CHAPTER 1

# What is Sound?

If a tree falls in a forest and no one is there to hear it, does it make a sound? In order to answer this classic philosophical question, you must first ask: what is sound? The too-short answer to this simple question is that sound is caused by vibrations in the air. A fuller definition of sound involves three components: generation, propagation, and reception.

## GENERATION AND PROPAGATION

The air around and in your ears is made up of molecules of various types: oxygen, nitrogen, carbon dioxide, carbon monoxide, and others that we probably don't want to think about. Between the molecules in the air is . . . nothing. This means that the air molecules can be pushed together, or compressed, into a smaller space. A property of air known as elasticity causes the molecules that have been compressed together to spring apart again.

You can see this property at work when you blow up and then pop a balloon. When you force air into a balloon with your lungs, the air inside the balloon becomes compressed. When you pop that balloon, thereby removing the material that was keeping the air compressed, the elasticity of the air causes it to quickly expand again.

Sound waves are generated when air molecules are pushed together, allowed to spring apart, and then pushed together again in a repeating pattern. This pattern of "push together, spring apart" is what allows sound to move through the air.

If you think of air molecules as a bunch of pool balls randomly distributed on a pool table with some space between them, and you hit the cue ball into one of the balls, those two balls will be compressed together. They will then spring apart and the energy you imparted to the cue ball will be transferred to the other ball. That ball in turn will hit another ball, which will hit another ball, which will hit another, and so on. In other words, hitting one pool ball causes a chain reaction in the other pool balls, which takes the form of a moving pattern of compressed-together pool balls across the table. The cue ball soon stops, but the *energy* imparted to the cue ball moves across the table through this chain reaction process. Another useful analogy is a crowded party.

If you are in a crowded party and you push the person in front of you, that person will, in addition to spilling their beverage, bump into the person in front of them who will bump into the person in front of them, and so on. You stay put, but the "bump" moves across the room, just as the collision of pool balls moves across the table, even though the balls themselves don't necessarily move very far.

To generate sound, then, you need a device that can cause molecules in the air to compress together and then allow them to spring apart again. Fortunately, every musical instrument, blown soda bottle, and human voice fits this description. Take a plucked guitar string as an example.

To pluck a string, you must first pull it out of its resting position. When you release the string, the tension pulls it forward toward its resting position and its momentum carries it beyond that resting point. In this way, it's a little like letting go of a pendulum. As the string moves forward, the molecules in front of the string are pushed together, temporarily compressing them. This region of air where the molecules have been compressed together is sensibly referred to as a **compression** (see Figure 1.1).

These compressed air molecules then spring apart and cause a compression further on. The molecules in that compression also spring apart and the cycle continues. The energy that was imparted to the molecules by the string thus moves, or **propagates**, through the air.

While this compression is propagating through the air, the guitar string continues to move. After it has reached its furthest forward point, the tension in the string pulls it back toward its resting point and its momentum again carries it beyond that point. By now, however, the forward motion of the string has "cleared out" many of the molecules in front of the string, leaving an area in front of the string in which there

