a measure of the power or intensity of the wave. As a longitudinal wave, amplitude is effectively measured along the direction of travel and is a little more difficult to visualise than in a transverse (sine) wave. The amplitude of a longitudinal wave increases as the pressure difference between compressions and rarefactions increases. The adjacent illustrations compare longitudinal wave representations with the more common sine wave representations of waves with different amplitudes. As the amplitude increases, the compressions of longitudinal waves become more dense (darker) and the rarefactions less dense (lighter).

While the power and the intensity of a wave are related, they are not the same. **Power** is the term used to define the energy at the source of a disturbance, while **intensity** is the energy at any particular point on the wave front. The two are related by the equation:

$$\textbf{Intensity} = \frac{\textbf{Power}}{\textbf{Area}}$$

In a spherical wave, such as a sound wave, energy propagates equally in all directions—no one direction is preferred over any other. In this case, the power emitted by the source (P) is distributed evenly over a spherical surface (area = $4\pi r^2$), assuming that there is no absorption in the medium. The above relationship can then be written:

$$\textbf{Intensity} = \frac{P}{4\pi r^2}$$

We can now see that the intensity of a sound wave decreases as the distance from the source (r) increases. This occurs because, as the distance from the source increases, the same amount of energy is spread over an increasingly larger area. It also follows from this equation that the intensity of sound waves is measured in watts per square metre ($W{\cdot}m^{-2}$). However, because the human ear is capable of detecting sound levels across a very large range (one to a billion—a million million) sound levels are more often measured using a logarithmic scale in units of **decibels**.

The **bel** (**B**), after the telecommunications pioneer Alexander Graham Bell (1847–1922), is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power) relative to a reference level:

$$N_B = \log_{10} (N/N_0)$$

The logarithmic nature of the **bel** allows very large or very small ratios to be represented by a convenient number, in a similar manner to scientific notation. Being essentially a ratio, it is a dimensionless unit.

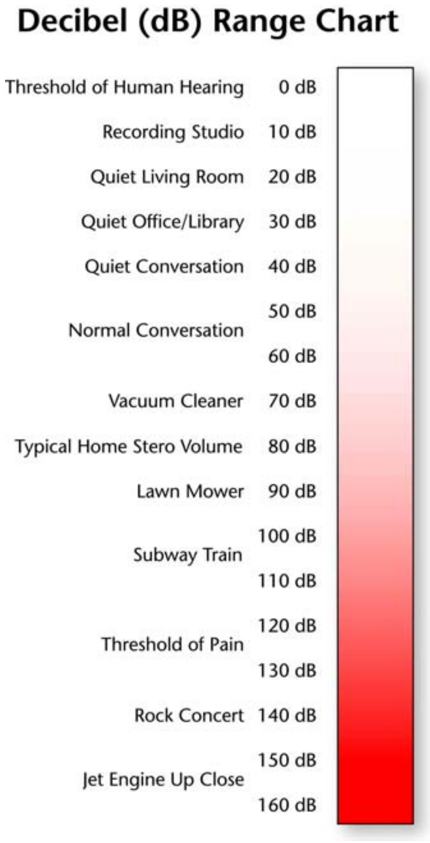
In many situations the **bel** has proved inconveniently large, so the **decibel** (**dB**), one tenth of a **bel**, has become the more commonly used unit. Thus, when dealing with sound and noise levels, the **dB** level (N_{dB}) is calculated using the equation:

$$N_{dB} = 10\log_{10} (N/N_0)$$

where **N** is the noise level in question and N_0 is the Threshold of Human Hearing, each measured using the same units (*e.g.* power, sound pressure, voltage, intensity) although the actual units are not important..

It appears to be a happy coincidence that, to the human ear, a one **B** increase in sound level represents, approximately, a doubling of the sound level.

While most people are familiar with the decibel scale because of its use in measuring sound levels, it is actually used more widely in the field of electronics and telecommunications to measure power levels in electronic circuits and telecommunications lines.


