1. The Story of Sound

At first blush, the answer to the question, “What is sound?”, might seem straightforward. It would probably go something like, “sound is anything that we hear” and for the most part that answer can get us pretty far in terms of the practical utility of the word. But if we separate sound from the sense of hearing for the time being, we can begin to capture its more basic nature. To truly understand the fundamental features of sound we’ll have to do a deep dive into some heady (yet beautifully simple) physical and mathematical concepts which we’ll introduce in this chapter. A cast of characters will be assembled for our story of sound—minor characters that we needn’t develop in detail, and major characters whose role is essential to our understanding of how and why sound exists and is utilized in the service of language. Our story of sound will ultimately form the foundation on which speech and hearing science rests, so it is essential that we understand the nuances of its story.

Before we get there, however, I want to impress upon you that the story of sound is conceptually quite easy to wrap your head around. Even before cracking open this book, you likely have a sophisticated understanding of how sounds happen. For example, you would know that *objects* make sounds when acted upon in some way, that sound is the result of doing something to an object. Stepping on dry leaves in the autumn makes a crackling sound, tapping your pint glass against another glass makes a chime-like sound, and so on. You might also know that different kinds of objects make different types of sounds when struck and that can tell us about the object itself, for example, how big or small the object is, how thick or thin the object is, or whether the object is close by or far away. You know all this simply by virtue of experiencing sounds on a daily basis. This knowledge will serve you well as we begin detailing the physical world of sound.

But back to our original question, the theme of our story—what *is* sound? Our story will conclude that the basic characteristic of sound is the movement of air which is registered by our ears. But sound, more fundamentally, exists even if there is no one to hear it. In this chapter we'll unpack the story of sound by introducing you to characteristics of the setting or medium in which sound occurs, **air**, and our protagonist, the **source**, here a vibrating object. The interaction of the vibrating object and the medium results in the message we call *sound.* As I introduce these physical features and properties that characterize air and its interaction with the source, it will be important to not lose sight of the fact that every single concept discussed in this chapter will have an application to our examination of the process of speaking.

1.1 *The Setting—Air*

The sounds we will be most concerned with in this book, namely speech sounds, as well as the vast majority of non-speech sounds we experience daily, occur in a gaseous medium that conducts sound energy—air. When we say "air" we're really referring to are the *molecules*, or the infinitesimally small particles, that make up air, such as nitrogen, oxygen, water vapor, etc. Although there is no such thing as an "air molecule" *per se*, we willl use that phrase as a shorthand to refer to the collective mixture of these elements and gases. In this section we will discuss the behaviour of air molecules on both a *micro* and *macro* level, that is, we will examine how a *collection* of air molecules move, as well as the properties of *individual* molecules.

> ***Think about it!***
>
> Sound can occur in media other than air. Maybe you've gone swimming in a pool with your friends and tried talking under water. The properties of water are quite different from air, so though water molecules react in a similar way to the air molecules when acted upon, the speed at which sound travels in water is much faster, almost 5 times faster! We'll talk about the "speed of sound" later in the chapter.

Air molecules surround us and occupy every nook and cranny on earth. You might imagine air molecules as the tiniest of floating ping pong balls (or specks of dust) are constantly moving around us in a random fashion (the movement is called **Brownian motion**) and bouncing off objects they encounter, including other air molecules. If you're old enough to remember the video game "Pong," where a dot on the computer screen bounces off the sides of the screen like an air hockey puck, you can imagine air molecules behaving in a similar way, only there are many, many (many) more. If you were to *zoom in* on an empty box, whose sides are one meter long, you would see approximately 10 trillion trillion (that's 10 with 27 zeros after it!) molecules, and all of them are moving around and bouncing off each other randomly. Air molecules are moving fast too, at speeds upward of 900 miles per hour!

ILLUSTRATION OF CUBE WITH RANDOM DOTS

Now that we've established what air is, we can now begin to describe some of the properties of air and principles underlying the behavior of air in conditions that result in sound.

1.1.1 Under Pressure

This brings us to the first physical concept we need to understand to capture the nature of sound, namely **pressure**. Pressure is a *force* (something that pushes or pulls on an object) that acts perpendicularly on an area. For example, the downward force of gravity pulling your body against the chair you're sitting in exerts pressure on the area of the seat.