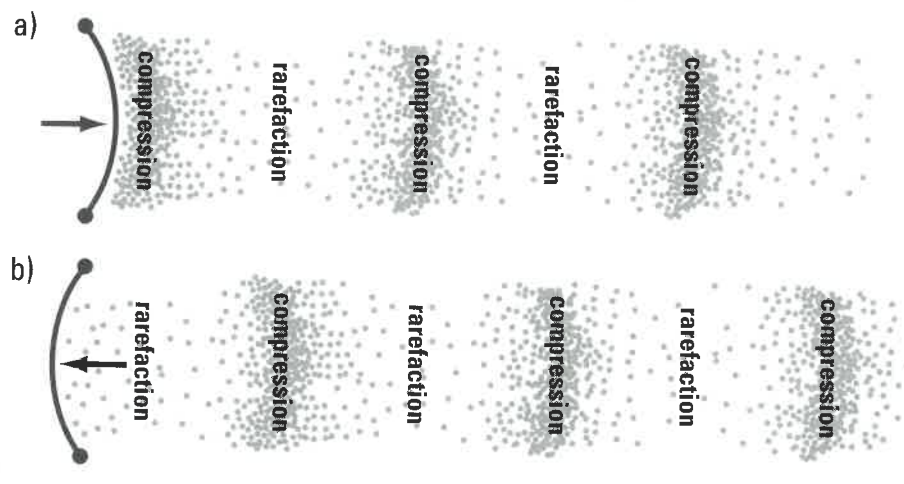


*Figure 1.1* (a) A string moving forward causing a compression; and (b) a string moving backward causing a rarefaction.

are fewer air molecules than before. This is the opposite of a compression and would logically be called something like a de-compression, but the official term for it is **rarefaction**. As the tension in the string again pulls the string forward, the cycle begins again. The string's motion will eventually subside due to forces such as friction.

As the string moves forward and backward it creates a series of compressions and rarefactions that propagate through the air. This type of wave, in which the disturbance of the medium is in the same direction as the wave propagates, is referred to as a **compression wave** or a longitudinal wave. In ocean waves, however, the disturbance of the medium is up and down while the wave propagates horizontally—this type of wave is called a **transverse wave**. The compression waves created by the string or some other vibrating body are the "vibrations in the air" that are usually described as sound.

## Sound Generation by Musical Instruments

While this discussion has used a guitar string as an example of sound wave generation, all vibrating bodies that make sound necessarily create chain reactions of compressions and rarefactions. Instruments such as plucked strings, drums, and cymbals all affect air in a similar manner by physically moving back and forth. For bowed strings, such as a violin, the bow uses its "stickiness" to first pull the string out of normal position, at which point the bow slips and the string snaps back. This fast stick–slip cycle creates the back and forth motion necessary to create compressions and rarefactions. For both plucked and bowed instruments, their connection to the body of the instrument plays an important role in generating sound. The force of the pluck or stick–slip bowing is partially transmitted to the thin wood that makes up the body of the instrument, which then vibrates and creates compressions and rarefactions in the air. A solid-body electric guitar isn't very loud without its amplifier because the strings' energy doesn't cause the solid block of wood to move very much.

A reed on an instrument such as a clarinet or saxophone creates compressions and rarefactions by moving up and down (see Figure 1.2). When air passes over the reed, it rises in the same way that an airplane wing lifts when air passes over it. While the reed is lifting up, the performer's air stream is causing the air molecules within the instrument to compress together. When the raised reed causes the opening to the mouthpiece to narrow, little air flows into the instrument. Since the compression has begun to move, or propagate, via chain reaction through the instrument, the absence of airflow allows a rarefaction to form. Also, due to the reduced airflow over the reed, there is no more lift on the reed and the reed opens back up, allowing the air to flow freely into the instrument again. The open–close–open cycle causes the performer's steady air stream to become a series of very fast puffs of air in the instrument creating compressions and rarefactions. A double-reed instrument such as an oboe works similarly, except that there are two reeds that close together due to the airflow.

An instrument like a flute also creates compressions and rarefactions by interrupting the performer's air stream. In the case of a flute, air blown across the blowhole is split by the edge of the blowhole and some of the air enters the flute, causing a

