Nice Physics Of Sound Review
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The Physics of Sound

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Auditory Scene Analysis

Auditory scene analysis is the process by which we perceive the distance, direction, loudness, pitch, and tone of many individual sounds simultaneously.

Analyzing auditory scenes is a complex human ability. Our environment surrounds us with constant sound. Even the smallest vibrations and echoes help us to identify our surrounding area. Sounds in a small area produce fewer echoes than sounds in a large area. Physical properties of an object can also be determined by sounds the object makes. When a ball is dropped onto a soft surface, it makes a different sound than it would if dropped onto a hard surface. As you walk across the floor you can hear the change in the sound of your footsteps when you cross from a carpeted area onto a tiled surface.

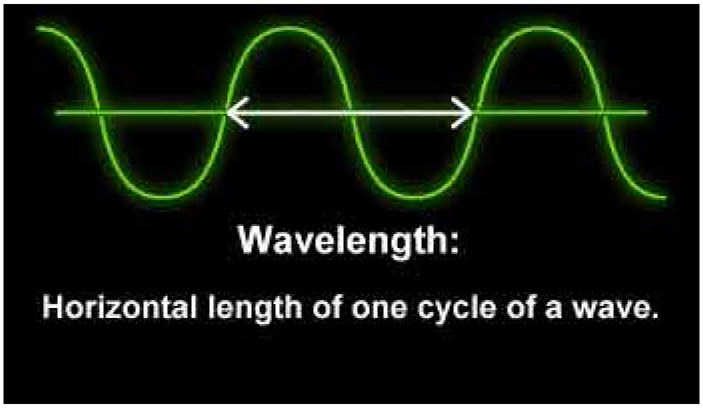
The simplest way in which we can determine the location of the source of a sound is by comparing the intensity of the sound in our ears. If we hear a greater intensity (a louder sound) in the right ear, we know that the sound is coming from somewhere to our right. Conversely, a sound that is louder in the left ear than in the right is identified as coming from our left. We can also use the overall intensity of a sound (the combined intensity of the sound reaching the left ear and the sound reaching the right) to determine the proximity of the source of the sound. Simply put, a soft sound is determined to be coming from farther away than a louder sound. Both the comparison of left and right ear receptions and the evaluation of the sound's intensity are done automatically, without any conscious thought, allowing us to quickly and easily identify the approximate location of the origin of a sound.

We can further pinpoint a sound's position in space by using the ear-body-brain combination to decode localization cues. Localization cues are divided into two categories. There are dynamic cues, such as vision, reverberation, early echo response, and head motion. For example, sounds that originate close to us produce relatively few echoes compared to those that originate farther away. There are also static cues: shoulder echo, pinna response, head shadow, and interaural time difference. The pinna response refers to the fact that the pinna filters out certain frequencies of sound depending on the direction from which the sound comes. Sounds coming from the back may, for example, have their 1000 Hz frequencies filtered out by the back of the pinna. We perceive this as a subtle change in the quality of a sound, but we are used to having sounds coming from behind us filtered in this way. Because of this we are able to use this change in quality as a way to determine if *the sound comes from in front of us, below us, behind us, or over us.*

The recording of sounds has progressed from simple to more complex levels in an attempt to replicate the way humans perceive sound. Early monophonic recordings progressed to stereo. Newer technologies, such as 3D sound and other advances in the digital era, are refining the process further. These recordings, however, are still crude imitations of the process by which the human ear receives and understands sound.

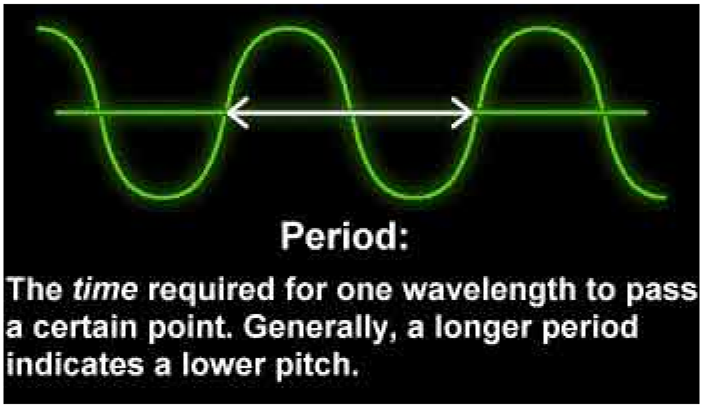
Wavelength and Period:

The wavelength is the horizontal distance between any two successive equivalent points on the wave. That means that the wavelength is the horizontal length of one cycle of the wave. The period of a wave is the time required for one complete cycle of the wave to pass by a point. So, the period is the amount of time it takes for a wave to travel a distance of one wavelength.