Decibel (dB) Range Chart

While the intensity of a sound is a very objective quantity that can be measured with sensitive instrumentation, the loudness of a sound is more of a subjective response that will vary with a number of factors. The same sound will not be perceived to have the same loudness to all individuals. Furthermore, two sounds with the same intensity but different frequencies will not be perceived to have the same loudness. Because of the human ear's tendency to amplify sounds having frequencies in the range from 1000 Hz to 5000 Hz, sounds with these intensities will seem louder. Nonetheless, more intense sounds will generally be perceived to be louder sounds.

8.3.2.4 The Speed of Sound

The speed of any mechanical wave depends upon the properties of the medium through which it is travelling. Wave speed if affected predominantly by the elastic properties of the transmission medium, and to a lesser extent by inertial properties.

Elastic properties are those that determine how easily a medium is deformed. A material like steel will experience very little deformation under stress, and is said to be highly **elastic**. A rubber band is easily deformed, but still tends to return to its original form when the stress is removed. It is elastic, but much less so than steel. Elasticity is a measure of how strongly particles with a medium bind together. Thus, liquids and gases are said to be **plastic**, essentially the opposite to elastic—they are easily deformed and tend not to return to their original form.

As a result, sound waves travel faster in solids than they do in liquids, and faster in liquids than they do in gases:

$$v_{\text{solids}} > v_{\text{liquids}} > v_{\text{gases}}$$

The speed of sound in steel (~5800 $\text{m}\cdot\text{s}^{-1}$), for example, is around four times faster than the speed of sound in water (~1500 $\text{m}\cdot\text{s}^{-1}$ @ 15 °C), which is around four times faster than the speed of sound in air (~340 $\text{m}\cdot\text{s}^{-1}$ @ 15 °C).

The speed of sound is also affected, although to a much lesser extent, by inertial properties such as the density of a medium. The heavier are the individual particles of the medium, the less responsive they will be to excitation. For example, sound travels nearly three times faster in helium than it does in air—a helium atom is 7–8 times smaller than either an oxygen or nitrogen molecule, the main constituents of air.

The speed of sound waves in air, however, is affected mostly by the ambient temperature. This temperature dependence can be approximated by the equation:

$$v = 331.3 + 0.606T \ \text{m}\cdot\text{s}^{-1}$$

where T is the ambient temperature in °C. Thus, at 0 °C, the speed of sound is:

$$v = 331.3 \ \text{m}\cdot\text{s}^{-1}$$

and at 15 °C, it is:

$$\begin{aligned} v &= 331.3 + 0.606 \times 15 \\ &= 331.3 + 9.09 \\ &= 340.4 \ \text{m}\cdot\text{s}^{-1} \end{aligned}$$

Pressure has essentially no impact on the speed of sound in air[2].

8.3.2.5 Interference and Beat Patterns

Interference between sound waves is of fundamental interest in the world of music. An analysis of musical sounds reveals that they invariably comprise a mixture of sound waves whose frequencies are mathematically related. What we hear as music is a complex wave pattern derived from sound waves, or notes, which typically have small-whole-number ratios between their frequencies. In fact, the major distinction between music and noise is that noise invariably comprises a mixture of wave frequencies that bear *no* simple mathematical relationship to one another.

A pure sine wave, with a frequency of 440 Hz, would sound a perfect concert pitch A, but it would sound entirely electronic. When a musical instrument plays the same

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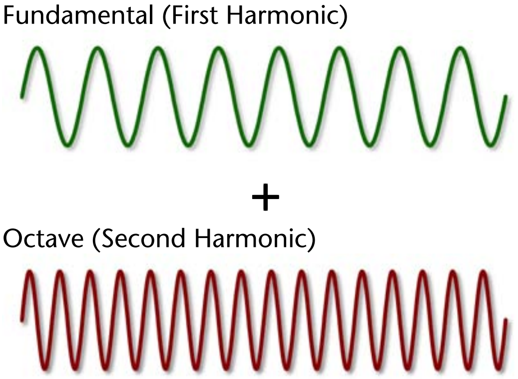
[2] http://www.sengpielaudio.com/calculator-speedsound.htm

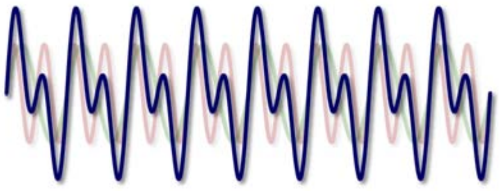
note, however, the wave form generated is a subtle combination of a 440 Hz wave and different proportions of various harmonics of this frequency. The interference pattern so generated, when a note is played on any particular instrument, is the foundation of the tonal quality of that instrument.

