# Sound

The obvious place to start an investigation of sound recording is with the study of sound. Sound is what we call our perception of the air movements generated by vibrating objects: it also refers to the waves of compression and rarefaction that propagate through the air. To understand the behavior of sound as it relates to music and recording, we need to consider the physics of the generation and propagation of sound, the physics of the conversion of sound into electricity by microphones and by our ears (and the conversion back from electricity to sound), and ultimately the psychoacoustic properties of our auditory system, which includes the ears and central nervous system. We start with an investigation of how sound waves behave.

The manner in which sound waves propagate and combine in a room affects how sounds recorded in such an environment will ultimately be perceived. Similarly, the way sound waves interact with the sensing element of a microphone will impose a characteristic signature on the captured signal, so understanding sound wave behavior will help clarify some critical steps in the recording process. Sound waves are longitudinal waves, which means the particle movement caused by the wave is parallel to the direction of propagation. (Transverse waves, like vibrating strings, involve movement perpendicular to the direction of propagation.) Since sounds behave as waves, we can begin to visualize how sounds behave in a room if we consider throwing rocks into pools of water and observing the resulting patterns of waves: different-shaped pools generate different patterns of peaks and valleys in the water's surface. Sounds are similar to water surface waves except that they propagate more rapidly, in three dimensions instead of just two, and involve a highly compressible gas in place of a minimally compressible liquid medium. Peaks in the water surface correspond to pressure maxima in air and troughs in the surface represent rarefactions in air. As a wave bounces off a surface, it is reflected back at the same angle from which it approaches. After many bounces, a complex pattern of peaks and valleys is created in the surface. In much the same way, air pressure variations build in a room and in decaying away take on a sound shaped by the acoustical properties of the room.

To get a more quantitative picture of sound wave behavior, we employ physics and mathematics to describe the system. Energy can be thought of as the ability to do work, that is, to cause a change in the physical state of an object. Energy exists in two forms: potential and kinetic. (These can be thought of as "I could do it" and "I am doing it", respectively.) A system can have both types of energy and they may be inter-converted over time, for example, in a mechanical system, a weight on a spring has both the kinetic energy of the moving mass and the potential energy of the spring tension. In acoustics, sound pressure is the potential energy component, particle velocity is the kinetic component and sound intensity (the acoustic power per unit area, W/m$^2$) is the product of the two. We must therefore consider both the pressure and velocity aspects of sound waves in order to explain the energy transfer between a sound wave and a microphone or an ear.

Air is a collection of gases, primarily nitrogen and oxygen. Air pressure, the force it exerts on a surface, is determined by the concentration of gas molecules per unit volume and the temperature. Since gas molecules are in constant motion from the energy associated with the ambient temperature, they bounce around and ricochet off each other continuously and the space between the molecules allows significant compression as well as expansion to take place. The relationship between pressure change and volume change is described by the bulk modulus ($B$) of the gas:

$$B = -\frac{\Delta p}{\Delta V / V},$$

where $\Delta p$ is the change in pressure, $\Delta V/V$ is the percent change in volume. The bulk modulus is a measure of the compressibility of the medium and is measured in the same units as pressure, the pascal ($Pa=N/m^2$). (The lower the bulk modulus, the more compressible a medium.) The bulk modulus and density determine the velocity of propagation ($v$):

$$v = \sqrt{\frac{B}{\rho}},$$

where $\rho$ is density (mass/unit volume).

In air, an average pressure is maintained until something perturbs the system. In the case of sound, this can be a compression or rarefaction of the air caused by the movement of an object in contact with the gas. Movement towards us creates a wave of compression while movement away creates a rarefaction. Once such an event occurs, the increase or decrease in pressure radiates through the gas as it moves outward from the source. If the original movement is of a periodic (repetitive) nature, it will set up concentric wave fronts of increased and decreased pressure relative to the average air pressure, and these “shells” will move outward at the speed of sound. While the individual molecules do not continue to move at that rate, a phenomenon we would call wind (of about 750 mph!), the pressure variations radiate outward at about 330 m/sec [1,100 ft/second] through the ever-turbulent gas. The individual air molecules do move a small amount as they surge ahead under increased pressure and back in areas of diminished pressure, but there is no net movement.

$$\mathrm{PV} = \mathrm{nRT}$$

The mathematical description of the pressure/volume relationship in gases is rather simple: it states that the product of pressure (P) and volume (V) is constant for a given amount of gas (n in moles [a mole is $6.02 \times 10^{23}$ particles: Avogadro’s number, the number of carbon 12 atoms in 12 grams of carbon] and constant temperature (T) [R is the gas constant: $8.3143\ m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}$]. Over the relatively small range of pressures involved in sound propagation, the relationship is simple. If we consider a point source of sound, the pressure waves propagate outward as an expanding sphere of concentric pressure variations. As the distance from the source grows, so does the volume of air through which the pressure wave passes and consequently the pressure variation decreases in amplitude as it occupies a larger and larger volume of air.