Amplitude:

The amplitude of a sound is represented by the height of the wave. When there is a loud sound, the wave is high and the amplitude is large. Conversely, a smaller amplitude represents a softer sound. A decibel is a scientific unit that measures the intensity of sounds. The softest sound that a human can hear is the zero point. When the sound is twice as loud, the decibel level goes up by six. Humans speak normally at 60 decibels.



Frequency:

Every cycle of sound has one condensation, a region of increased pressure, and one rarefaction, a region where air pressure is slightly less than normal. The frequency of a sound wave is measured in hertz. Hertz (Hz) indicate the number of cycles per second that pass a given location. If a speaker's diaphragm is vibrating back and forth at a frequency of 900 Hz, then 900 condensations are generated every second, each followed by a rarefaction, forming a sound wave whose frequency is 900 Hz.

Pitch:

How the brain interprets the frequency of an emitted sound is called the pitch. We already know that the number of sound waves passing a point per second is the frequency. The faster the vibrations the emitted sound makes (or the higher the frequency), the higher the pitch. Therefore, when the frequency is low, the sound is lower

The Speed of Sound

Sound travels at different speeds depending on what it is traveling through. Of the three mediums (gas, liquid, and solid) sound waves travel the slowest through gases, faster through liquids, and fastest through solids. Temperature also affects the speed of sound.

Gases

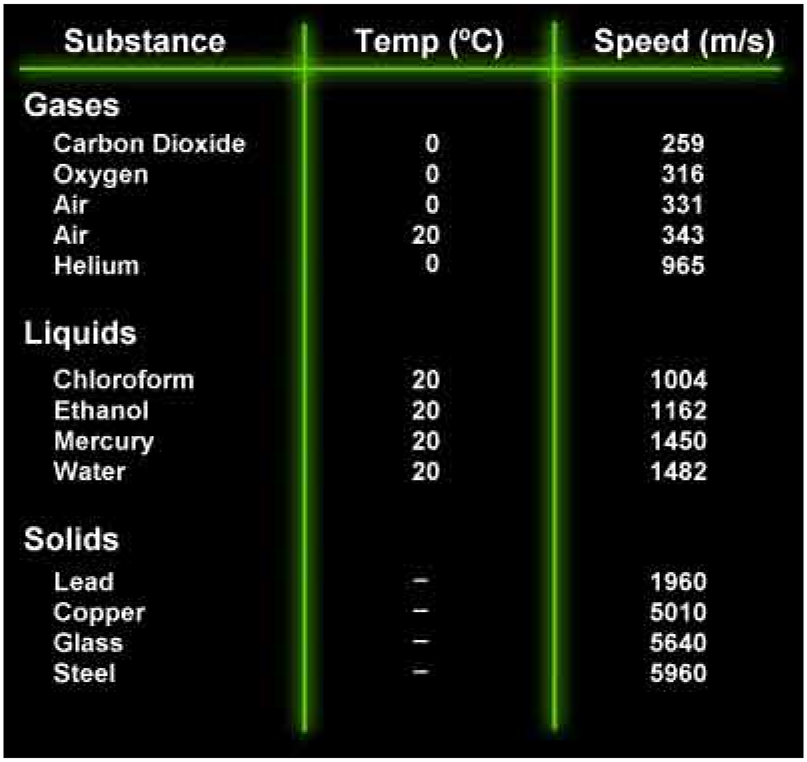
The speed of sound depends upon the properties of the medium it is passing through. When we look at the properties of a gas, we see that only when molecules collide with each other can the condensations and rarefactions of a sound wave move about. So, it makes sense that the speed of sound has the same order of magnitude as the average molecular speed between collisions. In a gas, it is particularly important to know the temperature. This is because at lower temperatures, molecules collide more often, giving the sound wave more chances to move around rapidly. At freezing (0º Celcius), sound travels through air at 331 meters per second (about 740 mph). But, at 20ºC, room temperature, sound travels at 343 meters per second (767 mph).