The illustrations that follow provide examples of the interference patterns that can result from the combination of waves with either specific or arbitrary frequency relationships.

When a fundamental is combined with its second harmonic, the frequencies of the two waves are in the ratio 1:2, or an **interval of an octave** apart. The resultant interference pattern displays a periodic nature, and we find this musical, and pleasing to the ear.

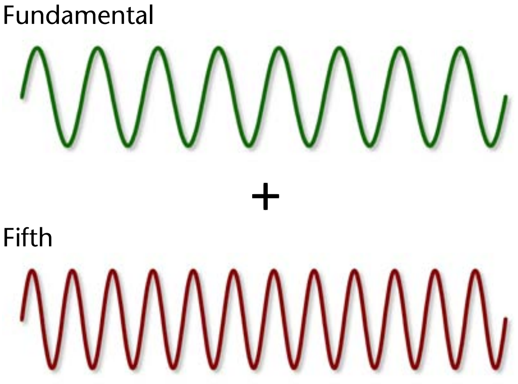


Interfering Waves
Frequency ratio: 1:2 (Octave)

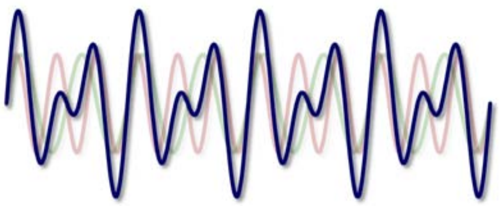


Resultant wave pattern
Pattern is periodic

A similar effect is produced when the frequencies of the two waves are in the ratio 2:3, or an **interval of a fifth** apart. Note once more that the interference between these two waves produces a resultant that has a periodic, repeating pattern. Once again the result is pleasing to the ear.

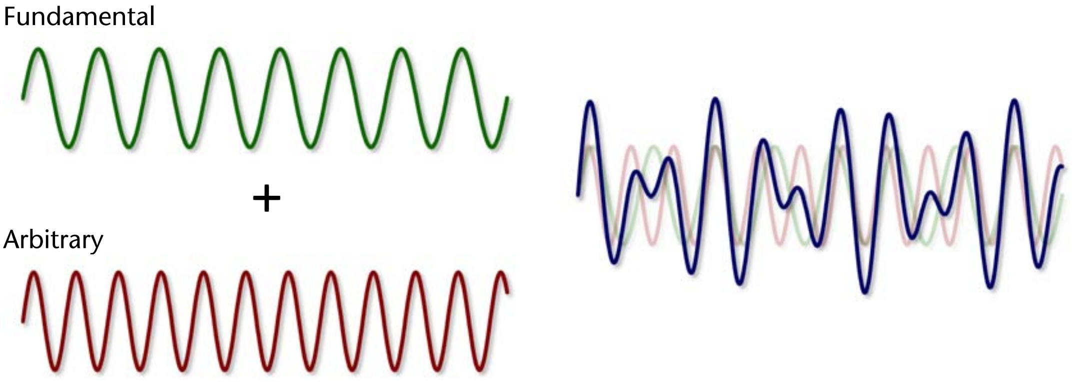


Interfering Waves
Frequency ratio: 2:3 (Fifth)