The small variations of air pressure we call sound are fluctuations in pressure around a much greater average pressure, the actual air pressure as measured by a barometer: weather conditions generate much larger changes in air pressure than do sounds. The average air pressure at sea level is around 760 mm Hg, which corresponds to 101 kPa (kiloPascals) or about 14.7 $lb/in^2$. The threshold of hearing is 0.0002 $dynes/cm^2$, which is only $2 \times 10^{-8}$ kPa, so we are talking about very small variations in air pressure when we consider sound waves. Even the threshold of pain is equivalent to about $2 \times 10^{-2}$ kPa, so the pressure variations involved with sound are very small compared to the average air pressure. (One might wonder why the comparatively large changes in air pressure (up to 1 kPa or more) associated with weather don’t hurt our ears? It is because for slow changes in air pressure, our ears equilibrate to the new average pressure by opening the Eustachian tube to equalize the pressure in the middle ear. Rapid pressure changes can hurt, for example the changes associated with flying.) Since the density of air decreases with altitude, atmospheric pressure decreases with altitude as well.

In addition to the sound pressure, the velocity of the air molecules is an important aspect of sound propagation. As a pressure wave moves outward, it causes local motion of the gas molecules through which it moves. Initially, the particles move in the direction of propagation as the pressure increases and then back as the pressure decreases. This movement, while it results in no net movement, does cause a local movement back and forth that is capable of moving objects with which it comes into contact. The movement of air molecules results in a displacement from the undisturbed position of extremely small distances, on the order of $10^{-11}$ meters for the softest sound we can perceive. Measuring this characteristic of sound is quite difficult and gives us an appreciation for the sensitivity of the microphone and the ear. Nevertheless, the total randomly-directed kinetic energy of air molecules in a quiet room can be astounding: a 57 $m^3$ [2000 $ft^3$] room containing about 1.5 x $10^{27}$ molecules weighing 73 kg [160 pounds] contains more kinetic energy than a 16000 kg [35000 pound] bus traveling at 160 k/h [100 mph]! The average velocity of individual molecules can exceed 450 m/s [1000 mph]. On the scale we perceive, however, this all averages out and we hear silence.

Sound intensity is a measure of the energy of a sound wave. The intensity of a sound is the power per unit area received at the sensing device. The intensity received from a point source decreases as the distance from the source increases because the same amount of power radiates through a larger and larger area. As the distance from the source increases, the area through which the radiated power flows increases with the square of the distance. Therefore, the intensity decreases with the square of the distance. What we perceive as the loudness of a sound is more closely related to the pressure level, though, rather than the intensity. For this reason and because sound power is difficult to measure directly, we commonly use sound pressure levels (SPL) as the measure of sound amplitude. Unlike intensity, sound pressure levels decrease linearly with distance from the source. This results in a 6 dB decrease in SPL for a doubling of distance.

Sounds propagate away from the source and continue to decrease in amplitude until all of the energy is dissipated as heat in the collisions between gas molecules and with other objects like walls. If an object is located within the area where pressure variations still occur, the object will begin to vibrate as the alternating higher and lower pressure waves strike the object. It is this coupling that allows a microphone to begin the transduction process. If the microphone’s sensing element is of low enough mass, it will be moved by the changes in air pressure and the moving gas molecules. We can then convert that motion into electrical current and begin the process of recording sound.

In addition to interacting with solid objects, the waves of higher and lower pressure interact with other sound waves, including the ones bouncing from the walls of a room, and reinforce and cancel each other. This interaction is responsible for some of the acoustical problems we encounter in the recording studio. As the waves come together, areas of high and low pressure combine as they fill the same space. Their interaction changes the pressure in these regions accordingly and the reinforcements and cancellations change the information content of the waves as well. The way the pressure waves interact with each other and with objects in their environment generates the characteristic ambient sound we recognize from listening in our physical surroundings. We are easily able to identify the size of a room by hearing the colorations generated as the sound waves bounce around. Because the sounds are changed in characteristic ways by these interactions, we can tell the difference between a small room and a large auditorium and between sounds generated nearby and sounds from a long distance away. Often, we seek to re-create these specific changes in the studio, as when we add artificial reverberation to a studio recording, so understanding them is important.

When a sound is measured close to the source, the direct sound is significantly louder than any reflections. This results in only the direct sound itself being perceived. An analogous state occurs in an anechoic chamber or in an outdoor area with no obstructions, a condition known as free field, where the sound field is unimpeded by obstacles and the sound is perceived directly without alteration by any reflections. In the studio, we may approach this condition if we listen to a loudspeaker at a short distance, the so-called near-field situation. This tends to reduce the contribution of the room acoustic signature and simplifies the task of dealing with poor room acoustics, becoming especially popular in home studios where room acoustics are often problematic. At greater distance, the direct and reflected sounds are more closely balanced and this is the mid-field while at even greater distance, the far field, the reverberations predominate.