Liquids

Sound travels faster in liquids than in gases because molecules are more tightly packed. In fresh water, sound waves travel at 1,482 meters per second (about 3,315 mph). That's well over 4 times faster than in air! Several ocean-dwelling animals rely upon sound waves to communicate with other animals and to locate food and obstacles. The reason that they are able to effectively use this method of communication over long distances is that sound travels so much faster in water.

Solids

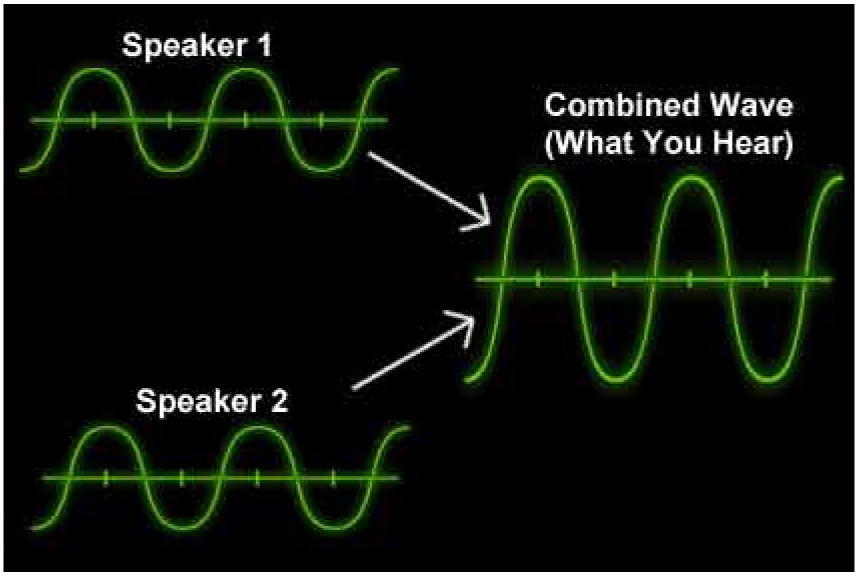
Sound travels fastest through solids. This is because molecules in a solid medium are much closer together than those in a liquid or gas, allowing sound waves to travel more quickly through it. In fact, sound waves travel over 17 times faster through steel than through air. The exact speed of sound in steel is 5,960 meters per second (13,332 mph)! But, this is only for the majority of solids. The speed of sound in all solids are not faster than in all liquids.



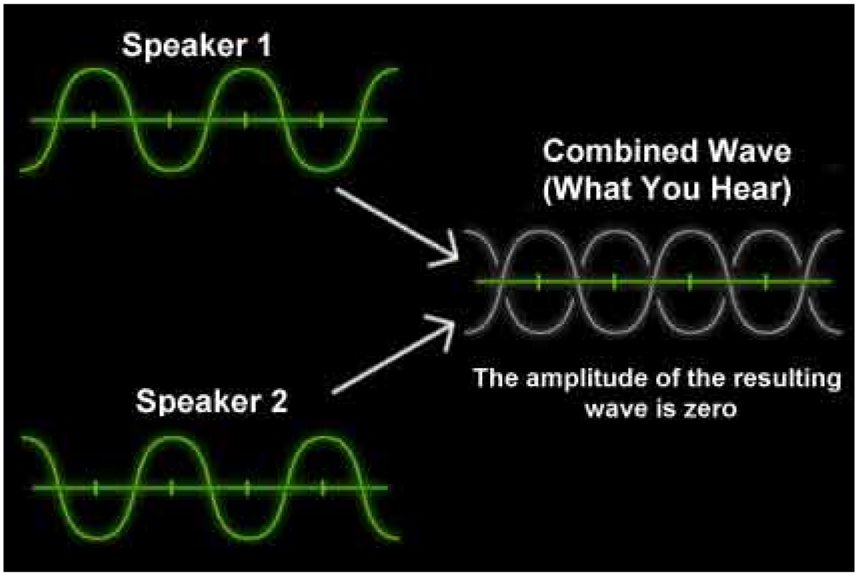
Substance	Temp (ºC)	Speed (m/s)
Gases		
Carbon Dioxide	0	259
Oxygen	0	316
Air	0	331
Air	20	343
Helium	0	965
Liquids		
Chloroform	20	1004
Ethanol	20	1162
Mercury	20	1450
Water	20	1482
Solids		
Lead	–	1960
Copper	–	5010
Glass	–	5640
Steel	–	5960