Resultant wave pattern
Pattern is periodic

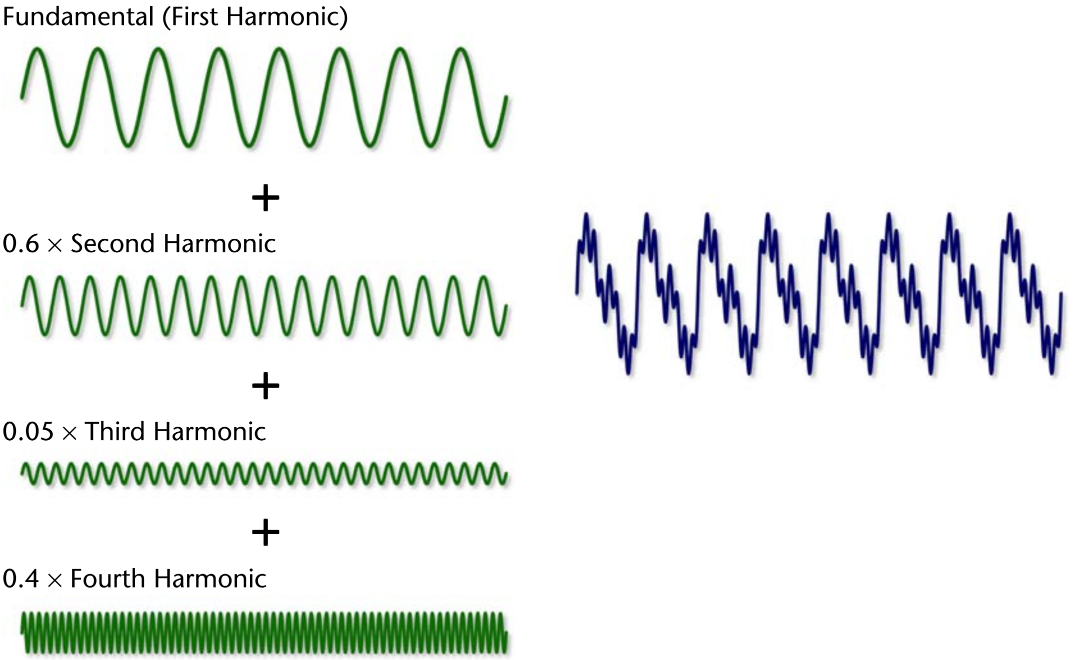
The next example illustrates what happens when there is no clear mathematical relationship between the frequencies of two waves. The pattern of the resultant does not display the periodic nature of the previous examples. In general, when sound waves that have no simple mathematical relationship between their frequencies combine, the resultant will display an irregular pattern and is commonly referred to as **noise**. In general, noise has no particularly pleasing musical characteristic.



Interfering Waves
Arbitrary frequency separation (40:57)

Resultant wave pattern
Pattern is irregular

One aspect of the tone quality in a musical instrument is the way in which the instrument generates overtones (harmonics) when any particular note is played. The way in which sound is produced by any particular kind of musical instrument, and the way in which individual instruments are made has a profound effect on the overtones that are generated as the instrument is played (the **timbre** of the instrument). The illustration below is a very simple example of the sort of complex wave structure that can result from a combination of different harmonics. In practice, the quality of an instrument also governs the 'purity' of the individual harmonics and produces more subtle effects in the resultant wave form.

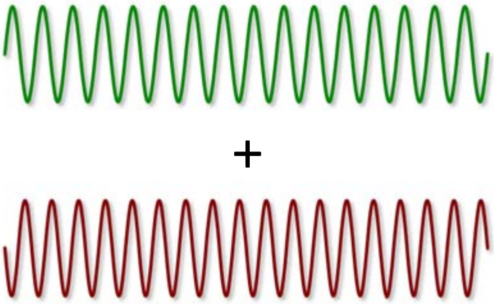


Interfering Waves
Combination of harmonics at different levels

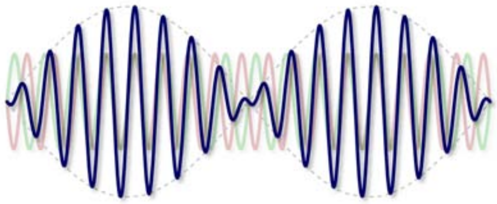
Resultant wave pattern
Complex but periodic

Sound wave interference, particularly destructive interference, is also an important consideration in the design of concert halls and auditoriums. If sound arrives at a particular location such that compressions meet rarefactions, then destructive interference will occur, and there will be a reduction in the loudness of the sound at that location. This type of interference may be apparent if the sound from two speakers meets at a particular location, or if sound from a speaker meets with sound reflected off the walls and ceiling. These effects can be minimised by careful placement of speakers and the use of materials, in the walls, ceiling, and baffles, that absorb sound rather than reflect it.