As sound waves propagate, the front of the wave moves at the velocity of sound. This distributes the concentric shells of higher and lower pressure in space. For periodic waves, the distance from one shell of maximum pressure to the next is known as the wavelength of the sound. The wavelength ($\lambda$) is calculated by dividing the velocity of the wave (c [m/sec]) by the frequency (f):

$$\lambda = \frac{c}{f}$$

The wavelength of a sound wave will describe how it spreads out in space: the distance from pressure peak to pressure peak varies as the frequency changes. For a 1000 Hz sine wave, the distance between pressure maxima is approximately 0.33 m [1.13 feet], while a 20 Hz sine wave has a wavelength of 16.5 m [56.5 ft] and a 20 kHz sine wave has a wavelength of about 16 mm [0.67 in]. These dimensions are of interest because they determine how waves of these frequencies behave when they encounter objects in their environment.

Waves interact with objects based on the dimensions of the object relative to the wavelength of the sound. Wavelengths much longer than an object will smoothly bend around edges and spread out in space. Wavelengths shorter than the dimensions of an object will shadow like light: they behave more as beams. This helps explains why bass sounds are so difficult to contain while high frequencies are more easily blocked. In between the extremes, waves may bend partially as they encounter a surface edge. This is known as diffraction. Reflection occurs when a wave strikes an object and bounces back, like light falling on a mirror. Sound waves reflect at the same angle at which they encounter an object. Since each collision absorbs some of the sound energy, repeated reflections will ultimately cause the sound to decay and since each collision removes energy in a frequency-dependent way, the timbre of the decaying sound changes as well as the intensity.

The velocity of sound depends on the density of the transmission medium, whether air, water, or a solid. (In air, sounds travel at about 330 m/sec [1,090 ft/sec] at 0ºC, while sound moves at about 1,450 m/sec [4,700 ft/sec] in water at 0ºC and over 5,130 m/sec [16,800 ft/sec] in iron at 20ºC.) When a sound wave encounters a change in the density of the medium through which it travels, its velocity changes. This causes a bending of the trajectory of the wave known as refraction. A classic case of refraction occurs when sound radiates upwards and encounters the atmospheric conditions known as an inversion layer, where upper layers of air become warmer instead of colder than those below. Because the velocity of sound is greater in warm air, the inversion layer causes the sound waves to speed up as they make the transition into the warmer layer, causing the wavefront to bend downward. This condition can make sounds come back to earth at a distance from their origin: not great for outdoor concerts with nearby residences.

The shape and dimensions of a space largely determine how sounds are altered as they radiate and decay inside that space. The dimensions are important because the distance a sound must traverse on its path from source to sensor will shape the cancellations and reinforcements that occur as a function of the wavelengths present. When a sound's wavelength is the same as the distance between two parallel walls, the sound will reflect back and forth in such a way as to have the pressure maxima coincide and add, making that sound frequency louder than other frequencies which cancel or add randomly at that particular distance. This behavior leads to the formation of standing waves, so that particular frequencies seem to build up in certain areas of the room. With their longer wavelengths, low frequency sounds are more likely to be affected in small to medium-size rooms because their wavelengths (or multiples or fractions thereof) match the dimensions of the room.

Another way reinforcement of certain frequencies may occur is by resonance: a structure tends to vibrate at certain frequencies and cause sound components at those frequencies to become louder than other components. Resonance is generated by systems with the ability to store energy and feed that energy back into the environment, as with walls which begin vibrating when driven by sound waves, causing the regeneration of sound waves that add with incident sound waves, attenuating the resonant frequencies less than others. The resonances of a room will color the sound of reverberation as certain frequencies reinforce and others do not. The phenomenon of resonance is not limited to rooms: resonance in solid objects like microphones also contributes to the sound of such devices and electronic circuits may exhibit resonance as well, and of course the bodies of musical instruments are designed to resonate, producing the characteristic sound of the instrument. In fact, any system with both kinetic and potential energy components may resonate at frequencies determined by the specific interaction of the two forms of energy.

Once sound has traversed the distance from the source to the transducer, the remaining pressure variations interact with the physical transducer and cause it to begin vibrating. The efficiency of the transformation from air pressure variations to mechanical vibrations will determine the quality of the transduction. When the information contained in the sound is transferred to the new medium, we have a new set of considerations. The mechanical vibrations should mirror the air pressure vibrations exactly. This requires that there be enough energy in the sound wave to transfer that information to the mechanical system without causing alterations in the signal. The ability to select the right microphone often depends on understanding how this transduction takes place and what limitations may be imposed by the physics of the available transducers.

Suggested reading:

The Master Handbook of Acoustics, 3rd Edition, F. Alton Everest, 1994, TAB Books. ISBN 0-8306-4437-7

Fundamentals of Physics, 7th Edition, Halliday, Resnick and Walker, 2005, John Wiley & Sons.
ISBN 0-471-21643-7