Constructive and Destructive Interference of Sound Waves

Let's set up a situation: two speakers are situated at the exact same distance (3 meters) away from you; and each speaker is emitting the same sound. We'll say that the wavelength of the sound is 1m. Finally, and most importantly, the speakers' diaphragms are vibrating synchronously (moving outward and inward together). Since the distance from the speakers to you is the same, the condensations of the wave coming from one speaker are always meeting the condensations from the other at the same time. As a result, the rarefactions are also always meeting rarefactions. One principle of sound is linear superposition, which states that the combined pattern of the waves is the sum of the individual wave patterns. So, the pressure fluctuations where the two waves meet have twice the amplitude of the individual waves. An increase in amplitude results in a louder sound. When this situation occurs it is said to be "exactly in phase" and to exhibit "constructive interference".



But, if we slightly change one of the variables, the resulting sound is nearly the opposite of what it was. Let's say we move one of the speakers .5m (1/2 of the wavelength) further away. We'll assume that the volume on this speaker is turned up so that the amplitude remains constant. This movement causes the condensations from one speaker to meet the rarefactions from the other sound wave and vice versa. Again referring to the principle of linear superposition, the result is a cancellation of the two waves. The rarefactions from one wave are offset by the condensation from the other wave producing constant air pressure. A constant air pressure means that you can hear no sound coming from the speakers. This is called "destructive interference" where two waves are "exactly out of phase".



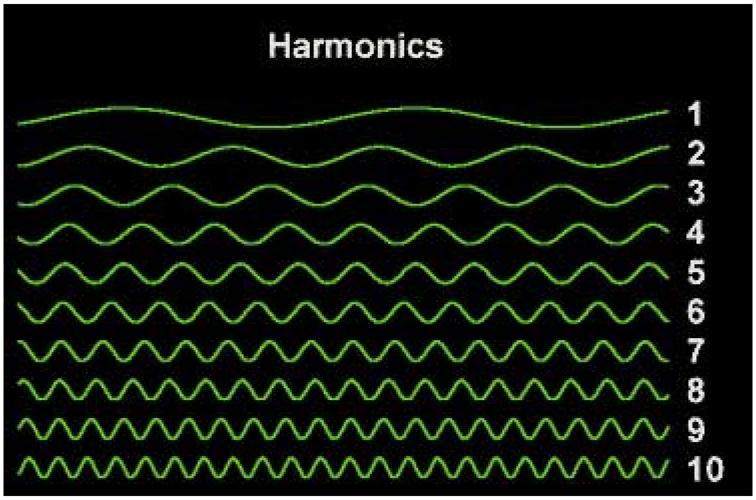
Noise Cancellation

Destructive interference, if applied correctly, can be very useful. It is very important that an airplane pilot hears what\'s going on around him, but engine noise presents a problem. So, pilots can use special headphones mounted with a microphone that picks up the engine noise. A component in the headphones then creates a wave that is the inverse of the wave that represents the engine noise. This wave is then played back through the headphones allowing destructive interference to produce a quieter background. Other applications for destructive interference are "quieting" rides in automobiles and passenger sections in airplanes.