We noted earlier that certain sound wave frequencies produce a pleasing effect when combined. When sound wave frequencies that are only slightly different interact, they produce an interference pattern with less pleasing variations in sound intensity. These variations are known as beats[3].



Interfering Waves
The red wave has oscillated 2 cycles more than the green wave over the sample period



Resultant beat pattern
Since there was a difference of 2 cycles between the two waves over the sample period, there will be 2 beats in the resultant wave

The number of beats per second corresponds to the difference in frequency between the two interfering waves. If the sample period for the waves in the above example is 1 second, the frequency of the first (green) wave would be 16 Hz, while that of the second (red) wave would be 18 Hz. Since the difference in frequency between the two waves is 2 Hz, the interference pattern will show 2 beats per second, as illustrated. Indeed, the interference pattern resulting from any two frequencies that differ by 2 Hz will have an *envelope* similar to the one above and will beat two times per second.

8.3.2.6 Reflection, Refraction and Diffraction

Sound waves undergo reflection, refraction and diffraction like any other waves.

The **reflection** of sound waves off surfaces can produce **reverberations** and **echoes**.

The effect of a particular sound wave on the human brain endures for about one tenth of a second. If a reflected sound wave reaches the ear within that period, the sound appears to be *prolonged*. The reception of multiple reflections off walls and ceilings within a tenth of a second of each other causes reverberations—the prolonging of a sound. A reverberation often occurs in a small room with height, width, and length dimensions less than around 17 metres. Why 17 metres? Sound waves travel at about 340 m/s at room temperature, and thus it takes approximately one tenth of a second for sound to travel the length of a 17 metre room and back. We often hear reverberations when talking in an empty room, when honking the horn while driving through a highway tunnel or underpass, or when singing in the shower. In auditoriums and concert halls, reverberations can sometimes lead to a displeasing garbling of sounds.

Reflection of sound waves in auditoriums and concert halls, however, does not always lead to displeasing results, especially if the room is designed to reflect sounds *correctly*. Smooth walls have a tendency to reflect sound waves in specific directions. As a result, individual members of the audience can receive large amounts of sound from one location along such a wall, as there would is only one possible path by which sound

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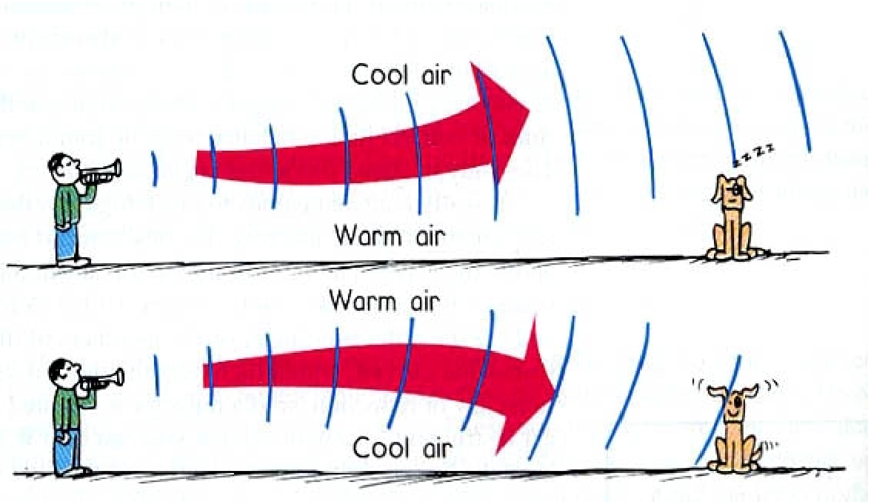
[3] While sound waves are longitudinal waves, they are often graphically represented as sine waves (like transverse waves) because wave behaviour is generally easier to visualise in this format.

waves could travel from the source to any particular member of the audience. Rough or uneven walls tend to diffuse sound, reflecting it in a many directions. Ideally, the audience will hear sounds from all parts of the room, giving a performance a fuller, more lively character. Hard surfaces also reflect waves strongly, so architects concerned with the acoustic quality of a room will tend to line it with softer materials.

