

Chapter 5: The speed of sound (and a brief discussion of the ear)

This chapter features two brief concepts linked together because our course usually reaches them about the same time. An instructor (or student) can study one part without studying the other.

Review

Previously, in this coursepack, we have seen:

- If v is the speed a wave travels, f is the wave's frequency, and λ is the wavelength, the quantities are related by the equation $v = f\lambda$.
- Waves can (in some cases) *reflect* off surfaces, *refract* (bend) in different media, and *interfere* with other waves.

In discussing the speed of sound, I will show how the “ v ” in the above equation can depend on medium and environment.

Speed of sound

We know that sound waves are disturbances that travel in a medium. Usually, the medium is air, but sound can travel in liquids and solids as well.

A question I've gotten in class a few times is this: does the speed of sound depend on how loud the sound is? It makes sense to ask this question – louder sounds seem to be able to travel farther, and perhaps the reason they travel farther is because they travel faster.

When one asks if intensity or loudness affects how fast a sound travels, he or she is technically asking if *speed* depends on *amplitude*. There is a brief thought experiment (the kind Galileo and Einstein liked) we can perform to decide this.

Picture a line of people holding hands with one another. Suppose we play a game: when the first person in line gets a signal, she squeezes the hand of the person next to her, who then squeezes the hand of the person next to him, etc. A question you could ask – should the speed that pulse travels depend on how hard the people squeeze hands?



Would the speed a “hand squeeze” travels down this line of people depend on how hard you squeeze?

The answer you should come up with is “no.” The speed at which the pulse travels depends more on the reaction times of the people involved. If each person squeezes the hand of his or her neighbor as soon as he feels the “signal” reach him, the strength of that signal shouldn’t matter provided it’s strong enough to feel.

Of course, media like air, water, or metal don’t have consciousness or feelings, but they do have physical properties that are analogous to reaction time. Briefly (and in words), the “stiffer” a material is, the faster sound waves travel in it. The denser a material is, the slower sound waves travel in it (as we saw in an earlier chapter, heavier masses accelerate less under a given force than light ones). Solids are usually both stiffer and more dense than gases, but normally the effect of greater stiffness is larger.

How sound speed in air depends on temperature

Since the 1930s, we have known that the speed of sound in air at 0°C (32°F) is about 331 m/s. It turns out that as air heats up, the gas version of the “stiffness” mentioned earlier increases. The relationship between speed of sound and temperature is not precisely or universally linear, but in the temperature range between -100°C and 100°C it is quite good. In general:

$$v_{\text{sound}} = (331 + 0.6T) \text{ m/s}$$

where T is the Celsius temperature. Therefore, at a reasonable room temperature of 20°C (68°F), the speed of sound in air is $331 + 0.6(20) = 343$ m/s. This speed is about 767 miles per hour.

It is vital that one use correct temperature units in the above equation. In different applications, you may be given temperature in degrees Fahrenheit or Kelvin. In those cases, you must convert temperature to Celsius first using one of the following relationships. Note that C here represents the Celsius temperature, F the Fahrenheit temperature, and K the Kelvin temperature:

$$C = \frac{5}{9}(F - 32) \text{ or } C = K - 273.15$$

There are a few examples we could do to illustrate the use of this equation. I’ll go back to my childhood (and perhaps yours, too!) My dad used to tell me a trick that if you see a bolt of lightning during a thunderstorm and you count seconds until you could hear the thunder, there is a way of determining how far away the lightning hit. When I first started teaching this class, I didn’t remember the trick!

Let’s figure it out. How long does it take sound to travel a mile through air on a hot day (86°F). Maybe you remember (from earlier in the coursepack or earlier in your schooling) that

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

If we rearrange twice,

$$\text{speed} \times \text{time} = \text{distance}$$

$$time = \frac{distance}{speed}$$

Now, light travels about three hundred million miles per second, so light can travel one mile in about three billionths of a second. That's not a long time at all! We must still work out the sound travel time. I gave the temperature in Fahrenheit, so let's first convert:

$$C = \frac{5}{9}(86 - 32)$$

$$C = \frac{5}{9}(54) = 30^{\circ}C$$

And now, to get the speed of sound:

$$v = (331 + 0.6 \times 30) = 349 \text{ m/s}$$

So the time it takes sound to travel a mile is equal to (1 mile) / (349 m/s). However, we need to convert here since miles and meters aren't the same; there are about 1609 meters in a mile. Using the time equation above, we get a time of (1609 m) / (349 m/s) or **4.6 seconds**.