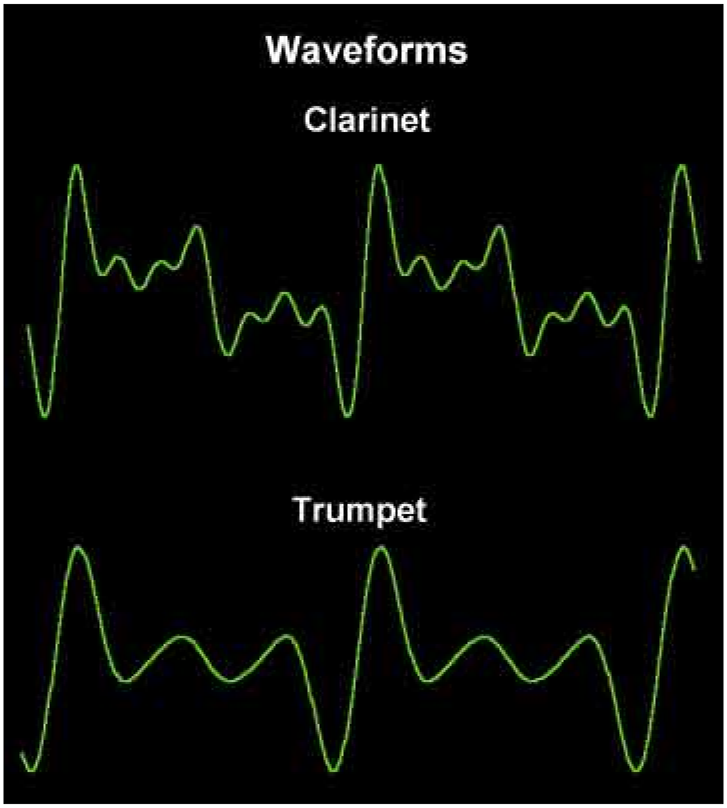
Harmonic Synthesis

If a clarinet and a trumpet play the same note, they sound very different from each other. Although they might have the same pitch and the same fundamental frequency (same note, for example, 440 Hz), they don't have the same tone quality. Where the two instruments differ is in harmonics.

Harmonics are tones whose frequencies are integral multiples of the fundamental frequency of the wave. For example, if an A is being played at 440 Hz, the frequencies of the harmonics will be 880 Hz, 1320 Hz, and so on. The harmonics are numbered in order of increasing frequency. Thus, the first harmonic is the fundamental frequency, the second is twice the fundamental frequency, etc. The relative strengths of these harmonics determine the timbre, or quality, of the tone.



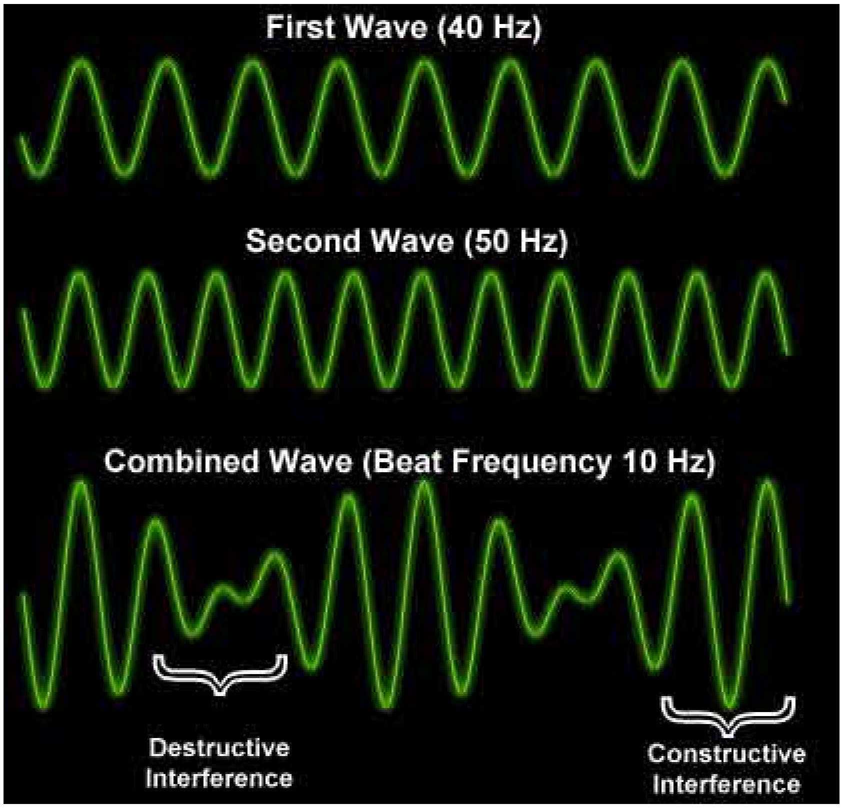
Each instrument is producing harmonics whose relative intensities depend on the type and make of the instrument and how the musician plays it. The graphs of the sound waves for these two instruments are called waveforms. The waveform of a tuner contains no other harmonics, only the fundamental frequency. However, the waveform of the clarinet contains large amounts of the third, fifth, and seventh harmonics, and smaller amounts of the second, fourth, and sixth harmonics, and of course, the first harmonic, the fundamental frequency. The trumpet's waveform consists of a large amount of the third harmonic, and some from the second, fourth, and fifth harmonics, along with the fundamental frequency



Harmonic synthesis is the construction of a sound wave from its harmonic components. In order to come as close as possible to the exact waveform of the instrument, more harmonics must be used in the synthesis of the instrument's sound. Electronic music synthesizers use a series of harmonics whose relative amplitudes can be adjusted to fit the desired instrument's waveform. On more advanced synthesizers, they can adjust the attack, decay, vibrato, tremolo, and release of each note. Bands today use synthesizers all the time in their music because the sound they produce is nearly indistinguishable from the real instruments sound. The reverse of harmonic synthesis is harmonic analysis, where a sound is broken up into it's harmonics. This requires complex math called Fourier analysis, after Jean Baptiste Joseph Fourier, a French mathematician who studied periodic functions.