Reflection of sound waves can also lead to echoes. Echoes occur when a reflected sound wave reaches the ear more than a tenth of a second after the original sound wave is heard. In this case, the arrival of the second sound wave will be perceived as a second sound rather than the prolonging of the first sound.

The **refraction** of sound waves is most evident in situations where the sound waves passe through a medium with gradually varying properties. For example, sound waves are known to refract when travelling over water. Even though the sound wave is travelling within the same medium (air), the properties of the medium vary with location. Water has a moderating effect upon the temperature of air, and the air directly above the water tends to be cooler than the air further away. Sound waves travel more slowly in cooler air than they do in warmer air. As a result, the part of the wavefronts directly above the water is slowed down, relative to the parts further away and the wave is bent downwards, towards the water.

A similar effect can be observed on land, when the air closer to the ground is warmer or cooler than that further above.



Refraction of sound waves in air[4]

Diffraction involves a change in direction as waves pass through an opening or around a barrier in their path. Bats use high frequency (low wavelength) ultrasonic waves to locate their prey, typically insects like moths, objects not much larger than a couple of centimetres. Why ultrasound? The answer lies in the physics of diffraction. Diffraction occurs when the wavelength of a wave is larger than an object that it strikes. When the wavelength is smaller than the object, it tends to reflect off the object, rather than diffract around it. Bats emit ultrasonic wave with frequencies of around 50 kHz. Using the wave equation, and 340 m/s as the speed of sound, we note that this corresponds to a wavelength in the order of 7 mm, small enough to reflect off the average insect or moth that might make a meal for a bat.

$$\lambda = \frac{v}{f} = \frac{340\ \text{m/s}}{50\,000\ \text{Hz}} = 0.0068\ \text{m} = {\sim}7\ \text{mm}$$

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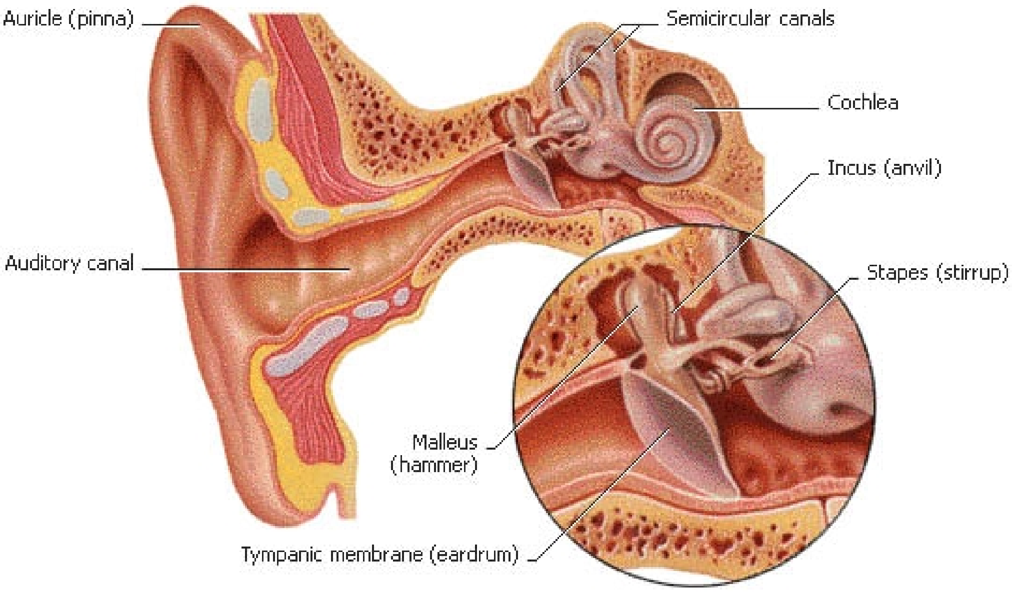
[4] http://sol.sci.uop.edu/~jfalward/physics17/chapter10/chapter10.html

8.3.2.7 The Human Ear

The human ear is an intricate receiver that turns sound energy to mechanical energy and then to a nerve impulse that is transmitted to the brain. The ear's ability to do this allows us to perceive the pitch of a sound by detection of its frequency, the loudness of a sound by detection of the wave's amplitude and the timbre of a sound by the detection of the various frequencies that make up a complex sound wave.

