Section I:
Sound

Overview

- The end result of music-making is sound.
    - All music technologies are fundamentally related to sound.
        - Audio recording is concerned with capturing sound.
        - MIDI sequencing is concerned with controlling sound.
        - Sampling and synthesis are concerned with creating sound.
        - Computer notation is concerned with encoding performance information that will be turned into sound.
        - Computer-assisted instruction is concerned with teaching us to relate sound to various musical concepts, such as intervals, scales, and melodies.

Chapter 1:
What Is Sound?

Introduction

- This chapter covers:
  - Sound generation and propagation, including the formation of a series of compressions and rarefactions by a vibrating source.
  - Sound generation by musical instruments, including strings, reeds, flutes, brass, and voices.
  - The impact of instrument bodies on pitch and timbre through resonance.
  - The need for a medium through which sound can pass and its essential properties.
  - The basics of hearing including the anatomy of the outer, middle, and inner ear and the function of the inner ear.
- Philosophical question:
  - If a tree falls in a forest and no one is there to hear it, does it make a sound?
    - 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 is made up of various types of molecules, and between the molecules is nothing.
  - Air molecules can be pushed together, or compressed, into a smaller space.
  - Elasticity is the property of air that causes the molecules that have been compressed together to spring apart again.
- Sound waves are generated when air molecules are pushed together, allowed to spring apart, and then pushed together again in a repeating pattern.
  - Analogy 1: When a cue ball hits another pool ball.
  - Analogy 2: When you bump into the person in front of you at a crowded party.
- To generate sound, you need a device that can cause molecules in the air to compress together and then allow them to spring apart again.
  - Think about plucking a guitar string:

- After you pull the string out of its resting position and release it, the tension pulls it toward its resting position and its momentum carries it beyond that resting point.
- As the string moves forward, the molecules in front of the string are pushed together, temporarily compressing them.
    - The region of air where the molecules have been compressed together is sensibly referred to as **compression**.
- The compressed air molecules then spring apart and cause a compression further on, and these molecules also spring apart, creating a continuous cycle.
- The energy that was imparted to the molecules by the string moves, or **propagates**, through the air.
- While the compression is propagating through the air, the guitar string continues to move.
- After the string 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, 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 are fewer air molecules than before.
    - This is the opposite of compression, which is known as **rarefaction**.

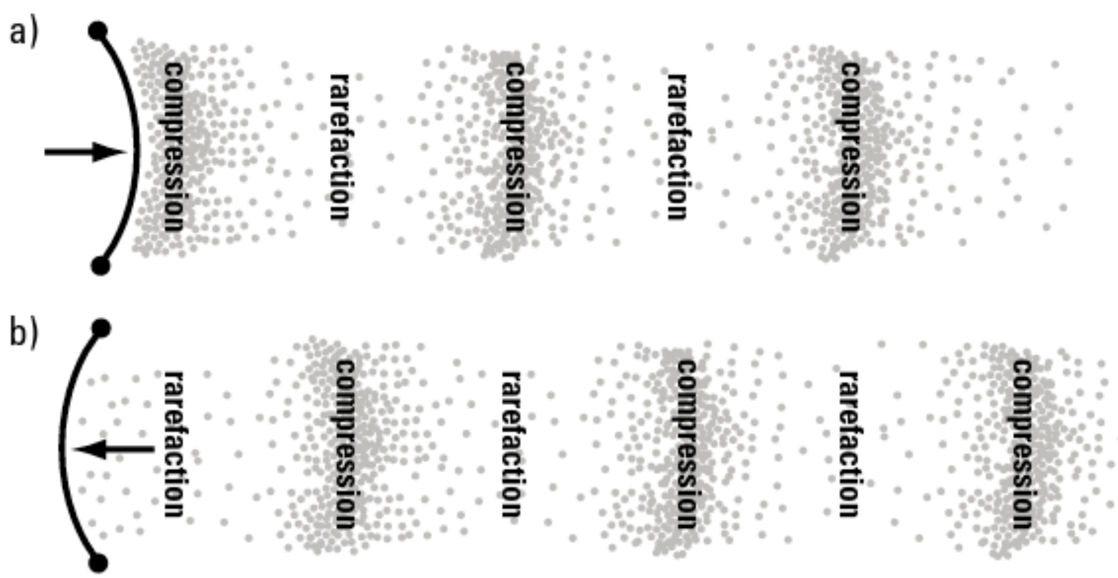

Figure 1.1 (a) A string moving forward causing a compression; and (b) a string moving backward causing a rarefaction.