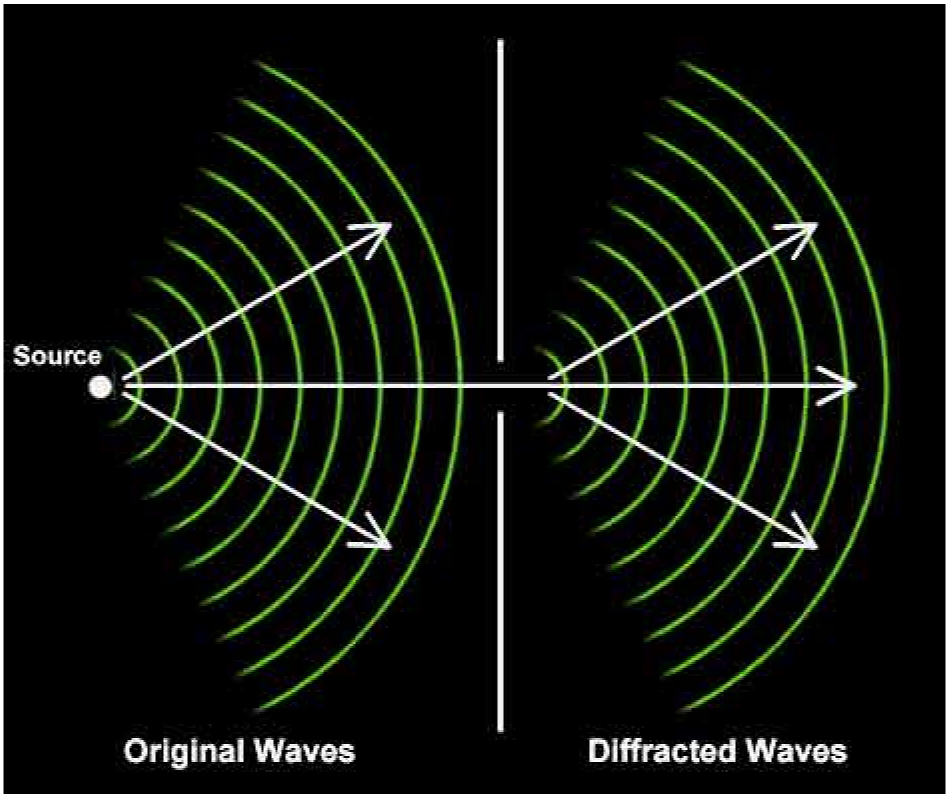
Beats

Now that we know what happens when two sound waves with the same frequency overlap, let's explore what happens when two sound waves with different frequencies overlap. Two instrument tuners are placed side by side, one set to emit a sound whose frequency is 440 Hz and the other set to emit a sound whose frequency is 438 Hz. If the two tuners (which have the same amplitude) are turned on at the same time, you will not hear a constant sound. Instead, the loudness of the combined sound rises and falls. Whenever a condensation meets a condensation or a rarefaction meets a rarefaction, there is constructive interference and the amplitude increases. Whenever a condensation meets a rarefaction and vice versa, there is destructive interference, and you can hear nothing. These periodic variations in loudness are called beats. In this situation you will hear the loudness rise and fall 2 times per second because 440-438=2. So, there is a beat frequency of 2 Hz. Musicians listen for beats to hear if their instruments are out of tune. The musician will listen to a tuner that has the correct sound and plays the note on his intrument. If the musician can hear beats, then he knows that the instrument is out of tune. When the beats disappear, the musician knows the instrument is in tune.



Diffraction

An obstacle is no match for a sound wave; the wave simply bends around it. For example, if a stereo is playing in a room with the door open, the sound produced by the stereo will bend around the walls surrounding the opening. This bending of a wave is called diffraction. All waves exhibit diffraction, not just sound waves. Without diffraction, the sound from the stereo could only be heard directly in front of the door. Instead, the air in the doorway is set into longitudinal vibration by the sound waves from the stereo. This means that each air molecule is a source of a sound wave itself. This results in each molecule producing a sound wave and emitting it outward in a spherical fashion. The final result is the diffraction of the sound wave around the doorway.