The ear can be divided into three sections—the outer ear, the middle ear, and the inner ear. Each part of the ear performs a specific function in the process of detecting and interpreting sound. The outer ear collects and channels sound to the middle ear. The middle ear transforms sound wave energy into mechanical vibrations that subsequently stimulate the generation of compression waves in the fluid of the inner ear. The inner ear then transforms the energy of these compression waves into nerve impulses that can be transmitted to the brain.



The human ear[5]

The outer ear consists of the auricle and an approximately 2.5-cm long auditory canal. The auricle provides protection for the middle ear, helping to prevent damage to the eardrum. The outer ear also channels sound waves that reach the ear through the auditory canal to the eardrum of the middle ear. As sound travels through the outer ear, it is still in the form of a pressure wave, with an alternating pattern of high and low pressure regions. It is not until the sound reaches the eardrum, at the interface between the outer and the middle ear, that the energy of the mechanical wave becomes converted into vibrations of the internal bone structure of the ear.

The middle ear is an air-filled cavity that consists of the eardrum and three tiny, interconnected bones—the hammer, anvil, and stirrup. The eardrum is a very durable and tightly stretched membrane that vibrates as the incoming pressure waves reach it. On reaching the eardrum, a compression forces it inward and a rarefaction draws it outward, vibrating the eardrum at the same frequency as the sound wave. Being connected to the hammer, the movements of the eardrum set the hammer, anvil, and stirrup into motion. These three tiny bones of the middle ear act as levers to amplify the vibrations of the sound wave. Also, since the pressure wave striking the larger area

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[5] http://www.uic.edu/classes/psych/psych352jw/ear.gif

of the eardrum is concentrated into the smaller area of the stirrup, the force of the vibrating stirrup is nearly 15 times larger than that of the eardrum. This enhances our ability of hear the faintest of sounds. The middle ear is connected by the Eustachian tube to the mouth. This connection allows for the equalisation of pressure within the air-filled cavities of the ear. When this tube becomes clogged during a cold, the ear cavity is unable to equalise its pressure; this will often lead to earaches.

The inner ear consists of a cochlea, the semicircular canals, and the auditory nerve. The cochlea and the semicircular canals are filled with fluid. The fluid and nerve cells of the semicircular canals serve no role in the task of hearing—they merely act as accelerometers, detecting movement and assisting in the task of maintaining balance. The cochlea is a snail-shaped organ that, if stretched out, would measure 2–3 cm. In addition to being filled with fluid, the inner surface of the cochlea is lined with over 20,000 hair-like nerve cells that perform one of the most critical roles in the hearing function. These nerve cells differ in length by minuscule amounts, and they have different degrees of resilience in the fluid that passes over them. As the stirrup vibrates against the wall of the cochlea, compression waves are generated in the fluid of the inner ear and the small hair-like nerve cells are set in motion. Each hair cell has a natural sensitivity to a particular frequency of vibration. When the frequency of the compression wave matches the natural frequency of the nerve cell, that nerve cell will resonate, oscillating with increased amplitude. As a result of this increase in amplitude, the cell generates an electrical impulse that passes along the auditory nerve to the brain. The brain, in turn, interprets different combinations of auditory signals as the different qualities of sound in our environment.

Interestingly, the fact that the auditory canal is about 2.5 cm long means that its resonant frequency is around 3,000 Hz, with the result that the human ear effectively amplifies, and is thus most sensitive to, sounds around this frequency.

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The Physics Classroom
(http://www.physicsclassroom.com/Default2.html)

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