- As the tension on 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, 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

- All vibrating bodies that make sound necessarily create chain reactions of compressions and rarefactions.
- For bowed strings, 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.
- 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.
        - This is why a solid-body electric guitar isn't very loud without its amplifier—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. There is an open–close–open cycle taking place.
    - 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 propagate via chain reaction through the instrument, the absence of airflow allows a rarefaction to form.
    - 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.

- ○ Double-reed instruments (oboe and bassoon) work similarly, except that there are two reeds that close together due to the airflow.

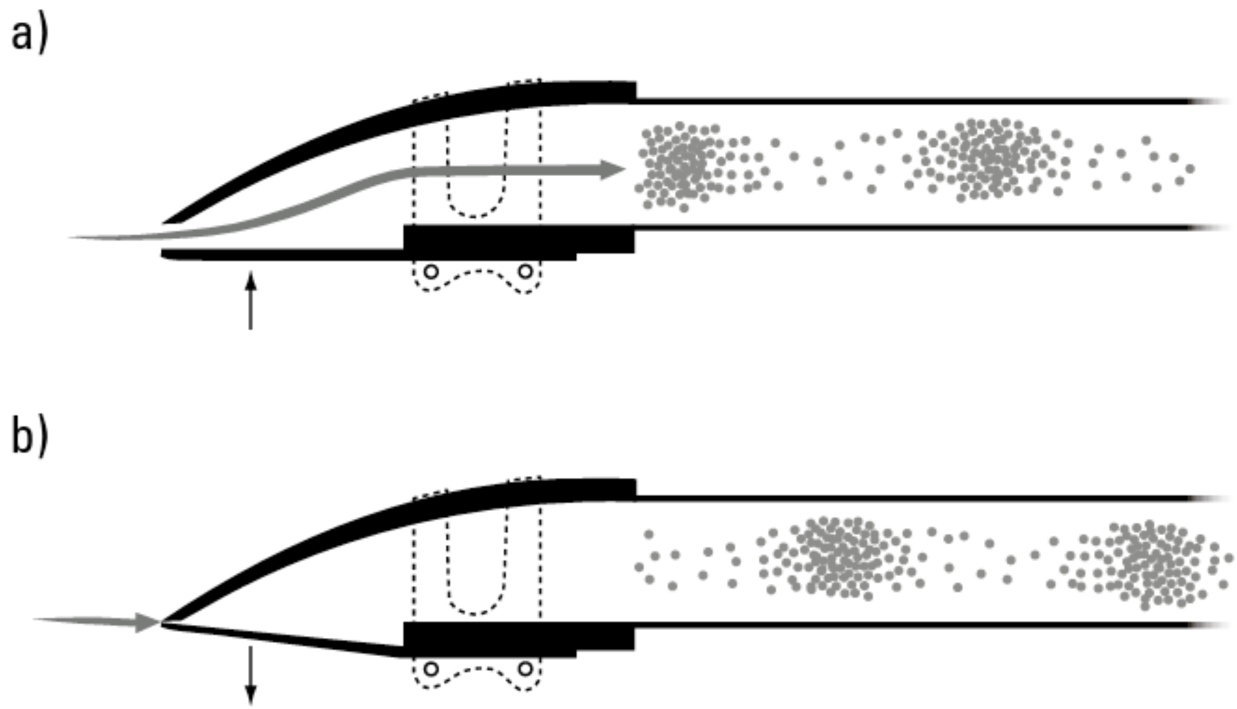

Figure 1.2 (a) Air entering a clarinet mouthpiece causes a compression in the barrel. The air over the reed causes the reed to rise and reduce the airflow. (b) With the reed closing off the air stream, a rarefaction forms in the wake of the compression. The reduced airflow over the reed causes the reed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

- The flute also creates compressions and rarefactions by interrupting the performer's air stream.
  - ○ With the flute, air blown across the blowhole is split by the edge of the blowhole and some of the air enters the flute, causing a compression.
  - ○ 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.

