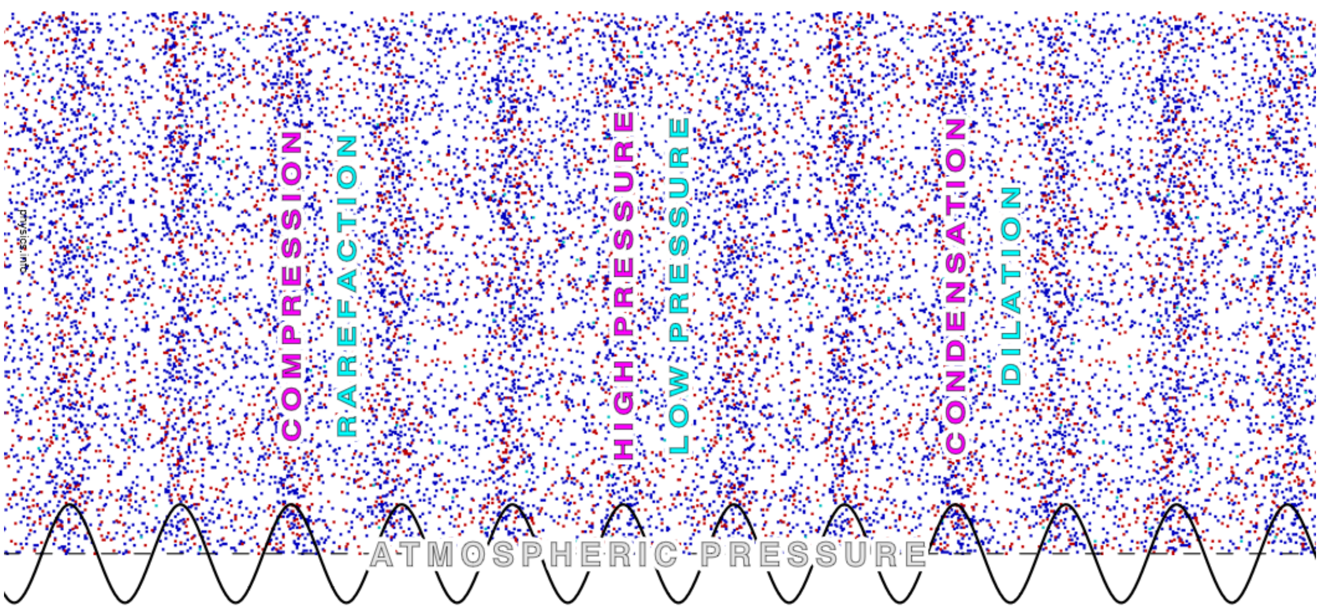
Sound

Sound is a longitudinal, mechanical wave. Sound can travel through any medium, but it cannot travel through a vacuum. There is no sound in outer space.
Sound is a variation in pressure.
A region of *increased* pressure on a sound wave is called a *compression* (or *condensation*).
A region of *decreased* pressure on a sound wave is called a *rarefaction* (or *dilation*).

snapshot of a longitudinal wave in air



instantaneous local pressure

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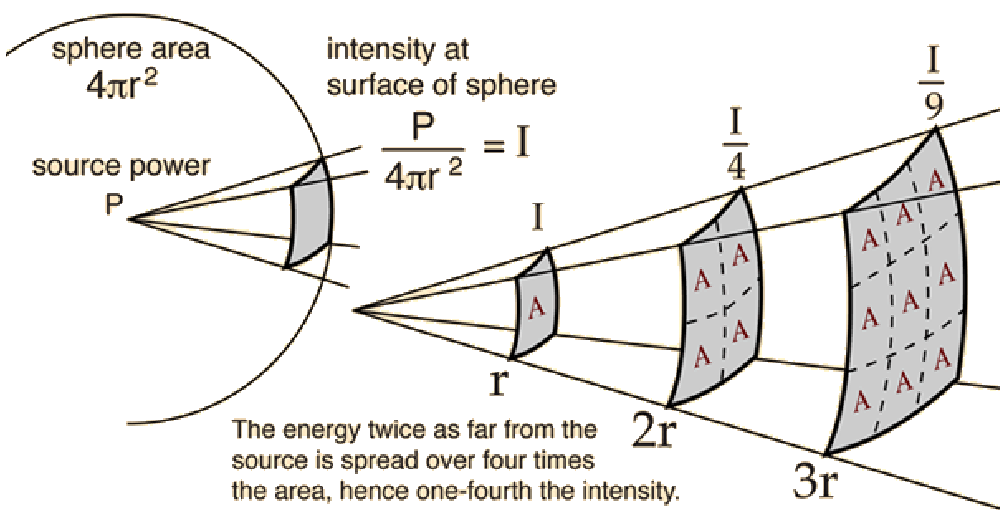
Inverse Square Law, Sound

The sources of sound
•vibrating solids
•rapid expansion or compression (explosions and implositons)
•Smooth (laminar) air flow around blunt obstacles may result in the formation of vorticies (the plural of vortex) that snap off or shed with a characteristic frequency. This process is called vortex shedding and is another means by which sound waves are formed. This is how a whistle or flute produces sound. Aslo the aeolian harp effect of singing power lines and fluttering venetian blinds.