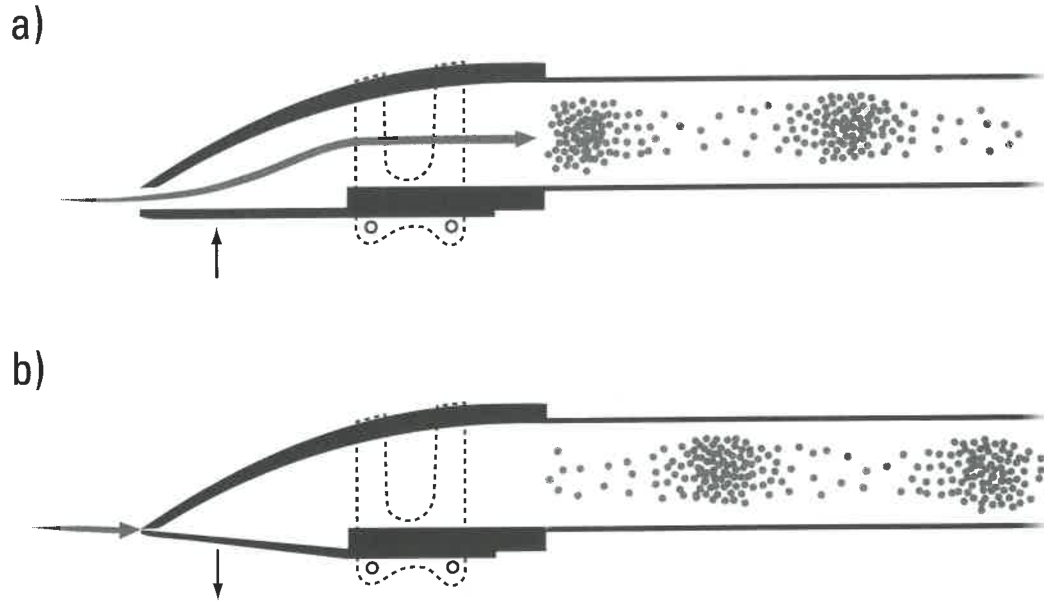


*Figure 1.2* (a) Air entering a clarinet mouthpiece causes a compression in the barrel. The air over the reed causes the reed to rise and reduce the airflow. (b) With the reed closing off the air stream, a rarefaction forms in the wake of the compression. The reduced airflow over the reed causes the reed to open back up and the cycle starts again.

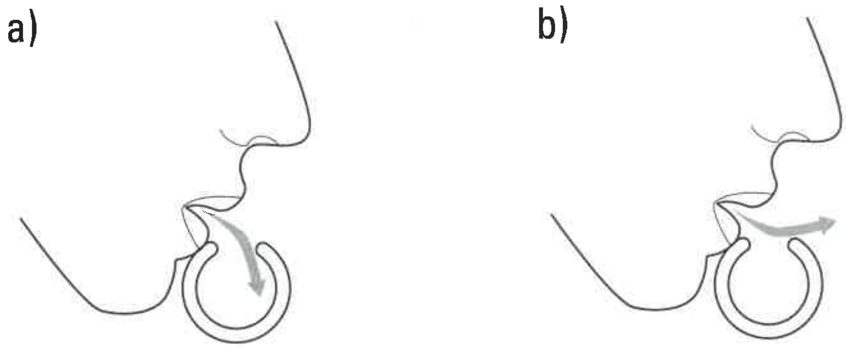


*Figure 1.3* (a) Side cutaway view of a flute blowhole. Air is blown across the blowhole of the flute and is deflected into the flute, creating a compression. (b) Pressure from the compression deflects air out of the flute. A rarefaction forms as the compression propagates down the pipe.

compression (see Figure 1.3). This build-up of pressure then deflects the entering air out of the blowhole. The compression moves down the inside of the flute and, with no air entering the mouthpiece, a rarefaction forms. With the backpressure thus relieved, the performer's blown air again enters the flute mouthpiece and creates another compression. As with the reed instruments, a steady stream of air from the performer is converted by the mouthpiece of the instrument into very fast puffs—compressions and rarefactions.

Flutes that you blow directly into, such as toy flutes, whistles, ocarinas, and recorders, work similarly in that when you blow into them the air is split by the edge of the vent.

The air that goes into the instrument creates a compression. This pressure build-up causes the air to be redirected out of the vent thereby creating a rarefaction. With the backpressure relieved, the air split by the edge of the vent again enters the pipe. The pipe organ, the "King of Instruments," works in a similar way to a toy flute, except that the lungs do not provide the air. In addition to "flue" pipes, which are flute-like, pipe organs also have reed pipes in which the air pumped into the pipe passes over a reed to generate the pitch.