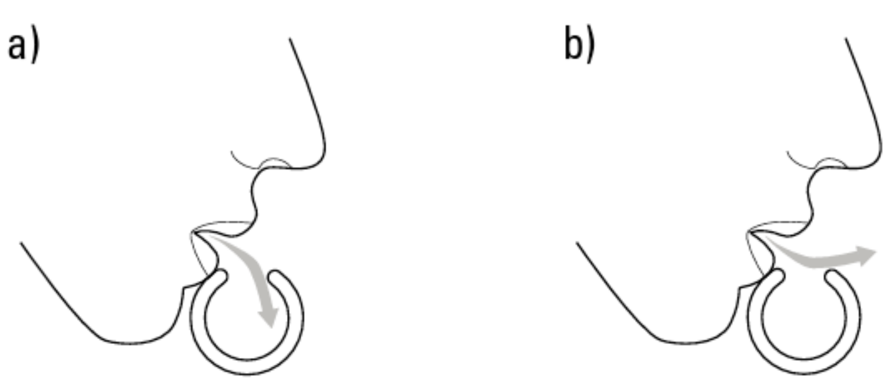

Figure 1.3 (a) Side cutaway view of a flute blowhole. Air is blown across the blowhole of the flute and is deflected into the flute, creating a compression. (b) Pressure from the compression deflects air out of the flute. A rarefaction forms as the compression propagates down the pipe.

- Other flutes (toy flutes, whistles, ocarinas, and recorders) work similarly; 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, and 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 byt the edge of the vent again enters the pipe.
- The pipe organ, known as the "King of Instruments," works in a similar way to a toy flute.
    - The pipe organ has "flue" pipes, which are flute-like, as well as reed pipes in which the air pumped into the pipe passes over a reed to generate the pitch.
- In brass instruments (trumpets, trombones, French horns, tubas), lip buzzing creates compressions and rarefactions.
    - When the performer blows into their closed lips, the pressure forces the lips open and air flows into the instrument, creating a compression.
    - 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.

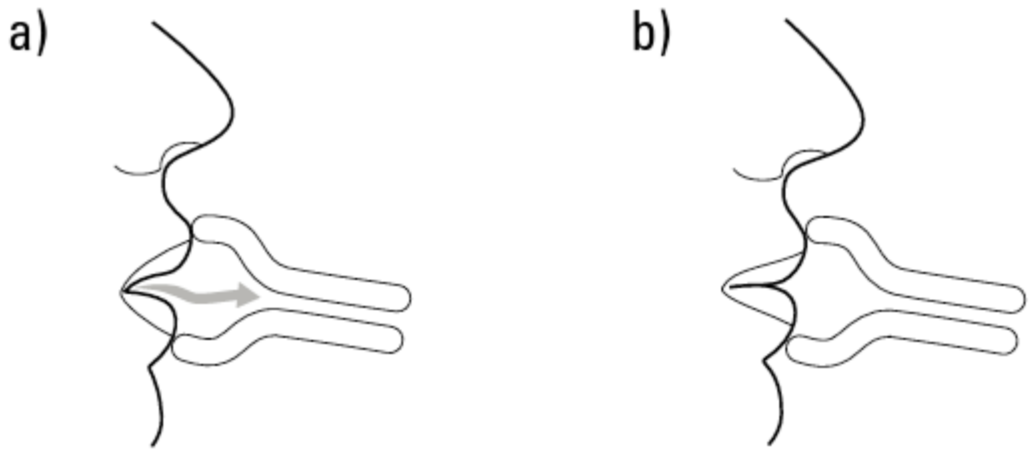

Figure 1.4 (a) Side cutaway view of the mouthpiece of a brass instrument. Air pressure from the lungs forces open the lips and causes a compression in the instrument's air column, which then propagates through the instrument. (b) The moving air and the tension of the lips close off the air stream and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

- Vocal production is similar in some ways to the production of sound in brass instruments.
    - The vocal folds ("vocal cords") located in the larynx start off closed and are forced open by the air pressure from the lungs.
    - Once air is flowing past the vocal folds, the pressure decreases, causing the folds to close together.
    - This repeated opening and closing creates the compressions and rarefactions necessary for sound.

- 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.
    - It is possible to sing one pitch while playing another.
        - The pitch of the singing voice is determined by the tension of the vocal folds.
        - The pitch of the instrument is determined by the vibration of the reed/mouthpiece coupled with the body of the instrument.

- Much of the music we listen to comes out of loudspeakers and headphones.
    - The combined compressions and rarefactions of the recorded instruments 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 electric signal from an electric guitar, stereo, or iPod.
        - An electromagnet attached to the speaker converts this electrical signal into the physical movement of the cone.