PICTURE OF F ACTING ON A

For air, pressure is a measure of how frequently air molecules are bouncing against objects in our environment. The more frequent these collisions, the higher the pressure. Pressure is measured in units like Pascals (*Pa*) (which we'll be seeing a lot in speech applications) or psi (pounds per square inch) (which you see when you're pumping up the tires on your bike). A more intuitive unit for pressure is "cm of water" or *cmH₂0*, which is the amount of pressure required to move a column of water. In this book you'll see both Pascals (or kilopascals, *kPa*) and *cm H₂0*.

PICTURE OF A U-SHAPED TUBE WITH WATER AND MOUTH BLOWING ON ONE END

All matter, including the air molecules in our atmosphere, has **mass**[1], which is a measure of the amount of *stuff* in an object. Because air molecules make up our atmosphere, they are acted upon by gravity. The pull of gravity on air molecules results in a pressure that is exerted on all the objects in our environment. This pressure is called **atmospheric pressure,** which we'll abbreviate as P_{atm} ("P" refers to pressure and the subscript tells you *where* the pressure is occurring, in this case, the atmosphere). Atmospheric pressure typically refers to the pressure of the atmosphere at sea level and equals around 101.33 kPa (or 101.33 x 1000 = 101,330 Pascals[2]), or around 1033 cm H_2O, or 14.7psi.

Think about it!

Every square inch of your body is holding up about 14 pounds of air, which, if you've ever lifted weights, you would know is not a trivial amount. So why don't our bodies crumble under that weight? There are a few reasons why this doesn't happen. Air molecules are moving around randomly so the pressure is distributed evenly around body. But the main reason is that the pressure in our body (blood, bones, organs, etc.) is roughly the same as atmospheric pressure, so the forces more or less cancel out.

The pressure exerted by the air in our atmosphere at sea level is different from the pressure exerted by atmospheric air at the top of a mountain, which your body responds to in the form of your ears "popping" as your elevation increases. The pressure of atmospheric air as you get further and further from sea level decreases because the

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[1] Don't confuse mass with weight.

[2] What's a "Pascal"? A Pascal is a unit of pressure, that itself depends on another unit called "Newtons." A Newton is the amount of force that's required to make a weight of 1kg go 1 meter per second squared (m/s^2). But pressure is exerted on an area and Newtons have no area specified. So a Pascal is one Newton per square meter (N/m^2). The force of 1 pascal is equal to around 10 cm of H_20.

force of gravity is greatest near the surface of the earth. P_{atm} at sea level is about 14.7psi, but at the top of Mt. Everest it's about 5.5psi! As a result, the air at sea level is denser (the molecules are more tightly packed, see below) than the air at the top of the mountain.

ILLUSTRATION OF DENSELY PACKED AIR AT SEA VS MOUNTAIN TOP

When we discuss sound and the sounds of speech, it makes more sense to talk about a more *local* pressure. The pressure in the room in which you're sitting might be more or less than that of atmospheric pressure at sea level, so we'll use the term **ambient pressure** (P_{am})[3]. Ambient pressure is the atmospheric pressure at a given location which will refer to more localized air pressure, not necessarily at sea level, and will be more useful when we talk about the nature of sound.

The pressure exerted by air is related to the space in which the air is contained. A good example of this relationship is a partially blown-up balloon. If you were to squeeze the end of the balloon you would be forcing the air into a smaller space or **volume** compared to when the balloon wasn't squeezed.

ILLUSTRATION OF BALLOON IN TWO DIFFERENT STATES

As a result, the end of the balloon that is not squeezed expands because the pressure exerted by the air increases. In the balloon example the volume of the unsqueezed end increases as a result of the increased pressure. But what if the volume doesn't (or can't) change? Imagine a cylindrical glass container with an air-tight plunger at the top. Depressing the plunger causes the

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[3] Keep in mind that P_{am} could refer to pressures other than that of the atmosphere as well, such as the pressure experienced under water. For example, the ambient pressure at 10 meters below the surface of the ocean is roughly twice the P_{atm} at sea level. But for our purposes, P_{am} will refer to the local or immediate air pressure where a sound event is occurring, like the pressure in the room where you're sitting right now.

air inside the container to become compressed, exerting more pressure on the sides of the glass and the plunger. As a result, it would be very hard to depress the plunger especially if the plunger had a tight fit.