In brass instruments, such as trumpets, trombones, French horns, and tubas, lip buzzing creates compressions and rarefactions. The performer starts with closed lips and no air flowing into the instrument. When the performer blows, the pressure forces the lips open and air flows into the instrument creating a compression (see Figure 1.4a). The tension of the performer's lips and the high flow of air through them cause the lips to close again thereby cutting off the airflow and creating a rarefaction (see Figure 1.4b). The pressure again builds up behind the performer's closed lips, the lips are forced open again, and air flow resumes.

Vocal production is similar in some ways to the production of sound in brass instruments. The vocal folds (also known as "vocal cords") located in the larynx start off closed and are forced open by air pressure from the lungs, just as a brass player's lips start off closed and are forced open. Once air is flowing past the vocal folds, the pressure decreases, causing the folds to close together, just as the air stream through a brass player's lips causes the lips to close. This repeated opening and closing creates the compressions and rarefactions necessary for sound. As with each of these physical descriptions, vocal production is actually somewhat more complex. Nevertheless, the description here gives you a sense of what's going on.

The vocal folds can vibrate, while at the same time that stream of air is also used to buzz a brass mouthpiece, vibrate a reed, or excite the air column in a flute. Since the pitch of the singing voice is determined by the tension of the vocal folds, and the pitch of the instrument is determined by the vibration of the reed/mouthpiece coupled with the body of the instrument, it is possible to sing one pitch while playing another.

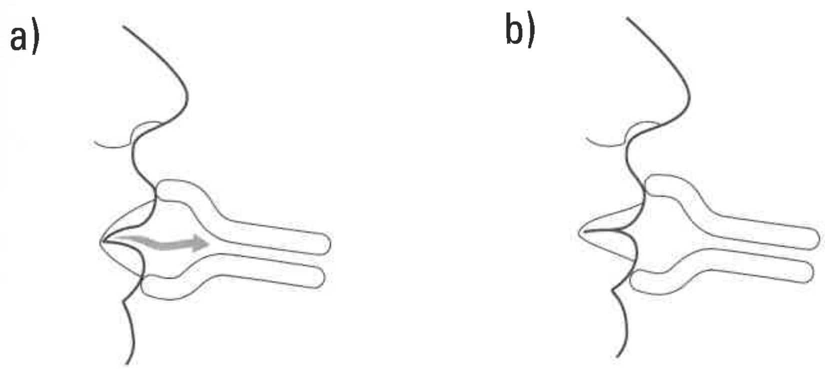


*Figure 1.4* (a) Side cutaway view of the mouthpiece of a brass instrument. Air pressure from the lungs forces open the lips and causes a compression in the instrument's air column, which then propagates through the instrument. (b) The moving air and the tension of the lips close off the air stream and a rarefaction forms. This repeated cycle creates the "buzzing" of the mouthpiece.

Singing-while-playing is a common contemporary classical performance technique used in music from the twentieth century to today. It's worth noting that there are other elements to vocal production that produce the unvoiced consonants and the noisy portions of voiced consonants.

Much of the music we listen to comes out of loudspeakers and headphones. Although this music may have originally been created in a variety of ways by the instruments discussed above, their combined compressions and rarefactions are re-created by the moving elements in speakers. The simplest kind of speaker has a cone that moves back and forth in response to an analog electrical signal from an electric guitar, stereo, or iPod (see Figure 1.5). An electromagnet attached to the speaker converts this electrical signal into the physical movement of the cone. When the cone moves forward, a compression forms and when it moves backward a rarefaction forms.

## Resonance

In the description above of sound generation by musical instruments, the discussion stopped once the mouthpiece, vocal cords, or string had produced a series of compressions and rarefactions. However, there is a reason that these instruments all have bodies, barrels, or pipes: **resonance**. Once the initial vibration is started, the sound wave passes into the body of the instrument, which can determine pitch and overall timbre.

