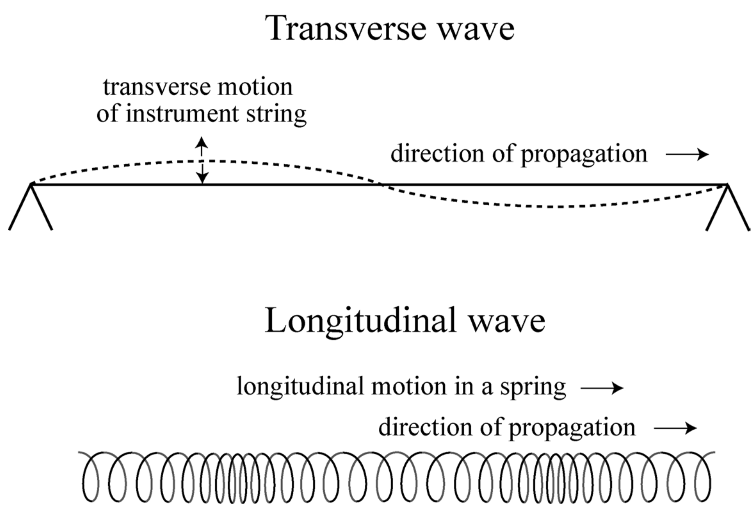
# Acoustics: the study of sound waves

Sound is the phenomenon we experience when our ears are excited by vibrations in the gas that surrounds us. As an object vibrates, it sets the surrounding air in motion, sending alternating waves of compression and rarefaction radiating outward from the object. Sound information is transmitted by the amplitude and frequency of the vibrations, where amplitude is experienced as loudness and frequency as pitch. The familiar movement of an instrument string is a transverse wave, where the movement is perpendicular to the direction of travel (See Figure 1). Sound waves are longitudinal waves of compression and rarefaction in which the air molecules move back and forth parallel to the direction of wave travel centered on an average position, resulting in no net movement of the molecules. When these waves strike another object, they cause that object to vibrate by exerting a force on them.




Examples of transverse waves:

vibrating strings
water surface waves
electromagnetic waves
seismic S waves

Examples of longitudinal waves:

waves in springs
sound waves
tsunami waves
seismic P waves

Figure 1: Transverse and longitudinal waves

The forces that alternatively compress and stretch the spring are similar to the forces that propagate through the air as gas molecules bounce together. (Springs are even used to simulate reverberation, particularly in guitar amplifiers.) Air molecules are in constant motion as a result of the thermal energy we think of as heat. (Room temperature is hundreds of degrees above absolute zero, the temperature at which all motion stops.) At rest, there is an average distance between molecules although they are all actively bouncing off each other. Regions of compression (also called condensation) and rarefaction (expansion) radiate away from a sound source in proportion to the movement of the source. It is the net force exerted by the moving air that acts on our ears and on transducers like microphones to produce the sensation of hearing and the electrical signals that become sound recordings. The same physics that describe oscillating mechanical systems like springs can be used to describe the behavior of gases like air: the equations derived to describe weights on springs can also be used to describe acoustics. Furthermore, electrical circuits exhibit similar behavior and can be described using very similar mathematical equations. This helps unify the field of sound recording, since mechanical, acoustical and electrical systems are all employed in the recording of sound.

Figure 2 shows how energy is interchanged between kinetic and potential energy in an oscillating system. Potential energy is energy that is capable of doing work, while kinetic energy is the result of active motion. As a mass suspended on a spring bounces up and down, it exchanges the potential energy of a raised mass and tension stored in a spring with the kinetic energy of the moving mass back and forth until friction depletes the remaining energy. At the top of its vertical motion, the mass has only potential energy due to the force of gravity while the spring is relaxed and contains no energy. As the mass falls, it acquires kinetic energy while tension builds in the spring. At the mid-point of its fall, the mass reaches its maximum velocity and then begins to slow as the force exerted by the spring's expansion builds to counter the force of gravity. At the bottom of its travel, the mass stops moving and therefore no longer has kinetic energy while the spring is maximally stretched and its potential energy is at its maximum, pulling the mass back upwards. Since air has both mass and springiness, it behaves much the same way as the mechanical spring and mass.