The *sound intensity* from a point source of sound will obey the ***inverse square law*** if there are no reflections or reverberation. A plot of this intensity drop shows that it drops off rapidly.



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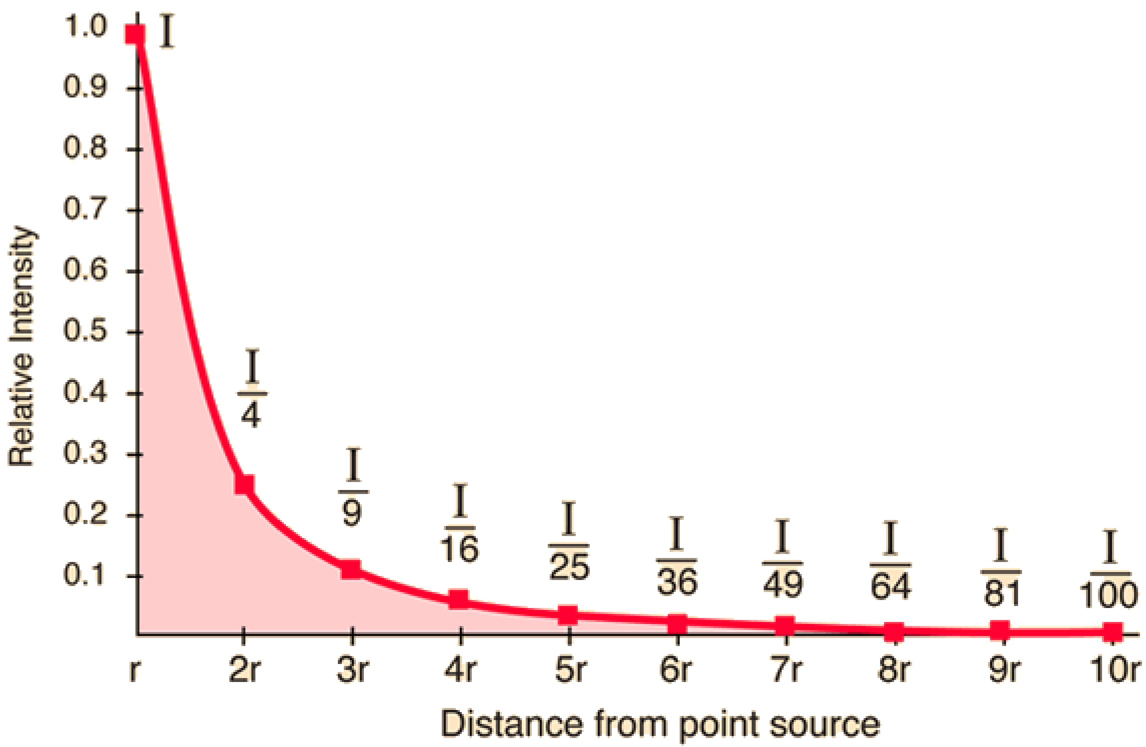
Inverse Square Law Plot

A plot of the drop of sound intensity according to the inverse square law emphasizes the rapid loss associated with the ***inverse square law***. In an auditorium, such a rapid loss is unacceptable. It is mitigated by the reverberation in a good auditorium. This plot shows the points connected by straight lines but the actual drop is a smooth curve between the points.



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Sound Speed in an Ideal Gas

The speed of sound for a uniform medium is determined by its elastic property (*bulk modulus*) and its density

$$v = \sqrt{\frac{elastic\ property}{inertial\ property}} = \sqrt{\frac{B}{\rho}}$$

where $B = bulk\ modulus = \frac{\Delta P}{-\Delta V/V} = -V\frac{dP}{dV}$; ρ – density.

When a sound travels through an ideal gas, the rapid compressions and expansions associated with the longitudinal wave can reasonably be expected to be adiabatic and therefore the pressure and volume obey the relationship

$$V^{\gamma}P = constant = C$$

The adiabatic assumption for sound waves just means that the compressions associated with the sound wave happen so quickly that there is no opportunity for heat transfer in or out of the volume of air. The bulk modulus can therefore be reformulated by making use of the adiabatic condition in the form

$$P = CV^{-\gamma}$$

so that the derivative of pressure P with respect to volume V can be taken.

$$B = -V\frac{dP}{dV} = CV\gamma V^{-\gamma-1} = \frac{C\gamma}{V^{\gamma}};$$

Sound Speed in an Ideal Gas

Since the gas density is $\rho = \frac{nM}{V}$ the speed of sound can be expressed as

$$v_{sound} = \sqrt{\frac{C\gamma V}{V^{\gamma} nM}} = \sqrt{\frac{\gamma PV}{nM}} \text{ since } \frac{C}{V^{\gamma}} = P$$

Using the ideal gas law $PV = nRT$ leads to

$$v_{sound\ in\ gas} = \sqrt{\frac{\gamma RT}{M}}$$

Where
γ – adiabatic constant, characteristic of the specific gas;
R – the universal gas constant = 8.314 J/mol K;
M – the molecular weight of the gas in kg/mol;
T – absolute temperature

The conditions for this relationship are that the sound propagation process is adiabatic and that the gas obeys the ideal gas law.