The pitch of stringed instruments, percussive instruments, and voices is determined by the vibrating elements of strings, membranes or bars, and vocal cords. The resonators for those instruments—the body of a violin, the shell of a drum, and the throat, mouth, and nasal cavities of a human—are responsible for shaping the timbre of the sound. This should not be thought of as a trivial task. For example, in order to speak, we must shape

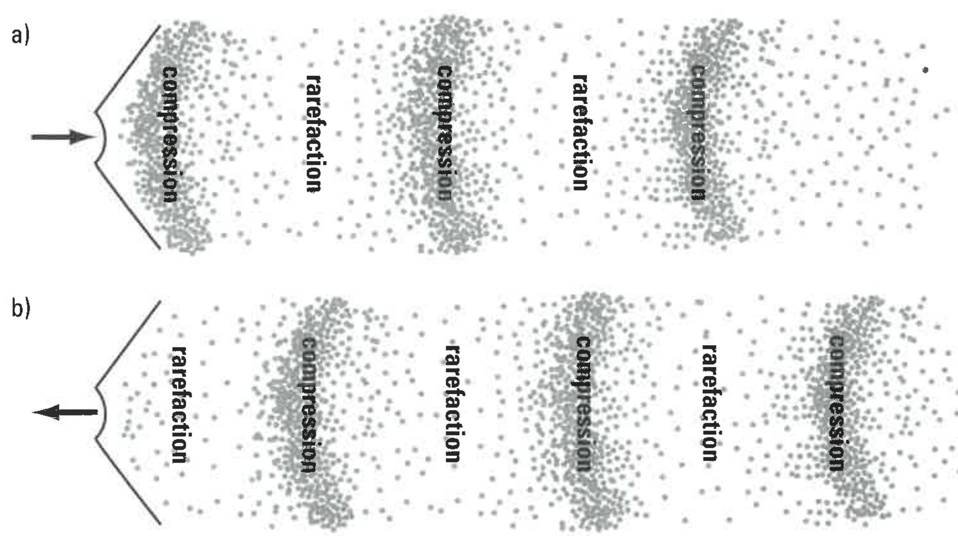


*Figure 1.5* (a) Side cutaway view of a speaker cone. The forward motion of the speaker cone causes a compression. (b) The backward motion of the speaker cone causes a rarefaction.

our resonators continuously to produce different vowels. To make a violin sound beautiful, the sound wave created by the bow and strings must be modified by the materials and overall shape of the body of the instrument. A bowed string without a resonator can sound quite thin and unimpressive.

The pitch of brass and woodwind instruments is determined by a combination of the mouthpiece and the resonator. These instruments have key or valve systems or other methods of changing the length of the resonator that determine which pitches can be "activated" by the sound wave generated by the mouthpiece. For brass instruments, the pitch is determined by the length of the air column and the pitch of the buzzing from the mouthpiece. For woodwinds, the pitch is almost entirely determined by the length of the air column as controlled by the keys. In addition to strongly influencing the pitch of brass and woodwind instruments, the resonator also shapes the timbre as it does with strings, percussion, and voice.

Most resonators have a fixed shape and fixed materials. As a result, the shape and materials have a strong influence on the timbre that results. For example, an acoustic guitar or violin with a small, plastic body will have a different, and likely less pleasing, sound than a larger one made of fine wood. Similarly, a brass or woodwind instrument sounds different when made of different materials. This is the reason that some brass performers prefer instruments without lacquer to the more traditionally shiny brass instruments.

The throat, mouth, and nasal cavities of the human body, on the other hand, can change shape to some degree, which allows us to change the timbre of our voices as we speak. Changing our resonators is what enables us to utter different vowel sounds and helps to imbue our utterances with a variety of emotional inflections. The resonances created by our vocal resonators—referred to as **formants**—will be discussed further in Chapters 3 and 12.