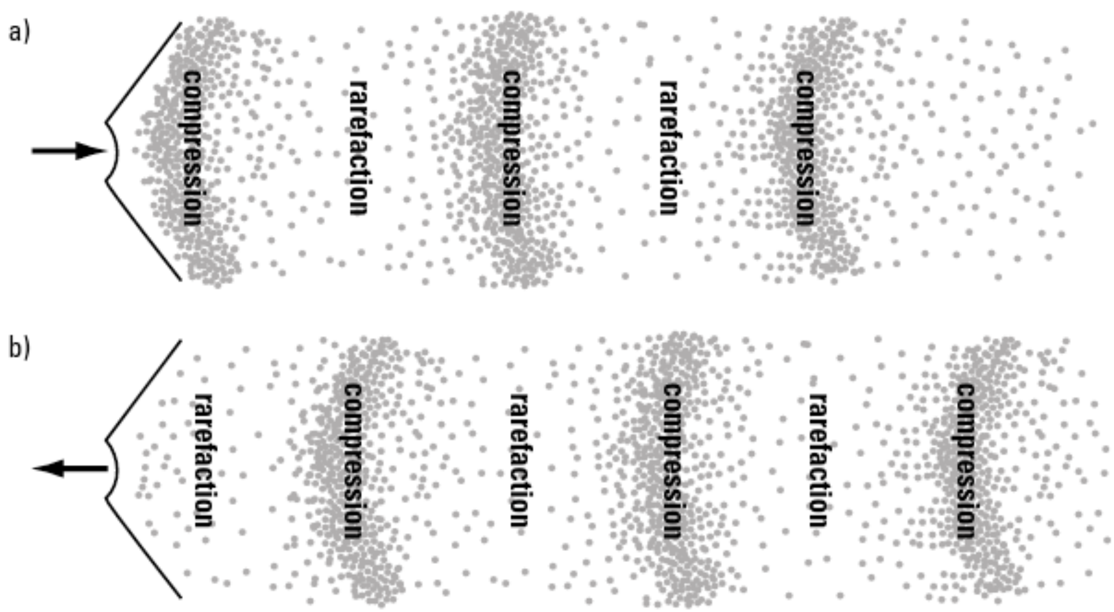

Figure 1.5 (a) Side cutaway view of a speaker cone. The forward motion of the speaker cone causes a compression. (b) The backward motion of the speaker cone causes a rarefaction.

Resonance

- There is a reason that instruments 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.
        - Think about speaking: we shape our resonators continuously to produce different vowels.
- 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 what 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.
    - The shape and materials have a strong influence on the timbre that results.
- The throat, mouth, and nasal cavities of the human body 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 are referred to as **formants**.
        - Acoustic instruments use items such as mutes to imitate formants.
- 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.

The Medium

- For sound to propagate, it requires an elastic medium.
    - The molecules in water fulfill this requirement, which is why you can hear sound underwater as well as in the air.

- The different properties of the various mediums have a strong effect on the quality of the sound.
    - Example: 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.
- Sound in "air" can change when the gas mixture is changed.
    - Example: the "Helium voice".
        - 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.
- 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.
        - The density of the molecules in between celestial bodies (asteroids, comets, planets, and stars) is not high enough to allow the chain reaction of compressions and rarefactions to form.

Reception: The Better to Hear You With

- After the generation of sound waves by a voice or instrument and the propagation of those waves through a medium, the next step is for someone/something to receive this series of compressions and rarefactions and interpret them.
- 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.