Speed of Sound in Air

The speed of sound in dry air is given approximately by

$$v_{sound\ in\ air} = 331.4 + 0.6T_C \quad (m/sec)$$

for temperatures reasonably close to room temperature, where T_C is the Celsius temperature.

If you measured sound speed in your oven, you would find that this relationship doesn't fit. At 200°C this relationship gives 453 m/s while the more accurate formula gives 436 m/s. This sound speed does not apply to gases other than air, for example the helium from a balloon.

It is important to note that the sound speed in air is determined by the air itself. It is not dependent upon the sound amplitude, frequency or wavelength.

Speed of Sound in Air

For air, the adiabatic constant γ = 1.4 and the average molecular mass for dry air is 28.95 gm/mol. This leads to

$$v_{sound} = \sqrt{\frac{1.4(8.314 J/mol{\cdot}K)}{0.02895\ kg/mol}}\sqrt{T} = 20.05\sqrt{T} \quad (m/sec)$$

The calculation above was done for dry air, and moisture content in the air would be expected to increase the speed of sound slightly because the molecular weight of water vapor is 18 compared to 28.95 for dry air. A revised average molecular weight could be calculated based on the vapor pressure of water in the air. However, the assumption of an adiabatic constant of γ = 1.4 used in the calculation is based upon the diatomic molecules N_2 and O_2 and does not apply to water molecules. So the detailed modeling of the effect of water vapor on the speed of sound would have to settle on an appropriate value of γ to use.

Sound Speed in Gases

Gas	Temperature (°C)	Speed in m/s
Air	0	331.5
Air	20	344
Hydrogen	0	1270
Carbon dioxide	0	258
Helium	20	927
Water vapor	35	402

Sound in Liquids

The propagation speeds of traveling waves are characteristic of the media in which they travel and are generally not dependent upon the other wave characteristics such as frequency, period, and amplitude. The speed of sound in air and other gases, liquids, and solids is predictable from their density and elastic properties of the media (bulk modulus).

In a water the wave is:

$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.2 \times 10^9 N/m^2}{1000\ kg/m^3}} = 1483\ m/s$$

This agrees well with the measured speed of sound in water, 1482 m/s at 20°C. The situation with solids is considerably more complicated, with different wave speeds in different directions, in different kinds of geometries, and differences between transverse and longitudinal waves.

For example, a general tabulated value for the bulk modulus of steel gives a sound speed for structural steel of

$$v = \sqrt{\frac{160 \times 10^9 N/m^2}{7860\ kg/m^3}} = 4512\ m/s$$

Sound in Liquids and Metals

Selected Sound Speeds in Metals

Metal	Density (gm/cm^3)	V_l m/s	V_s m/s	V_{ext} m/s
Aluminum, rolled	2.7	6420	3040	5000
Brass (70 Cu, 30 Zn)	8.6	4700	2110	3480
Steel, 347 stainless	7.9	5790	3100	5000

- V_l = velocity of plane longitudinal wave in bulk material
- V_s = velocity ofplane transverse (shear) wave
- V_{ext} = velocity of longitudinal wave (extensional wave) in thin rod

Sound Speed in Liquids

Liquid	Temperature (°C)	Speed in m/s
Water	0	1402
Water	20	1482
Methyl alcohol	0	1130
Sea water 3.5% salinity	20	1522

The speed of sound in liquids depends upon the temperature. This is useful in monitoring the temperature of oceans and other large bodies of water because pulses of low frequency sound can travel thousands of kilometers through the ocean and still be detected. The pulse traverse time can be measured with a network of stations to monitor changes in the temperature of the intervening water. When compared to changes predicted by climate models, this can give some indication of whether global warming from the greenhouse effect is occurring.

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Sound Intensity

Sound intensity is defined as the sound power per unit area. The usual context is the measurement of sound intensity in the air at a listener's location. The basic units are watts/m^2 or watts/cm^2. Many sound intensity measurements are made relative to a standard threshold of hearing intensity I_0 :

$$I_0 = 10^{-12}\, watts/m^2 = 10^{-16}\, watts/cm^2$$

The most common approach to sound intensity measurement is to use the ***decibel scale***:

$$I(dB) = 10 \log_{10} \left[\frac{I}{I_0}\right]$$

Decibels measure the ratio of a given intensity I to the threshold of hearing intensity , so that this threshold takes the value 0 decibels (0 dB). To assess sound loudness, as distinct from an objective intensity measurement, the sensitivity of the ear must be factored in.

Sound Pressure

Since audible sound consists of pressure waves, one of the ways to quantify the sound is to state the amount of pressure variation relative to atmospheric pressure caused by the sound. Because of the great sensitivity of human hearing, the threshold of hearing corresponds to a pressure variation less than a billionth of atmospheric pressure.

The standard threshold of hearing can be stated in terms of pressure and the sound intensity in decibels can be expressed in terms of the sound pressure:

$$P_0 = 2 \times 10^{-5}\ Newtons/m^2$$

$$I(dB) = 10\log_{10}\left[\frac{I}{I_0}\right] = 10\log_{10}\left[\frac{P^2}{P_0^2}\right] = 20\log_{10}\left[\frac{P}{P_0}\right]$$

The pressure P here is to be understood as the amplitude of the pressure wave. The power carried by a traveling wave is proportional to the square of the amplitude. The factor of 20 comes from the fact that the logarithm of the square of a quantity is equal to 2 x the logarithm of the quantity.