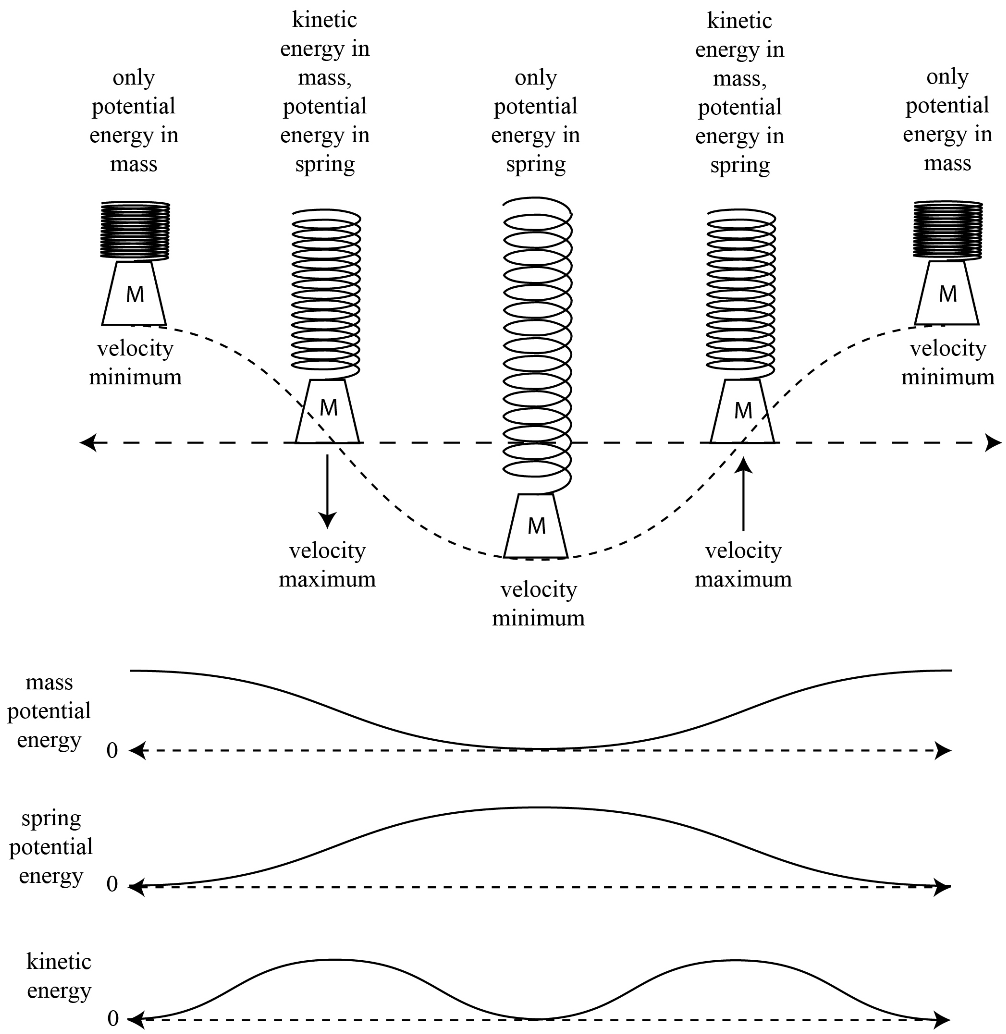



Figure 2: Oscillating mechanical systems interchange kinetic and potential energy - the same principle applies to acoustic systems.

Figure 3 shows how the time-varying characteristics of a sound wave may be measured. The amplitude can be measured as either pressure, velocity, or particle displacement of the air. Pressure is often used because it is predominantly what is perceived by the ear and by many microphones. Peaks of increased pressure and troughs of reduced pressure alternate as they radiate away from the source. Their wavelength and period can be used to describe the flow of the wave. The reciprocal of the time between peaks or troughs is the frequency ($f$) in cycles/second or Hertz (Hz). The distance between peaks as they move outward is the wavelength ($\lambda$). The two quantities are related by the speed of sound ($c$), about 340 m/s or 1130 ft/s.