Changing resonances of this type can be imitated by acoustic instruments using items such as mutes. The brass "plunger" mute—often literally the end of a bathroom plunger—has long been used by jazz performers to give a vocal-like sound quality to their playing. Joe "Tricky Sam" Nanton, a trombone player in the classic Duke Ellington bands of the 1920s, 1930s, and 1940s, was well known for utilizing a plunger mute to create uncanny vocal-like sounds on his instrument. Decades later, composer Luciano Berio called for a metal plunger-style mute in his *Sequenza No. 5* to allow the performer to imitate his or her own voice with the trombone.

Resonance can be simulated in electronic instruments using **filters**, which are typically software plug-ins that shape the timbre of a sound. Fixed resonances can be simulated by the filters found in **equalizer** plug-ins. Changeable resonance can be simulated by filters found in various plug-ins and software instruments. Equalizers and filters will be discussed in more detail in Chapters 3, 4, 11, and 12.

## The Medium

Thus far, it has been assumed that the forward and backward activity of a vibrating object is taking place in air, but if you've ever dived into a pool you know that you can hear sound underwater as well. For sound to propagate, it requires an elastic medium, and the molecules in water fulfill this requirement. The different properties of the various mediums have a strong effect on the quality of the sound. Saying that something sounds like it is "underwater" typically means that the sound is muffled and less intelligible than it would be if heard through the air.

Even sound in "air" can change when the gas mixture is changed. A notable example of this is the comical "helium voice" produced by filling the throat, mouth, and nasal cavities with helium from a balloon [warning: breathing helium can cause death by asphyxiation]. Sound travels faster in helium, which raises the frequencies of the resonances (formants) created by the vocal cavities, though the pitch doesn't change much. Conversely, denser gases in which sound travels more slowly can lower the resonances of the voice.

There are places where sound cannot travel either because the medium is not elastic or because the molecules aren't close enough together to create a chain reaction. The classic example of the latter is the vacuum of space. Technically, "space" contains a great many molecules—actually, *all* of them—in the form of asteroids, comets, planets, and suns. However, the density of the molecules in between these celestial bodies is not high enough to allow the chain reaction of compressions and rarefactions to form. In the words of the advertising campaign for the 1979 movie *Alien*: "In space, no one can hear you scream."

## RECEPTION: THE BETTER TO HEAR YOU WITH

So far, we've discussed the generation of sound waves by a voice or instrument and the propagation of those waves through a medium such as air. The next step is for someone, or something, to receive this series of compressions and rarefactions and interpret them. In other words, we need ears with which to hear. The ear can be divided into three basic parts: the outer ear, the middle ear, and the inner ear (see Figure 1.6).

The outer ear consists of the fleshy part on the outside of your head and a canal that funnels sound waves into your head. The flesh of the ear, or **pinna**, helps us locate the sound source, because it changes the incoming sound subtly (filters it) depending on what direction the sound is coming from. The two ears working together also provide directional cues through the time difference between when sound reaches one ear and the other and through an intensity difference if sound arriving at one ear is partially blocked by the head.

The shape and length of the **ear canal** influence the frequency balance of the sound waves that pass through it by emphasizing frequencies between about 2,000 and 5,000 Hz, just as speaking into a tube changes the quality of your voice by emphasizing certain frequencies. As a result, our hearing is most acute around those frequencies.

The middle ear consists of the tympanic membrane, or **eardrum**, and a series of three bones, collectively referred to as the **ossicles**, which connect the eardrum to the inner ear. When a sound wave reaches the eardrum, it vibrates in sympathy. To get a