Since common microphones such as dynamic microphones produce a voltage which is proportional to the sound pressure, then changes in ***sound intensity incident on the microphone*** can be calculated from

$\Delta I(dB) = 20\log_{10}\left[\frac{V_2}{V_1}\right]$, where V_1 and V_2 are the measured voltage amplitudes .

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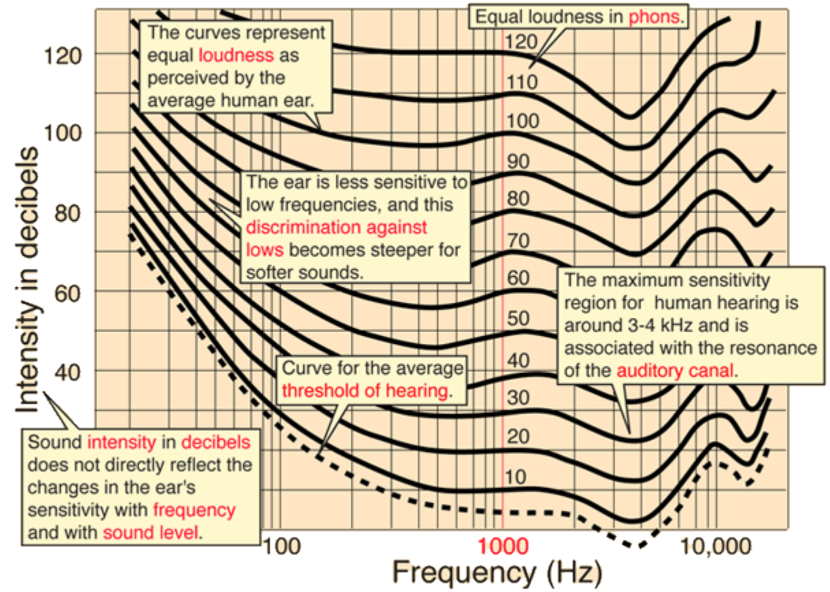
Threshold of Hearing

Sound level measurements in decibels are generally referenced to a standard threshold of hearing at 1000 Hz for the human ear which can be stated in terms of sound intensity:

$$I_0 = 10^{-12} watts/m^2 = 10^{-16} watts/cm^2$$

or in terms of sound pressure:

$$P_0 = 2 \times 10^{-5} Newtons/m^2 = 2 \times 10^{-4} dyne/cm^2$$



This value has wide acceptance as a nominal standard threshold and corresponds to 0 decibels. It represents a pressure change of less than one billionth of standard atmospheric pressure. This is indicative of the incredible sensitivity of human hearing. The actual average threshold of hearing at 1000 Hz is more like 2.5×10^{-12} watts/m^2 or about 4 decibels, but zero decibels is a convenient reference. The threshold of hearing varies with frequency, as illustrated by the measured hearing curves.

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Threshold of Pain

The nominal dynamic range of human hearing is from the standard *threshold of hearing* to the *threshold of pain*. A nominal figure for the threshold of pain is 130 decibels, but that which may be considered painful for one may be welcomed as entertainment by others. Generally, younger persons are more tolerant of loud sounds than older persons because their protective mechanisms are more effective. This tolerance does not make them immune to the damage that loud sounds can produce.

The ear has incredible sensitivity

Threshold of hearing I_0 less than one billionth of atmospheric pressure

and an incredible power range of operation.

Threshold of pain $10^{13}\ I_0 = 10\ 000\ 000\ 000\ 000\ I_0$

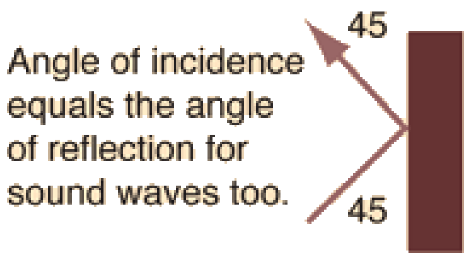
Some sources quote 120 dB as the pain threshold and define the audible sound frequency range as ending at about 20,000 Hz where the threshold of hearing and the threshold of pain meet.

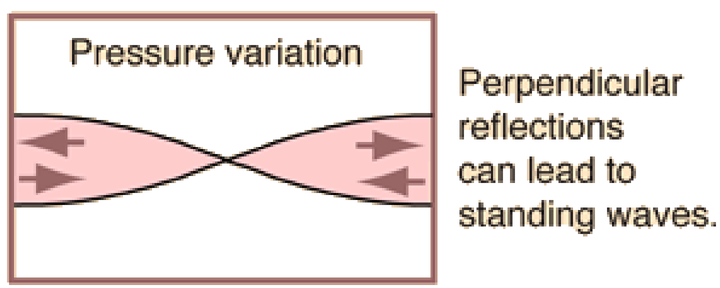
Reflection of Sound

The reflection of sound follows the ***law "angle of incidence equals angle of reflection",*** sometimes called the ***law of reflection.***

The same behavior is observed with light and other waves, and by the bounce of a billiard ball off the bank of a table. The reflected waves can interfere with incident waves, producing patterns of constructive and destructive *interference*. This can lead to *resonances* called *standing waves* in rooms.