$$\lambda = c / f$$

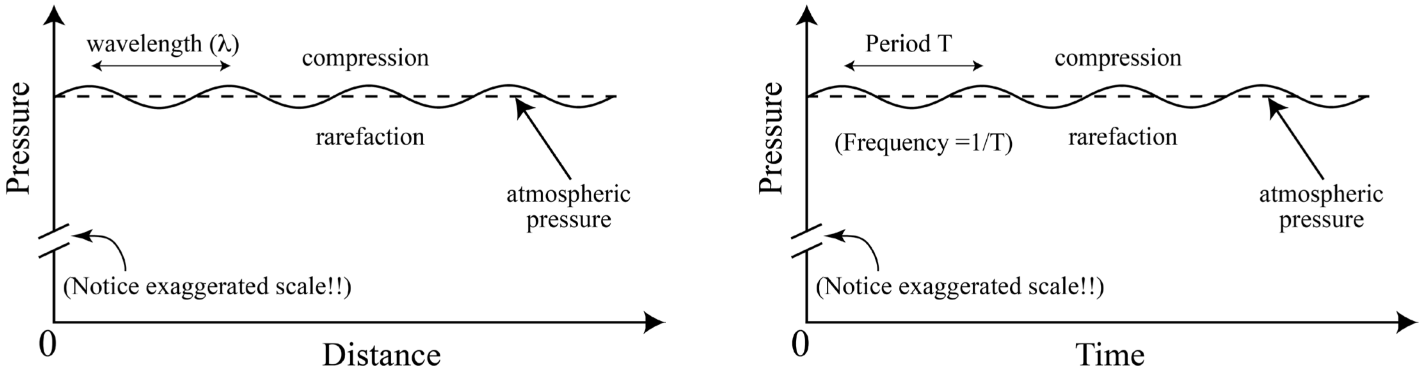



Figure 3: The period of a sinusoidal sound wave is the time between subsequent pressure peaks or troughs. The wavelength is the distance between those same peaks and troughs. As long as the speed of sound is constant, the two are related.

The pressure variations associated with sound are extremely small compared to the average air pressure. Barometric pressure at sea level is about 101 kPa [Pa (pascal) = $N/m^2$] or 14.7 $lb/in^2$. The pressure variation considered the threshold of audibility is 20 $\mu$Pa, on the order of one billionth of atmospheric pressure! The sensitivity of the ear is quite impressive. This also begins to explain why sound transmission is so hard to control. Further, any device used to convert sound into electricity must be similarly sensitive and able to respond over a huge range of pressures and frequencies.

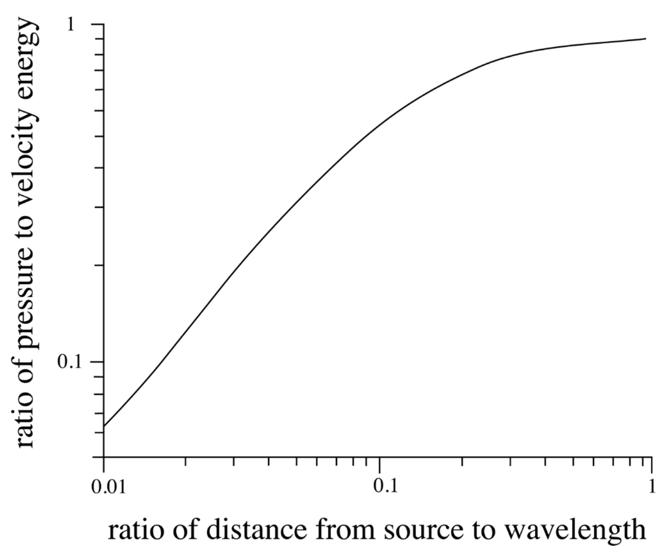



Figure 4: The ratio of energy contained in pressure to that of velocity as a function of the ratio of the distance from the source to the wavelength of the sound wave.

As a vibrating object begins to move, it forces the air molecules in contact with its surface to move. Thus, the air is accelerated by the sound source, causing a net increase in particle velocity. Particle velocity refers to the movement of a hypothetical small mass of air rather than to the turbulent individual air molecules that vibrate locally with extreme velocities but only over infinitesimal distances. (*Volume velocity* is also used to describe the velocity component - it's the flow of bulk fluid - air in this case.) The dimensions of nitrogen and oxygen molecules are on the order of about 3 Angstroms ($10^{-10}$ m). This is many orders of magnitude smaller than wavelengths of sound so considering air as a bulk mass is sensible. As the movement continues outward from the source, the molecules are forced together, increasing the local pressure. Very near a sound source, most of the energy is contained in the form of particle velocity while far from the source the energy is transmitted predominantly in the form of pressure (See Figure 4.) Close to a small source, the sound wavefront expands in two dimensions as the spherical surface area grows with the square of the distance from the origin (See Figure 5.) Far from the source, the wavefront is practically planar and the energy radiates through the same area as it flows outward hence there is no decrease in sound pressure due to geometric dispersion. This distinction affects how sensors respond to the sound, as some are sensitive only to pressure while others are sensitive to the velocity of the sound wave that is driven by the pressure difference along the axis of movement.