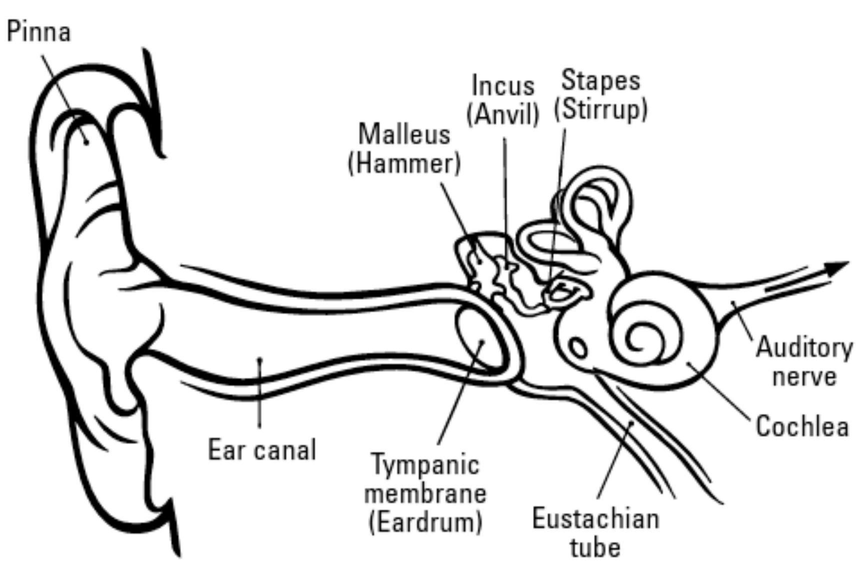

Figure 1.6 Basic anatomy of the human ear. (Based on a drawing in Chittka, L. and A. Brockmann. 2005. Perception space—the final frontier. *PLoS Biol* 3(4): e137.)

- 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; our hearing is most acute around those frequencies.
        - This is similar to how speaking into a tube changes the quality of your voice by emphasizing certain 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.
        - Demonstrations:
            - Point a loud instrument at the head of a timpani drum and play loudly.
                - The drumhead will vibrate madly without ever being struck.
            - Sing into a piano while holding the damper pedal down.
                - The strings will 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 (hammer), incus (anvil), and the stapes (stirrup).
            - The nicknames are based on their respective shapes.
        - These three bones work together to mechanically amplify the relatively small movement of the eardrum.
            - This is a reason why our hearing is so sensitive.
    - The middle ear also connects to your **Eustachian tubes**, which connect at the other end of your throat and allow your body to keep the air pressure in the middle ear matches with the air pressure outside of your head.
    - 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.
    - Keep in mind that all of the changes in energy have been mechanical so far: vibrating string to vibrating air to vibrating eardrum to vibrating ossicles to vibrating fluid.
        - The cochlea 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.
        - 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.

        - Later, we will see that most pitches are made up of more than one frequency, but only one of those frequencies is heard as the “pitch.”

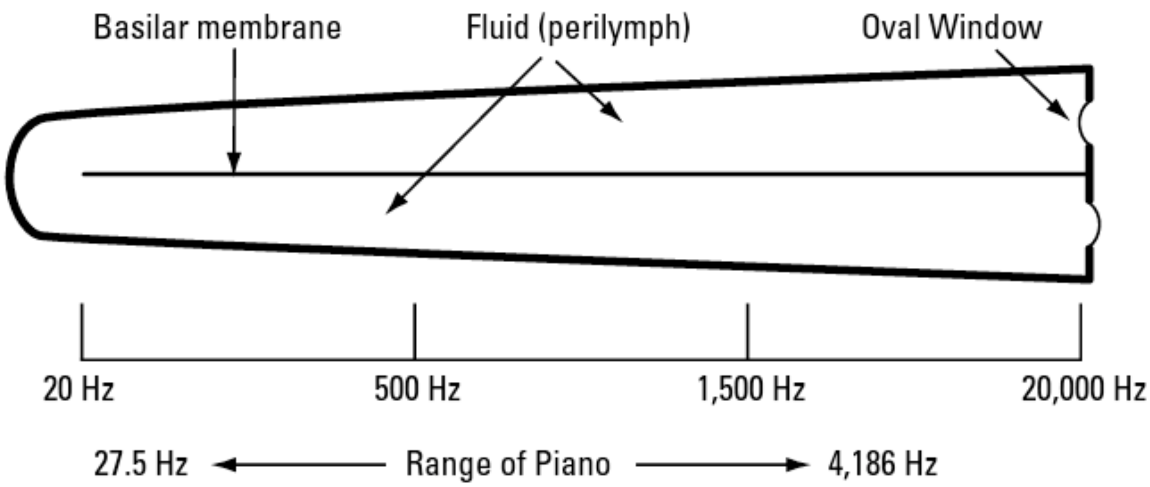

Figure 1.7 A simplified view of an “unrolled” cochlea, showing the positions on the basilar membrane that are responsible for detecting various frequencies according to place theory. The frequency range of the piano is given for reference.

- 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 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.
    - The cochlea is a powerful, but sensitive, organ; damage to it is irreversible.
- Once the cochlea has done its job, the nerve signals are sent to the brain.
    - The brain decodes these impulses, remembers them (or forgets them), analyzes them, and acts on them.
- 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**.
- The study of mental processes and mental representation in music is referred to as **music cognition**.
    - 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.
    - 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.