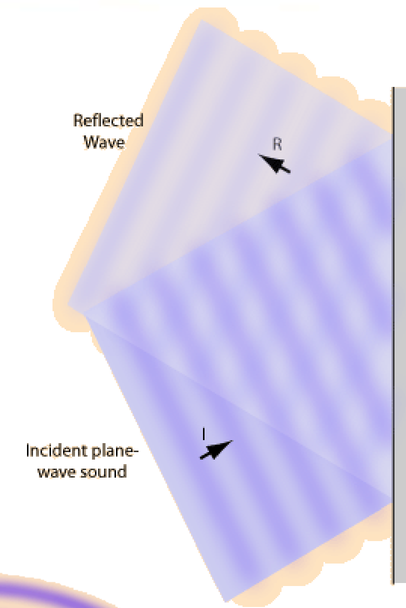
It also means that the sound intensity near a hard surface is enhanced because the reflected wave adds to the incident wave, giving a pressure amplitude that is twice as great in a thin "pressure zone" near the surface. This is used in *pressure zone microphones* to increase sensitivity. The doubling of pressure gives a 6 decibel increase in the signal picked up by the microphone. Reflection of waves in strings and air columns are essential to the production of resonant standing waves in those systems.





Plane Wave Reflection

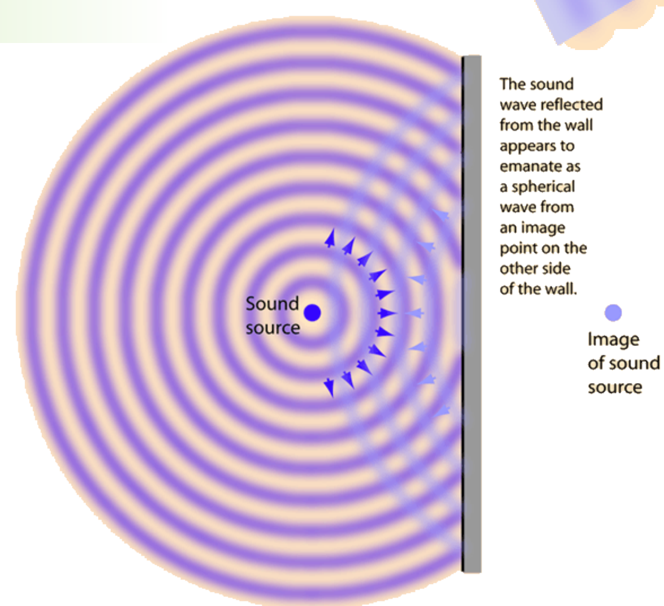
"The angle of incidence is equal to the angle of reflection" is one way of stating the law of reflection for light in a plane mirror.



Point source of sound reflecting from a plane surface

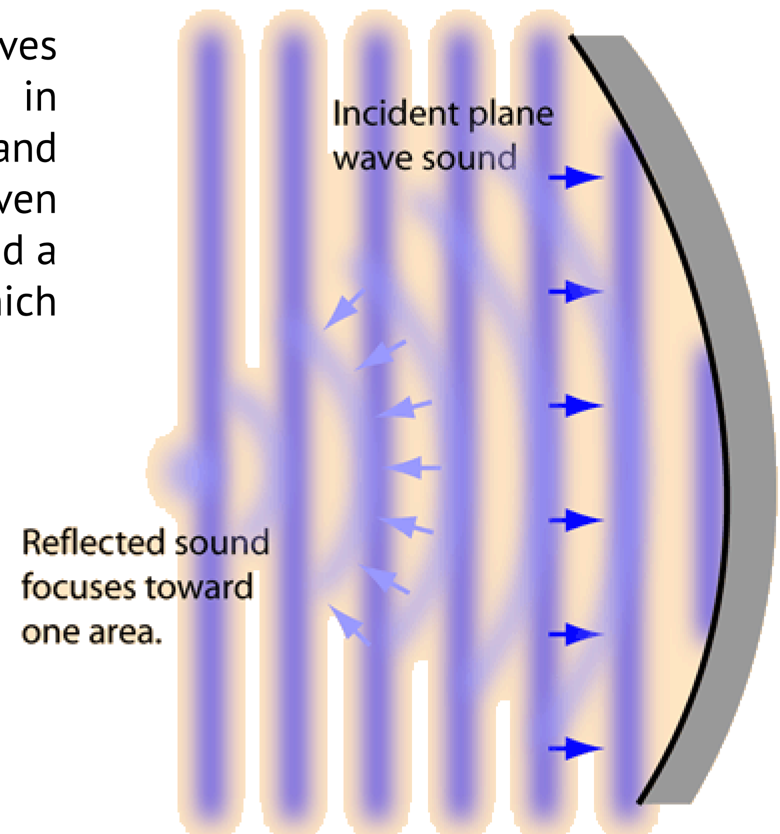
When sound waves from a point source strike a plane wall, they produce reflected spherical wavefronts as if there were an "image" of the sound source at the same distance on the other side of the wall.