Consider how the problem would be different if it were a little colder outside. If it's colder, the speed of sound is smaller, and the denominator I just used would therefore be smaller. It would take sound *longer* than 4.6 seconds to travel a mile in air. Once I saw this, I remembered the rule – for every five seconds or so that pass between seeing the lightning and hearing the thunder, you are one mile away from the lightning strike.

Speed of sound in other materials

As stated before, sound tends to travel faster in liquids than gases, and faster in solids than liquids. The temperature of the medium matters as well, but not all media behave the same, that is, just because sound in air gains 0.6 m/s in speed for every degree Celsius it warms up doesn't mean sound in other substances share the same temperature dependence.

Here is a table of some speeds of sound in common materials (with referenced Wolfram Alpha links). :

Substance (at 20° C)	Speed of sound (m/s)
Air	343
Carbon dioxide	267
Water	1482
Ethyl alcohol	1156
Aluminum	6420
Iron	5130
Pyrex glass	5640
Diamond	12000

([Source for the solids](#))

Stating a speed of sound for solids is a simplification since there are multiple types of waves that can travel through solids, that is, longitudinal (P-waves) and shear (S-waves) travel with different speeds.

The fact that sound travels through different materials differently causes real physical effects. One of my colleagues who enjoys boating says that if he's on a boat and a single source plays a sound far away, he is able to perceive it twice (once as the sound travels through the water, and once through the air).

Example: Suppose a horn on the water about half a mile away from you (800 meters) makes a loud sound. How long does it take the sound to reach you through each medium if we assume it's 20°C outside?

Solution: Use $time = \frac{distance}{speed}$ to figure out how long the sound will take to travel. For the water, use $(800 \text{ m}) / (1482 \text{ m/s})$ to get 0.54 seconds. For the air, use $(800 \text{ m}) / (343 \text{ m/s})$ to get 2.33 seconds. Therefore, there is almost a two second delay between the sound that reaches you via water and the sound that reaches you via air.

Speed of a wave on a string

We have discussed how fast sound vibrations can travel in various solid media, but a vibrating string provides a common yet different physical case. In the last chapter, we discussed the shape and origin of standing waves on strings, but did not discuss what factors affect the actual propagation speed of waves on a string.

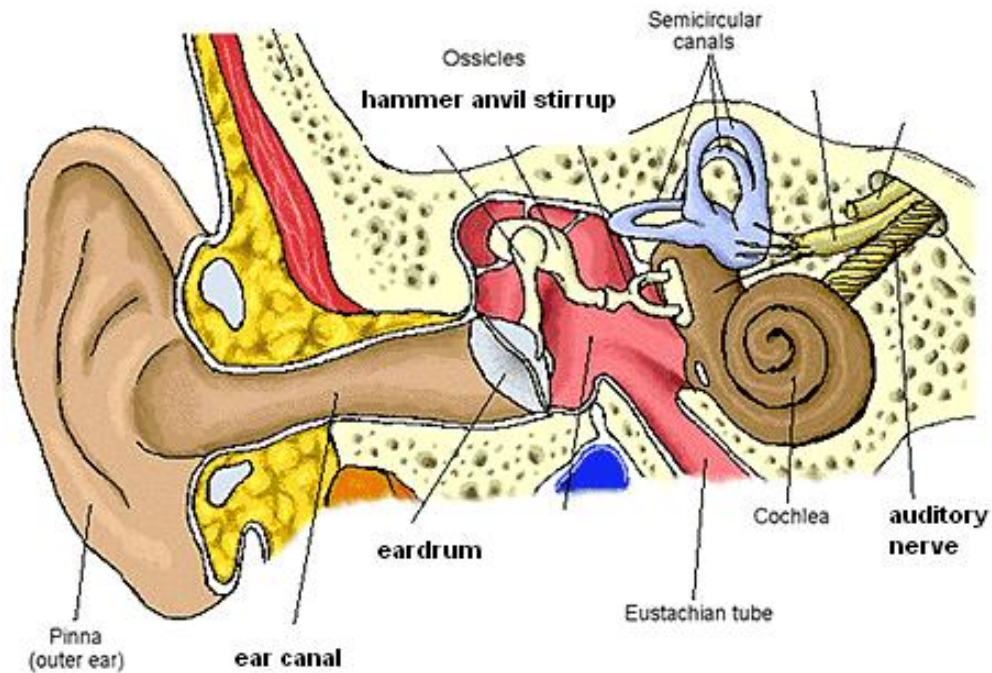
It is helpful to picture the different ways to change the frequency produced by a guitar. One could press down on the fretboard, lowering the possible wavelengths, and therefore increasing frequencies for each given string speed. Aside from that, notice that there are at least six different strings. Strings that produce higher frequencies are lighter and thinner than the bass note strings. Each string can also be tuned by changing the tension with the tuning pegs. These latter two factors can be mathematically linked. If T is the amount of string tension and μ represents the *mass density* (that is, mass divided by the string length), we saw in Chapter 4 that the speed of waves on the string (v) is given by:

$$v = \sqrt{\frac{T}{\mu}}$$

The tension and mass density put together in this way is analogous to the "reaction time" idea from the example discussed earlier involving a chain of people holding hands.

It must be made clear that the sound a guitar or other stringed instrument produces travels to your ear at the speed of sound *in air*. This speed (about 343 m/s at room temperature) is not the speed waves travel along the string, nor is it the speed of transverse back-and-forth vibrations of the string. At the interface between the string and the saddle and bridge of the instrument, vibrations happen with equal *frequency*. The *impedance mismatches* between string, saddle, instrument top, and air cause the differences in vibrational speeds of these media.

The Ear: A Natural Transducer



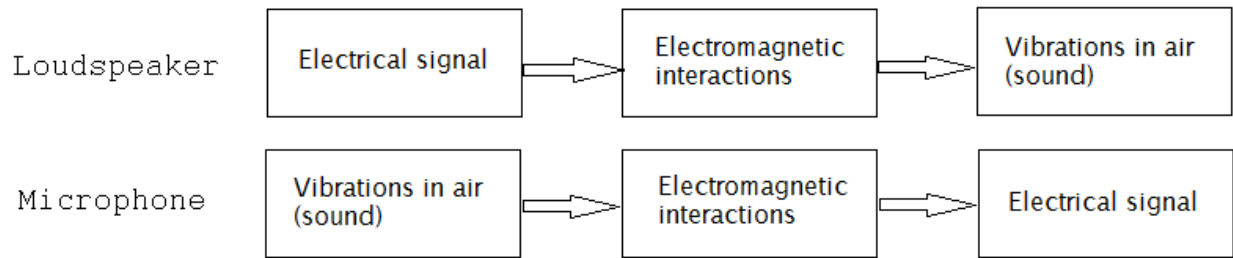
A diagram of the ear ([source](#))

The ear is the organ that detects and processes sound. A diagram of the parts is shown above. The purpose of this section is to outline the basics of how the ear works. First, I will describe what I mean by a *transducer*, of which the ear is an example. Then I will describe the parts of the ear.

Transducers

This is the first time I'll mention transducers in this pack of course notes, but it won't be the last. A *transducer* is a device (normally electrical in nature) that converts one form of energy to another. There are many examples, for example, light emitting diodes, antennas, accelerometers (like one you might find, say, in a phone or smart watch), as well as many acoustical examples.

Among the more prominent examples of transducers in acoustics are the loudspeaker and the microphone. These two devices perform essentially inverse operations:



I'll go more into the electromagnetism later, but this is essentially what happens with these two devices. Either an electrical signal is converted via electromagnetic interactions to mechanical vibrations in air or vice versa.

Question: Which of these more resembles what the ear does?

To figure this out, consider the input. The ear receives sounds, so that would lead us to believe the ear behaves more like a microphone. Though the center box depicting the internal mechanism is different for the ear, the *kind* of energy transformation in an ear is quite similar.

The ear is subdivided into three parts, each of which handles one of the steps hinted at in the boxes above:

- The *outer ear* collects and transmits acoustical energy from sounds in the environment.
- The *middle ear* is an air-filled cavity containing bones that act as an energy transference mechanism.
- The *inner ear* processes the mechanical vibrations and converts them into electrical signals the brain can process.