The sound outside of the room has varying intensity depending on where you stand. Directly in front of the center of the doorway the intensity is a maximum. As you move further away from the center, the intensity decreases until it is at zero, then increases to a maximum, falls to zero, rises to a maximum...and so on. Each maxima gets progressively softer further away from the center. Waves diffract differently depending on the object they are bending around. If we let angle x be the location of the first minimum intensity point on either side of the center, W be the wavelength, and D be the width of the doorway, the equation

$$\sin x = \frac{W}{D}$$

gives x in terms of the wavelength and the width of the doorway. For a circular opening, the equation is slightly different. Angle x, W for wavelength, and D for width are all still the same. The equation looks like this:

$$\sin x = 1.22\,\frac{W}{D}$$

So, looking at these two equations you can tell that the extent of the diffraction depends on the ratio of the wavelength to the size and shape of the opening. If the ratio of W/D is large, then x is large. In this case, the waves are said to have a wide dispersion and the sound waves are spread out wider through the opening. Conversely, if the ratio of W/D is small, then x is small and the waves are said to have a narrow dispersion and *the sound waves go through the opening without spreading out very much. So, it makes sense that lower-frequency sounds typically have a wide dispersion and sounds with small wavelenths have a narrow dispersion*

The Doppler Effect

As an ambulance speeds towards you, sirens blazing, the sound you hear is rather high in pitch. This is because the sound waves in front of the vehicle are being squashed together by the moving ambulance. This causes more vibrations to reach your ear per second. As you know, more vibrations per second results in a higher pitched sound. When the ambulance passes you, the sound becomes lower in pitch. Behind the ambulance there are fewer vibrations per second, and a lower sound is heard. This change in pitch is known as the Doppler Effect. When a vehicle travels faster than the speed of sound, about 330 meters per second, a sonic boom can be heard. As the vehicle overtakes its own sound, the sound waves spread out behind in a shockwave, or sonic boom.

The Intensity of Three-Dimensional Waves

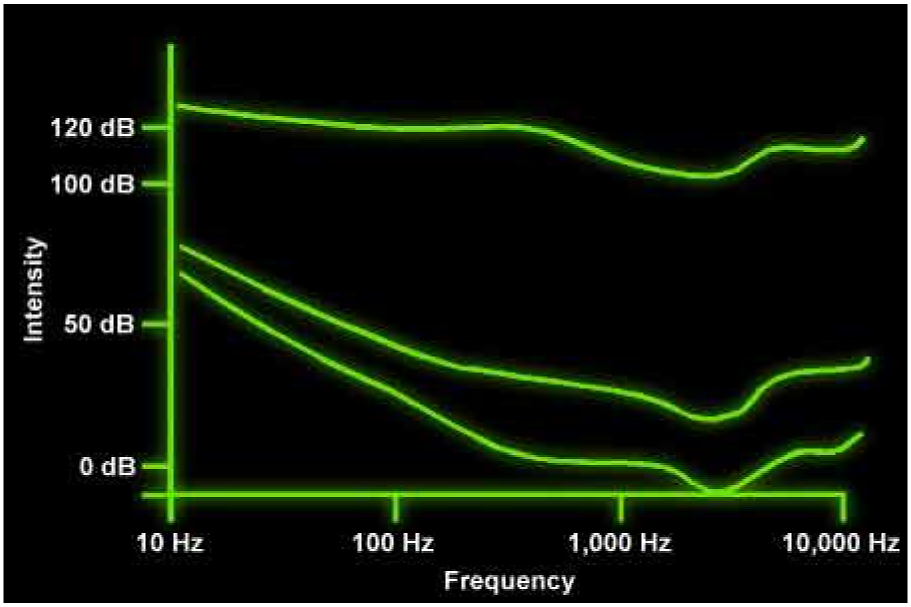
A two-dimensional sound wave looks like a series of concentric circles that get bigger as they move further away from their origin. These circles are called wavefronts. In real life, sound waves grow in three dimensions. Three-dimensional waves move out in all directions away from their origin in wavefronts that are concentric spherical surfaces. The space in between wavefronts is the wavelength. Rays indicate the motion of a set of wavefronts. Rays are lines perpendicular to the wavefronts that originate at the source of the sound and follow the wavefronts outward. If the sound is emitted evenly in all directions, the energy at a distance r from the source will be uniform on the spherical shell. If we let P equal the original power the sound has when emitted from the source, the intensity per unit area (the surface area of a sphere is the denominator) at a distance r from the source will be:

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

The intensity level of sound is measured in decibels (dB). Decibels are units of intensity that are based upon a logarithmic scale. This means that a sound with an intensity of 20 dB is ten times as loud as one with an intensity of 10 dB, 30 dB is ten times as intense as 20 dB, and so on. The reason for this logarithmic scale is that humans hear intensity on a similar logarithmic scale. So, while a 20 dB sound is ten times as intense as a 10 dB sound, we perceive it as only twice as loud. The hearing threshold (level at which humans begin to perceive sound) is 0 dB. When a sound reaches upwards of 120 dB, it is above the threshold of pain (point at which most people begin feeling pain). Everything in between can be heard by a human with normal hearing

Source	Decibels	Description
	0	Hearing Threshold
Normal Breathing	10	Barely Audible
Rustling Leaves	20	
Soft Whisper	30	Very Quiet
Library	40	
Quiet Office	50	Quiet
Conversastion	60	
Busy Traffic	70	
Average Factory	80	
Niagara Falls	90	Constant Exposure Endangers Hearing
Train	100	
Construction Noise	110	
Rock Concert	120	Pain Threshold
Machine Gun	130	
Jet Takeoff	150	
Rocket Engine	180	

But, these levels aren't constants. What a human perceives as loud or soft depends on the frequency as well as the intensity of the sound. The graph below displays intensity levels compared with the frequencies for sounds of equal loudness for humans. The bottom line is the threshold of hearing. At a 1 kHz frequency, the hearing threshold is 0 dB, but at 60 Hz the decibel level is 50. Only one percent of all human beings can hear sounds this low, so, the lower line is mainly for those with very good hearing. The next line up is the hearing threshold for the majority of people. The top line is the pain threshold. Other than at one point, about 4 kHz, this line varies little. All of the other lines also dip down at 4 kHz. We can gather from this graph, then, that the human ear is most sensitive at about 4 kHz.



APPLICATIONS OF SOUND

Ultrasonic Waves (know infrasonic too…frequencies BELOW 20 Hz)

Humans can normally hear sound frequencies between 20 and 20,000 Hz (20kHz). When a sound wave's frequency lies above 20 kHz, it is called an ultrasonic wave. While we cannot hear ultrasonic waves, we apply them in various technologies such as sonar systems, sonograms, surgical tools, and cleaning sytems. Some animals also use ultrasonic waves in a specialized technique called echolocation that alows them to pinpoint objects and other animals, even in the dark.

Sonar

Sonar stands for SOund NAvigation Ranging. Sonar is used in navigation, forecasting weather, and for tracking aircraft, ships, submarines, and missiles. Sonar devices work by bouncing sound waves off objects to determine their location. A sonar unit consists of an ultrasonic transmitter and a receiver. On boats, the receiver is mounted on the bottom of the ship. To measure water depth, for instance, the transmitter sends out a short pulse of sound, and later, the receiver picks up the reflected sound. The water depth is determined from the time elapsed between the emission of the ultrasonic sound and the reception of its reflection off the sea-floor. In the diagram below, a ship sends out ultrasonic waves (green) in order to detect schools of fish swimming beneath. The waves reflect off the fish (white), and return to the ship where they are detected and the depth of the fish is determined.

Echolocation

In 1944, Donald R. Griffin coined the term echolocation. Echolocation is the use of echoes of sound produced by certain animals to detect obstacles and food. Animals that live where lighting is unpredictable use echolocation. Some of these animals are bats, porpoises, some kinds of whales, several species of birds, and some shrews. The first step in echolocation is emitting a sound. High-frequency sounds provide better resolution of targets than lower-frequency sounds. Not every animal uses ultrasonic sounds in echolocation, but they are more effective. Still, sounds used in echolocation can be produced in the voice box, the mouth, or some other part of the head. Then, a highly refined auditory system detects the returning echoes (the sounds that bounced of the object). In order for echolocation to work, the outgoing pulses of sound need to register in the organism's brain, so it can be compared to its echo. Using echolocation, some animals can effectively catch prey and "see" in the dark.