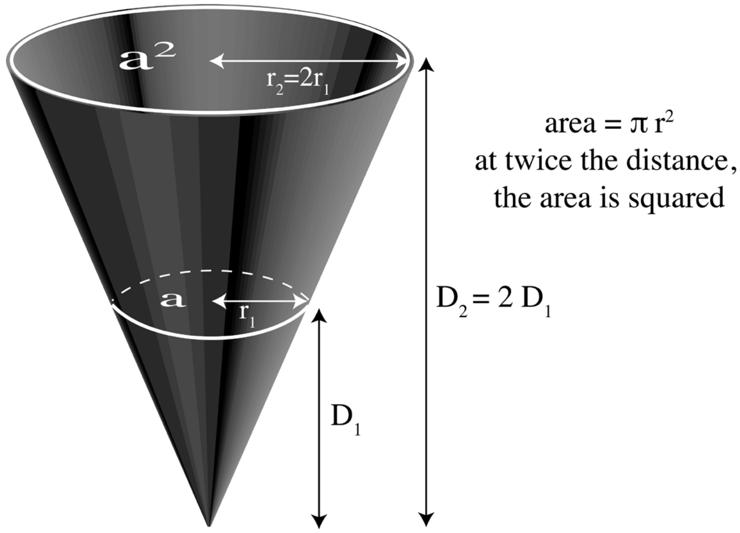



Figure 5: Spherical waves propagate through increasingly large area *a* proportional to $\pi r^2$.

The ear functions mainly as a pressure sensor as do omnidirectional microphones, designed as pressure sensors. Other types of microphones are sensitive to the air pressure gradient (often called velocity microphones.) These behave differently than pure pressure sensors, as we will see when we examine microphone design and performance. The core of this difference depends on the fact that pressure is a scalar quantity while velocity is a vector quantity. [A scalar quantity has only a magnitude while a vector has both magnitude and direction.] In order for a microphone to respond differently with respect to the direction from which a sound originates, it must be at least somewhat sensitive to the velocity vector while pressure microphones respond only to the pressure of a sound wave and not to the direction from which it originates.

In directional microphones, it is the pressure difference between two points (the front and back of the microphone), the pressure gradient, that is responsible for the forces that are converted to electrical signals in the transducer. While some directional microphones do respond to the velocity directly, like dynamic and ribbon microphones, others use multiple pressure-sensitive elements to produce a signal proportional to the pressure difference without actually moving at the equivalent velocity. For this reason, it is preferable to refer to directional microphones in general as pressure-gradient microphones.

Air is a gas mixture, predominantly nitrogen and oxygen. The molecules are in constant motion. The hotter the gas, the more frequent and energetic the molecular collisions. The kinetic energy of the gas exerts a force on other objects in contact with the air, which we call pressure. The relationship between the pressure and volume occupied by the gas in a closed system is reflected in the basic law of gases, Boyle's Law:

$$PV=\mathrm{n}RT$$

where *P* is pressure, *V* is volume, n is the amount of gas in moles, *R* is a constant and *T* is the absolute temperature. The most important aspect of this relationship is that the product of pressure and volume is constant - if one goes up, the other goes down. (Related changes in temperature may complicate this relationship slightly.) The pressure goes up when the gas is compressed by reducing the volume it occupies because the molecules are forced closer together where their collisions become more frequent. The compressibility of air can be observed using a syringe. With the plunger half-way into the syringe body, block the open end of the syringe and push or pull on the plunger. When you release the plunger, it returns to its original position much like air molecules do during a passing sound wave.

There is plenty of confusion about how to measure sound amplitude. Sound *intensity* is the product of pressure and velocity and reflects the power (energy/time) of the sound wave:

Intensity = pressure x velocity = power / area

Near the sound source, intensity decreases with the square of the distance from the source. Intensity measures the total power of the sound wave - its ability to do work. What we hear as loudness is more closely related to the pressure of the sound wave, which decreases linearly with distance from the source. When we are concerned with our perception of loudness, we need to consider the sound pressure level rather than the intensity. We can also consider only the pressure when we use omnidirectional pressure microphones. When using directional microphones, however, we will need to also consider the velocity component of the sound wave. Directional microphones have the ability to respond differently to sounds originating from different directions because they are sensitive to the sound wave pressure gradient, which changes as a function of the angle from which the sound originates. It is more complicated to measure the velocity of a sound wave than it is to measure its pressure, therefore most audio systems use sound pressure as a measure of amplitude. Most often, amplitude is measured as sound pressure level (SPL).