If something obstructs the direct sound from the source from reaching your ear, then it may sound as if the entire sound is coming from the position of the "image" behind the wall. This kind of sound imaging follows the same law of reflection as your image in a plane mirror.



Reflection from Concave Surface

Any concave surface will tend to focus the sound waves which reflect from it. This is generally undesirable in auditorium acoustics because it produces a "hot spot" and takes sound energy away from surrounding areas. Even dispersion of sound is desirable in auditorium design, and a surface which spreads sound is preferable to one which focuses it.



Phase Change Upon Reflection

The phase of the reflected sound waves from hard surfaces and the reflection of string waves from their ends determines whether the interference of the reflected and incident waves will be constructive or destructive. For string waves at the ends of strings there is a reversal of phase and it plays an important role in producing resonance in strings. Since the reflected wave and the incident wave add to each other while moving in opposite directions, the appearance of propagation is lost and the resulting vibration is called a standing wave.

When sound waves in air (pressure waves) encounter a hard surface, there is no phase change upon reflection. That is, when the high pressure part of a sound wave hits the wall, it will be reflected as a high pressure, not a reversed phase which would be a low pressure. Keep in mind that when we talk about the pressure associated with a sound wave, a positive or "high" pressure is one that is above the ambient atmospheric pressure and a negative or "low" pressure is just one that is below atmospheric pressure. A wall is described as having a higher "acoustic impedance" than the air, and when a wave encounters a medium of higher acoustic impedance there is no phase change upon reflection.

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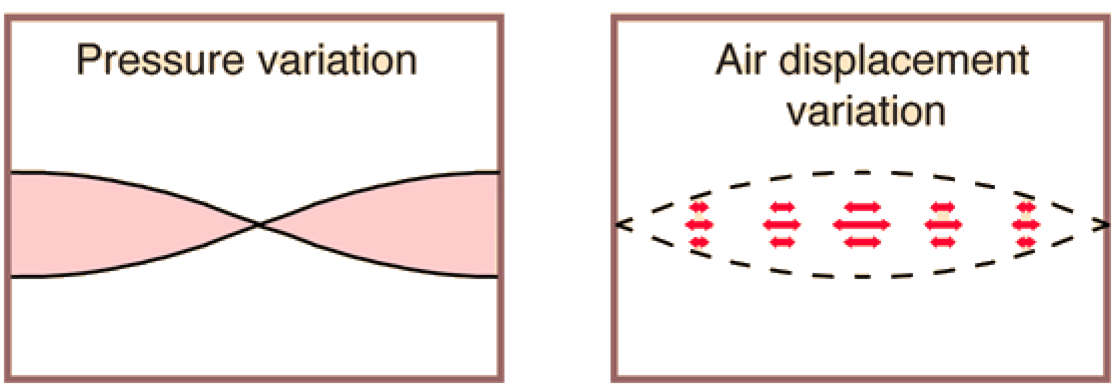
Phase Change Upon Reflection

On the other hand, if a sound wave in a solid strikes an air boundary, the pressure wave which reflects back into the solid from the air boundary will experience a phase reversal - a high-pressure part reflecting as a low-pressure region. That is, reflections off a lower impedance medium will be reversed in phase.

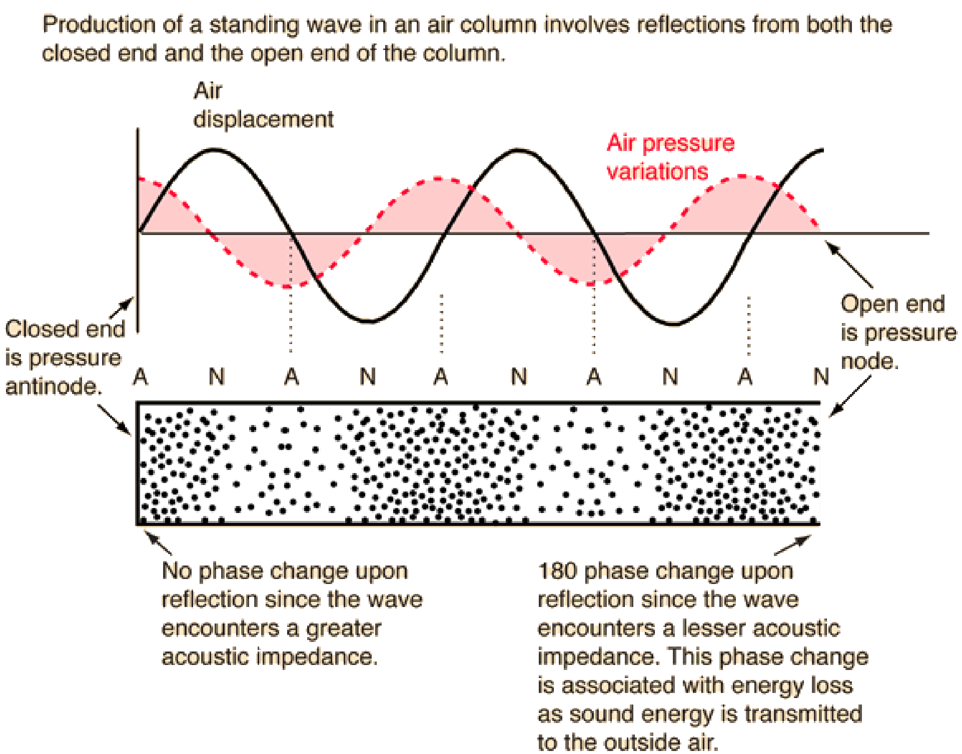
Besides manifesting itself in the "pressure zone" in air near a hard surface, the nature of the reflections contribute to standing waves in rooms and in the air columns which make up musical instruments.