ILLUSTRATION OF CYLINDRICAL CONTAINER WITH PLUNGER

So, a mass of air in a large volume container has lower pressure than if that same mass of air were forced into a smaller volume container. Again, imagine the moving air molecules in [FIG1]. If we were to reduce the size of this box and squeeze the same number of moving dots into a smaller square, you would clearly see the dots striking the sides of the box (the pressure)

more often than if the box were bigger. This inverse relationship between pressure and volume was formalized by the 17th century Irish chemist, Robert Boyle. **Boyle's Law** states that if the volume of a container increases, the pressure of the air (or any gas) inside the container decreases, and vice versa. He formalized the relationship with the equation:

$$P_1V_1 = P_2V_2$$

> ***Think about it!***
>
> You've probably heard the TV weather person talk about "areas of high pressure" or "areas of low pressure." Did you ever make the connection between high or low pressure to the temperature outside? It turns out that pressure and temperature are directly related. When pressure increases, so too does temperature--which is measure of the kinetic energy (energy due to motion) of the fast-moving air molecules. The faster they move, the higher the temperature. It's colder at the top of a mountain than at sea level because the air is less dense and lower pressure than at lower elevations.

In our plunger example above, suppose the container has a volume of 1liter (V_1) and the air has a pressure slightly above that of atmospheric pressure at 102kPa (P_1). When you depress the plunger, the volume is reduced to 0.9 liters (V_2). What would be the new pressure (P_2) of the air inside the glass cylinder?

$$(102\text{kPa})(1\text{L}) = (P_2)\ (0.9\text{L})$$

$$P_2 = 102/0.9 = 113.33\text{kPa}$$

Depressing the plunger so the volume of the container is reduced by just a tenth of a liter increases the pressure inside the container by 10kPa or around 1.5psi! This relationship between air pressure and the volume of its container will be important when we discuss breathing and speech sounds.

1.1.2 Density

When you squeezed the balloon or depressed the plunger in the examples above, the mass of air is forced to occupy a smaller space, as a result the pressure exerted by the air increases. But why? Well, the mass of air molecules in the smaller space has increased in **density** relative to when it occupied the larger space. Density is the amount of mass you have per unit of volume (the measure of a region in three dimensions). So, if the container gets smaller and the mass stays the same, then you have higher density, the space between the floating air molecules decreases. Imagine there are ten soap bubbles floating around in a five-gallon bucket. The bubbles would be floating around relatively freely, bouncing off each other and the walls of the bucket, but generally with space between them. If you were to force those 10 bubbles toward the bottom of the bucket so they didn’t get past the one-gallon mark, the bubbles would become more tightly packed, or the density of bubbles would be increased relative to their density when they took up the entire five gallons. So, the same amount of bubble mass, occupying a smaller volume (the container size), results in higher density. Importantly, a higher density of bubbles (or air molecules) exerts more pressure than a lower density of bubbles, that is, density and pressure are directly proportional. When density goes up, so does pressure, and vice versa.

PICTURE OF BUBBLES IN A BUCKET

Now what about the density of air in our atmosphere? The units of density are kilograms (or the mass) per cubic meter of volume (or space), or the amount of *stuff* in a space. If we were to capture air inside a cardboard box where each side is one meter long, the density of that air would be approximately 1.23kg/m^3. If we imagine our atmosphere as a cardboard box, the air at the bottom of our atmosphere box is denser than the air at the top. Remember when we discussed atmospheric pressure at sea level versus at the top of Mt. Everest?

> ***Think about it!***
>
> Have you ever wondered why mountain climbers who ascend the tallest peaks have to train their lungs to maximize their oxygen intake? Well, there is simply less available oxygen molecules (which are part of air) at that high elevation because of the air being less dense than at sea level. A less dense mass of air means that the molecules are more dispersed. The more dispersed they are the less concentrated the oxygen is for breathing. So, at the top of Mt. Everest there is only 33% of the oxygen available at sea level.