The distinction between spherical and plane waves is of practical importance because it explains how different microphone types respond depending on their distance from the sound source. For spherical waves, the intensity decreases with the square of the distance but the sound pressure level decreases linearly with distance. A spherical wave sound pressure decreases by 1/2 or 6 dB for a doubling of distance. In a more distant plane wave, any decrease in sound pressure is due to absorption and scattering rather than geometric considerations. In theory, plane wave pressures do not decrease with distance as they do for spherical waves. Equations for spherical and plane waves are presented below. These equations show how pressure *p* and velocity *u* change as a function of both time and distance from the source and as a function of wavelength.

| Plane wave | Spherical wave |
|---|---|
| $p = akc^2\rho \sin k(ct - x)$ | $p = \dfrac{S\rho ck}{4\pi r} \sin k(ct - r)$ |
| $u = akc \sin k(ct - x)$ | $u = -\dfrac{Sk}{4\pi r}\left[\dfrac{1}{kr}\cos k(ct - r) - \sin k(ct - r)\right]$ |

$a$ = particle displacement (cm)
$k = 2\pi/\lambda$
$\lambda$ = wavelength (cm)
$c$ = velocity of sound (cm/sec)
$\rho$ = density of air (g/cm$^3$)
$t$ = time (sec)
$x$ = distance from source (cm)
$S$ = maximum rate of fluid (gas) emission from source (cm$^3$/sec)
$r$ = radius or distance from source (cm)

Though somewhat complicated, the significant difference in the equations relates to the two terms in the velocity expression for spherical waves. There, the cosine term contributes when *r* is small in contrast to the case when *r* is very large. For large *r*, the spherical wave velocity equation reduces to the plane wave equation. One important feature of the behavior of sound fields near the source is that the pressure and velocity are not in phase as they are in the more distant plane wave. In spherical waves, the velocity leads the pressure by up to 90º for low frequency waves. Figure 6 shows the relationships between displacement, pressure and velocity for spherical and plane waves. The relationship is simple for plane waves, but for spherical waves the relationship depends on the proximity to the source in a complex way. For the purposes of understanding microphone behavior, it is only necessary to recognize the difference between spherical and plane waves in a general way.

$$Z_s = \frac{p}{u} = \rho_0 c$$

The ratio of pressure *p* to velocity *u*, known as the specific acoustic impedance $Z_s$, remains constant in plane waves but varies with distance in a spherical wave. (Velocity here is a complex number as it represents a vector quantity while pressure is a scalar, thus $Z_s$ is a complex number.) In a plane wave, the acoustic impedance is also equal to the product of the density of the medium $\rho_0$ and the velocity of sound *c*. In a spherical wave, the acoustic impedance is a function of the distance from the source. As we will see when we discuss directional microphones, this phenomenon is responsible for the low frequency boost known the as proximity effect.