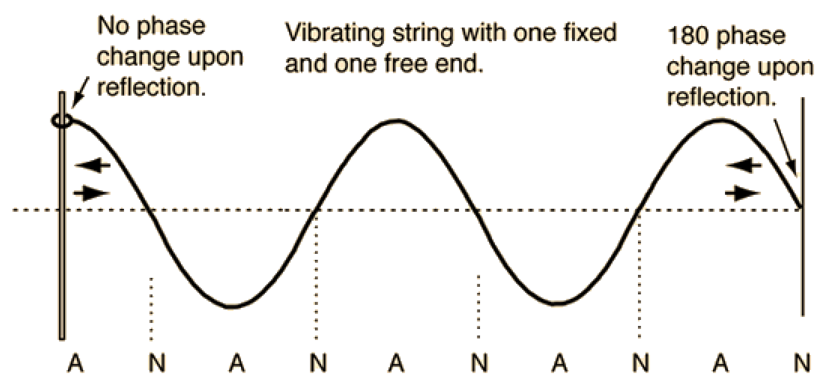
The longest wavelength standing wave in a room has a wavelength twice the room dimension.



Phase Change Upon Reflection

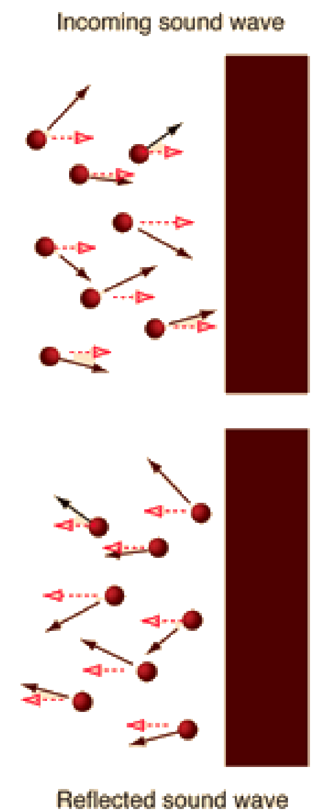
The conditions which lead to a phase change on one end but not the other can also be envisioned with a string if one presumes that the loose end of a string is constrained to move only transverse to the string. The loose end would represent an interface with a smaller effective impedance and would produce no phase change for the transverse wave. In many ways, the string and the air column are just the inverse of each other.





Pressure Zone

The sound intensity near a hard surface is enhanced because the reflected wave adds to the incident wave, giving a pressure amplitude that is twice as great in a thin "pressure zone" near the surface. This is used in pressure zone microphones to increase sensitivity. The doubling of pressure gives a 6 decibel increase in the signal picked up by the microphone.



This is an attempt to visualize the phenomenon of the pressure zone in terms of the dynamics of the air molecules involved in transporting the sound energy. The air molecules are of course in ceaseless motion just from thermal energy and have energy as a result of the atmospheric pressure. The energy involved in sound transport is generally very tiny compared to that overall energy. If you visualize the velocity vectors shown in the illustration as just that additional energy which associated with the sound energy in the longitudinal wave, then we can argue that the horizontal components of the velocities will just be reversed upon collision with the wall. Presuming the collisions with the wall to be elastic, no energy is lost in the collisions.

Viewing the collection of molecules as a "fluid", we can invoke the idea that the internal pressure of a fluid is a measure of energy density. The energy of the molecules reflecting off the wall adds to that of the molecules approaching the wall in the volume very close to the wall, effectively doubling the energy density and hence the pressure associated with the sound wave.

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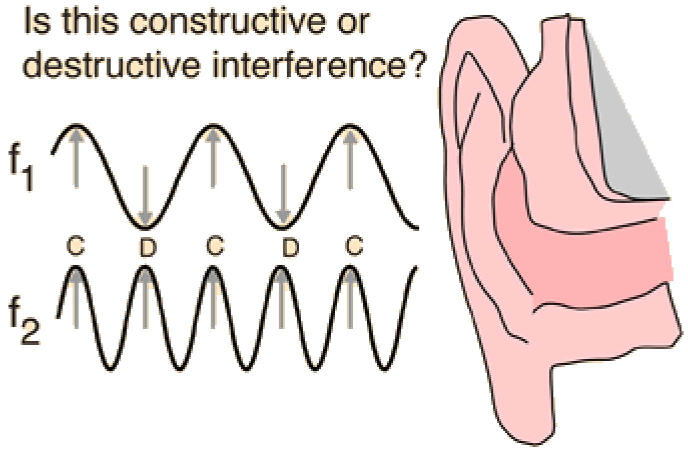
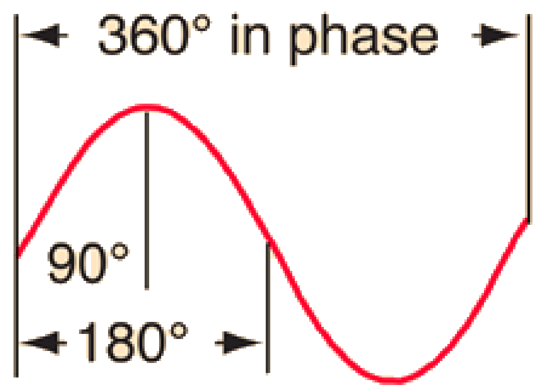
Interference of Sound

Two traveling waves which exist in the same medium will interfere with each other. If their amplitudes add, the interference is said to be constructive interference, and destructive interference if they are "out of phase" and subtract. Patterns of destructive and constructive interference may lead to "dead spots" and "live spots" in auditorium acoustics.