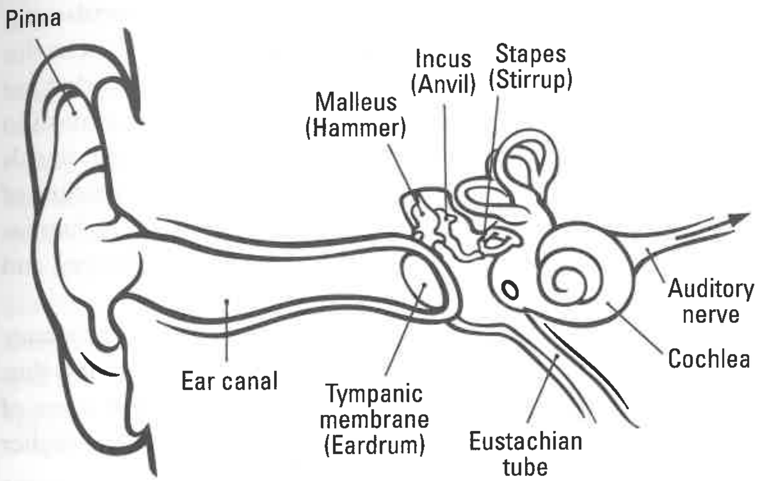


*Figure 1.6* Basic anatomy of the human ear. (Based on a drawing in Chittka, L. and A. Brockmann. 2005. Perception space—the final frontier. *PLoS Biol* 3(4): e137.)

sense of how this works, try pointing a trumpet, or some other loud instrument, at the head of a timpani drum and playing loudly. The drumhead will vibrate madly without ever being struck. Similarly, you can also sing into a piano while holding the damper pedal down and hear the strings vibrate in sympathy with your voice. With your eardrum moving back and forth, the energy that a voice or instrument originally imparted to the air has now been turned into a vibration in your body. The vibration of the eardrum is next passed to the ossicles.

The individual ossicles are called the malleus, the incus, and the stapes, and are known colloquially as the hammer, the anvil, and the stirrup due to their respective shapes. These three bones work together to amplify mechanically the relatively small movement of the eardrum; this is one of the reasons why our hearing is so sensitive. The middle ear also connects to your **Eustachian tubes**, which connect at the other end to your throat and allow your body to keep the air pressure in the middle ear matched with the air pressure outside of your head. It's the pressure imbalance between the inner and outer ear that makes your ears pop when going up or down in a plane or going up or down in the elevator of a tall building. The last of the three ossicles connects to the **oval window** of an organ called the cochlea, which makes up your inner ear.

The **cochlea** is a fluid-filled tube that is coiled up like a snail. When the ossicles move back and forth in response to the movement of the eardrum, the stapes transfers that vibration to the fluid inside the cochlea through the movement of a membrane called the oval window. So far all of the changes in energy have been mechanical: vibrating string to vibrating air to vibrating eardrum to vibrating ossicles to vibrating fluid. It's the cochlea that finally does the job of translating this mechanical energy into neural impulses that are then transferred to the brain through the auditory nerve.

The vibrating fluid in the cochlea causes various parts of the **basilar membrane**, which runs down the middle of the cochlea, to vibrate as well (see Figure 1.7). On this membrane are thousands of tiny hair cells and corresponding nerve receptors that are part of the **organ of Corti**. As different parts of the basilar membrane are set in motion by the vibrating fluid, the moving hair cells cause nerves to fire, sending signals down the auditory nerve to the brain. Just how the cochlea translates the motion of the basilar membrane into neural signals is not entirely clear. Two prominent theories are currently used in combination to describe this translation: **temporal theory** and **place theory**.

Temporal theory—also called **frequency theory**—hypothesizes that the frequency of a wave traveling in the cochlea causes nerve fibers to fire at that frequency thus transmitting the timing pattern of the wave to the brain. This theory explains some of the ear's capability at relatively low frequencies (up to about 5,000 Hz), but not at higher frequencies.

Place theory hypothesizes that different parts of the basilar membrane are sensitive to different frequencies: high frequencies nearest to the oval window, low frequencies toward the center of the spiral. In this way, the basilar membrane separates the incoming sound wave into its component frequencies. Place theory is most convincing when explaining the perception of higher frequencies and thus two theories can both contribute to our understanding of frequency perception. In Chapter 3, we'll see that most pitches are made up of more than one frequency, but only one of those frequencies is heard as the "pitch."