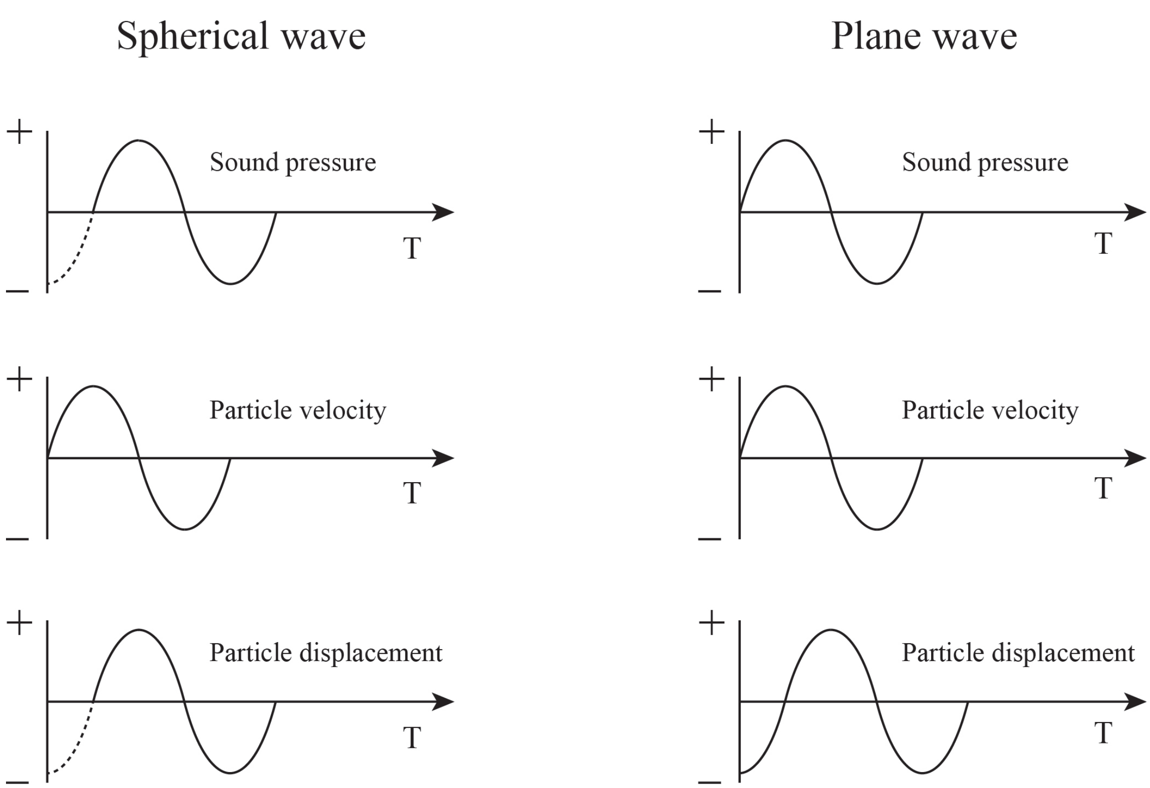



Figure 6: Sound wave pressure, velocity and displacement relationships for spherical and plane waves. Exact relationship in spherical waves depends on distance from sound source.

Plane waves can be assumed to occur at a distance from the source that depends on the relative wavelength of the sound itself. Low frequency sound has long wavelengths, about 17 m at 20 Hz while the wavelength at 20 kHz is only 1.7 cm. High frequency waves can be considered planar a few centimeters from the source while low frequency sounds require many meters of separation from the source to be close to planar. Of course, real sounds contain many component frequencies so the issue gets complicated. The difference in behavior between spherical and plane waves does pertain to the differences we observe between close and distant microphone placement. Pressure gradient microphones are more sensitive to their distance from the source than are omnidirectional microphones, particularly when placed close to the source.

| Frequency (Hz) | Loss [@ 25º C, 50%RH] (dB/km) |
|---|---|
| 50 | 0.67 |
| 500 | 3.2 |
| 5000 | 37 |
| 10000 | 131 |

Figure 7: Air absorption of sound pressure varies significantly with frequency.

For very large distances, the absorption of sound energy by the air becomes the dominant cause of sound pressure decrease. (See Figure 7) This is more pronounced for high frequencies than for low, a phenomenon sometimes observed at large outdoor concerts. A 1 kHz wave loses 6 dB at a distance of 20 miles purely through absorption while a 10 kHz loses 6 dB at about 1000 feet and 20 kHz loses 6 dB at just under 300 feet. Fortunately, these distances rarely if ever affect microphone placement.

The sound field intercepted by a microphone is dependent on its distance from the source. There are alternative ways of characterizing the qualities of the sound field created by a source. The terms near field and far field apply to individual sound sources and are based on the balance between pressure and velocity at a given distance. The near field conditions involve spherical waves and the consequent acoustical behavior while the far field relates to plane wave behavior. The dividing line betwen the two conditions is wavelength (frequency) dependent. The terms free field (direct field) and diffuse field (reverberant field) apply to sounds measured in a room. Near the source, the direct sound is dominant while further away the reverberant sound dominates. In the direct field, sound pressure decreases linearly with distance while there is no decrease in sound pressure with distance in the diffuse field. The distance at which the direct and reverberant sounds are at equal pressure is called the critical distance.

Unfortunately, there is no direct correspondence between near field and direct field and between far field and diffuse field. Both sets of terms are used but they are not interchangeable. While it can be helpful to understand how the behavior of sound changes with the distance from the source, the decisions about microphone placement ultimately depend on how the converted signal sounds to the engineer. The physical acoustic relationships can help to explain why microphones sound as they do but they cannot tell you where exactly to place a microphone in order to get the desired sound. That relies more on experience and careful listening.