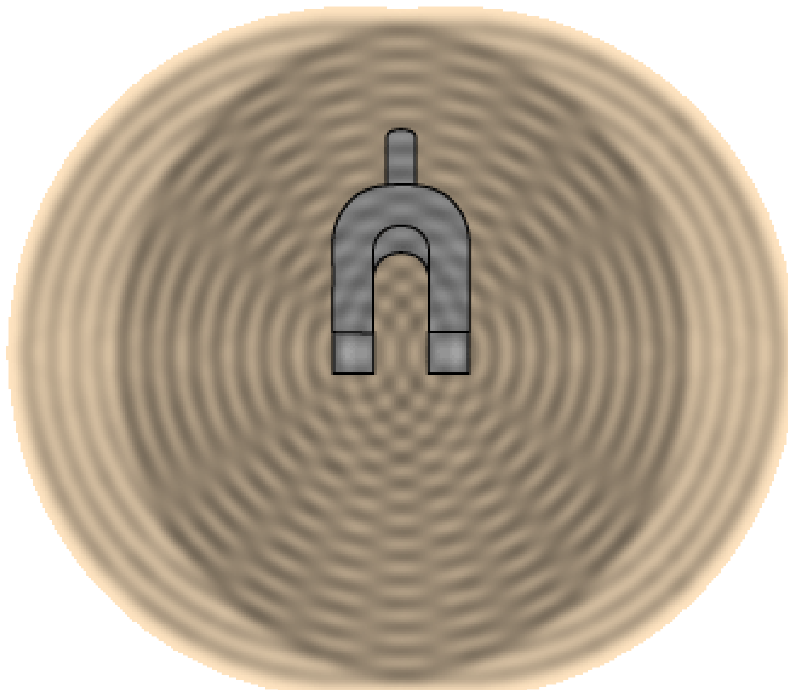
Interference of incident and reflected waves is essential to the production of resonant standing waves.

Interference has far reaching consequences in sound because of the production of "beats" between two frequencies which interfere with each other.





Interference with a Tuning Fork



If you strike a tuning fork and rotate it next to your ear, you will note that the sound alternates between loud and soft as you rotate through the angles where the interference is constructive and destructive.

Each tine of the fork produces a pressure wave which travels outward at the speed of sound. One part of the wave has a pressure higher than atmospheric pressure, another lower. At some angles the high pressure areas of the two waves coincide and you hear a louder sound. At other angles, the high pressure part of one wave coincides with the low pressure part of the other.

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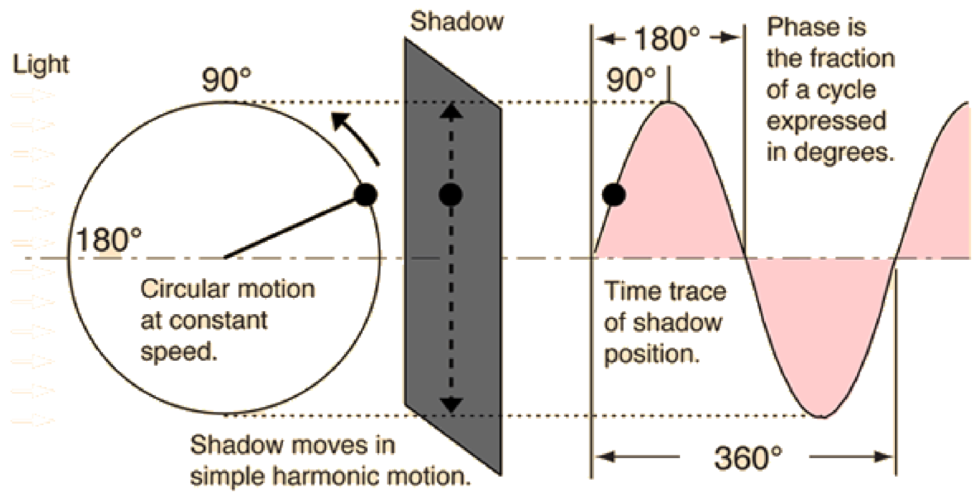
Phase

If a mass on a rod is rotated at constant speed and the resulting circular path illuminated from the edge, its shadow will trace out simple harmonic motion. If the shadow vertical position is traced as a function of time, it will trace out a sine wave. A full period of the sine wave will correspond to a complete circle or 360 degrees. The idea of phase follows this parallel, with any fraction of a period related to the corresponding fraction of a circle in degrees.



Interference and Phase