Parts of the ear

The *outer ear* is made up of the *pinna* and *ear canal* (or *auditory canal*), and the *eardrum* (or *tympanic membrane*) separates this from the middle ear. The pinna is the visible part of the ear and it performs several functions: it directs sound into the ear canal, it influences the frequency spectrum we perceive (which is useful in sound localization), and it makes for interesting [stories about artists](#).

The ear canal is filled with air and acts like a channel that directs pressure waves to the eardrum. The eardrum is a cone-shaped membrane that starts the energy transformation process; mechanical vibrations within the ear start here. Perforations in the eardrum can cause pain or hearing loss.

The *middle ear* is filled with air and contains three small bones. The three bones are called the *hammer*, *anvil*, and *stirrup*. The Latin names for the bones are the *malleus*, *incus*, and *stapes*. Collectively, the bones are called the *ossicles*. The hammer is connected to the eardrum, and the set of three bones acts like a lever system. The stirrup is given the name because it looks like a stirrup, and the base of this bone is attached to the *oval window* that separates the middle and inner ear. The stirrup is the smallest

and lightest of the 206 bones in the adult body. You may also notice the *Eustachian tube* in the diagram – this tube is connected to the middle ear and largely serves to equalize pressure in certain situations between the middle and outer ears. This tube is opened, for example, when your ears pop on an airplane!

The *inner ear* performs multiple functions. The *semicircular canals* shown in the diagram are part of the vestibular system that aids in balance. The *cochlea* is the part of the inner ear responsible for converting mechanical vibrations to electrical signals. The name *cochlea* comes from the Latin word for snail shell, which is the shape of this structure (there are 2.5 “turns” in it). Vibrations in the oval window stimulate motion in a fluid called the perilymph. A structure called the *organ of Corti* contains “hair cells” that act as pressure sensors. Hairs located in different locations along the organ respond to different frequencies: those close to the oval window pick up high frequencies while those nearer the center of the spiral respond only to low frequencies. These hair cells begin a complex chemical process that results in electrical impulses output through the auditory nerve. This nerve transmits the electrical impulses to the brain.

Summary

- Sound travels at different speeds in different media.
- In air, the speed of sound is temperature dependent.
- The ear acts as a natural transducer – it converts acoustic energy to electrical energy via the parts of the outer, middle, and inner ear.

Homework problems

1. Blue whales communicate with infrasound and insects communicate with ultrasound. Find (a) the SHORTEST infrasound wavelength a blue whale can make in 0°C (icy) **water** (**Hint:** If you want a short wavelength, do you want a higher or lower frequency for a given wave speed?) and (b) the LONGEST ultrasound wavelength an insect can make in (room temperature) **air**.
2. A blue whale emits a 12-Hz sound signal toward its mate. If it takes 1 minute for the signal to arrive (and both whales are swimming in icy water), how many miles apart are the whales? (Note that 1 mile is 1609 m).
3. Lightning strikes some distance away, and it takes three seconds after the flash to hear the thunder. How many miles away from you did the lightning strike if it's 77°F outside? See the next problem (or my notes online) if you need the formulas.
4. The speed of sound in air is $331 + 0.6 \cdot T$ m/s where T is the Celsius temperature. Fill in the table and find the speed of sound in air at all of these temperatures. The extreme temperatures shown are records for Chicago:

Air temp (°F)	-27	0	23	86	105
Air temp (°C)					
Speed of sound (m/s)					

$$F = \frac{9}{5}C + 32 \quad C = \frac{5}{9}(F - 32)$$

5. Find the wavelength of a 262 Hz sound (middle C) in the following substances at a 0°C temperature: (a) air, (b) water, (c) steel, (d) diamond
6. Does the ear behave more like a microphone or a speaker? Briefly justify your answer.
7. A tsunami traveling across deep water can have a speed of 750 km/hr and a wavelength of 200 km. (a) What is the frequency in Hz of this wave? (b) Waves moving through shallow water of depth h have a speed given by $v = \sqrt{gh}$. Since the wavelength of a tsunami is much longer than the typical depth of oceans, we can consider oceans

“shallow” in this relative sense. What is the speed of a tsunami at an average depth of 4.3 km?