As we age, the part of the cochlea responsible for transmitting high frequencies to our brains gradually becomes less responsive and we hear less of the high frequency content of sound. If you expose your ear to damagingly loud sounds, you may cause

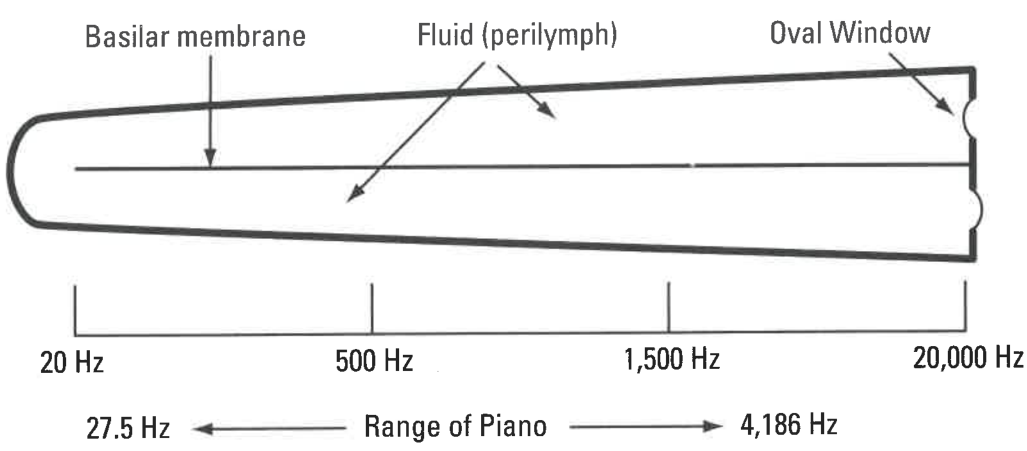


*Figure 1.7* A simplified view of an "unrolled" cochlea, showing the positions on the basilar membrane that are responsible for detecting various frequencies according to place theory. The frequency range of the piano is given for reference.

more severe degradation to your cochlea's high frequency response, which can lead to profound hearing loss. Since the consonants in your speech that help you determine what words are being said often contain relatively high frequencies ("s," "t," "k," etc.), severe loss of high frequencies results in difficulty distinguishing between words that contain the same vowel sounds but different consonants. Your cochlea is a powerful, but sensitive, organ, and damage to it is irreversible. Hearing loss will be discussed in the next chapter, where the amplitude of sounds is considered.

Once the cochlea has done its job, the nerve signals are sent to the brain. It's in the brain itself that we decode these impulses, remember them (or forget them), analyze them, and act on them. It is our brain that decides that a sound represents squealing tires and we'd better move quickly or that a sound represents music that we can analyze and appreciate.

The study of our auditory system and the way the brain decodes and analyzes the resultant nerve impulses is referred to as **music perception**, or **psychoacoustics**. Some aspects of this field of study will be taken up in future chapters as they relate to sound, audio, sampling, and synthesis. The study of mental processes and mental representation in music is referred to as **music cognition**. Naturally, there can be a great degree of overlap between the study of music perception and the study of music cognition.

Fundamentally, sound "happens" in the brain. So if a tree falls in the forest and no one is there to hear it, the tree still causes a pattern of compressions and rarefactions that propagate through the air, but with no ears to receive the disturbances and no brain to process the signals, there is no sound. Do squirrels count?

## REVIEW OF KEY TERMS

| | |
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| compression 8 | eardrum 14 |
| propagation 8 | ossicles 14 |
| rarefaction 9 | Eustachian tubes 15 |
| compression wave 9 | oval window 15 |
| transverse wave 9 | cochlea 15 |
| resonance 12 | basilar membrane 16 |
| formants 13 | organ of Corti 16 |
| filters 13 | temporal/frequency theory 16 |
| equalizers 13 | place theory 16 |
| pinna 14 | music perception/psychoacoustics 17 |
| ear canal 14 | music cognition 17 |