Earth's gravity has a weaker effect the higher in elevation you go, so the mass of air is more tightly packed (denser), with molecules more frequently bouncing off things (higher pressure) at sea level than at the top of Mt. Everest.

1.1.3 Flow

Back to our balloon example. If you were to prick the end that you've tied off with a small needle, you would expect the balloon to slowly deflate. Why does this happen? Recall that the mass of air inside the balloon is slightly higher than P_{am} (if it weren't higher, it wouldn't take the shape of a balloon). If there were a small hole in the balloon the higher than P_{am} air leaks out because P_{am} has a lower pressure. That is, air **flows** from a region of higher pressure to a region of lower pressure, a **pressure differential**. The pressure of this flow is called **driving pressure**. Importantly, the air in the balloon leaks out only up to a certain point. The air leaks out only until the pressure in the balloon equals P_{am}. If the pressure inside the balloon is equal to P_{am} then there is no driving pressure.

PICTURE OF AIR LEAKING OUT OF A BALLOON

Just *how* this air flows from an area of high pressure to lower pressure will be important to our later discussion of speech sounds. There are primarily two kinds of flow, **laminar** and **turbulent.** With laminar flow, air (or any gas or liquid) moves relatively slowly, in smooth and steady fashion with no sudden changes in speed or direction. With turbulent flow, on the other hand, air moves faster and there are lots of small and sudden changes to the speed and direction of the moving air. Turbulent flow results from air either flowing through a *channel* or an *obstruction.* So, the air leaking out of our balloon is likely turbulent because it travels through a small channel, the pin hole, because of the pressure differential between the inside of the balloon and the atmosphere.

1.2 *The protagonist--The Vibrating Object*

So far, we have been discussing our setting, air, as a medium with physical characteristics like mass, density, and the consequences of the movement of air molecules—pressure. We can now turn our attention to the protagonist in our story of sound, the vibrating object, or the sound **source,** and later, the effect it has on the P_{am} surrounding it.

1.2.1 The tuning fork

The classic example of a well-behaved (we'll get to objects that are more erratic in their vibration later) vibrating object is the *tuning fork*. Perhaps you've seen one before, but if you haven't, a tuning fork is a highly engineered metal fork with two "tines." The tines are manufactured in such a way that when you strike the fork against your knee (never hit one against a blunt or hard surface!) they vibrate in a very regular fashion. You might see a number on the side of the for like "440," which refers to the number of times the tines move back and forth in one second.

Before you strike the fork, the tines are said to be in a position of **equilibrium**, their original state. But once you strike the fork, the tines get displaced inward (see below). The tines start moving, from an equilibrium/rest position, because of **inertia**, which is directly proportional to the mass of the tines. Inertia is what Isaac Newton described in his *First Law of Motion*, where he said that objects at rest will stay at rest unless acted upon by a force.

The displaced tines reach a maximum inward position. What determines the maximum position? Well, the harder you strike the fork, the further inward the tines are displaced.

When they've reached this maximum displacement, they stop for a moment, and then bounce back toward equilibrium. The metal tines, and all matter, have the property of **elasticity**, which is a measure of how much resistance the tines have against being displaced. Or put another way, elasticity explains why the tines that have been displaced from equilibrium bounce back toward their original position. Elasticity is a relatively simple concept because we have all interacted with the elastic property of rubber bands, which snap back after you stretch them. Elasticity is said to be a **restoring force** or a force that brings the displaced body (the tines, the rubber band) back to equilibrium. At some point as you are stretching your rubber band it becomes impossible to stretch further and the band snaps back. With our tuning fork, when the elastic force becomes greater than the force of inertia the tines bounce back toward their original (unstruck) position. In this way, inertia and elasticity are opposing forces.

You might think that the tines would bounce back from the maximum inward displacement back to equilibrium, and that would be the end of story. But that's not what happens. Elasticity causes the tines to be restored to their original position, but inertia again propels the tines, but this time beyond equilibrium to a position of maximum outward displacement. This is captured by the second part of Newton's *First* Law, that objects in motion will stay in motion unless acted upon by a force.

So, in this way, the tines of the tuning fork move back and forth. The tines on the tuning fork I'm holding in my hand at the moment oscillate 329 times per second!

1.3 *Pushing air—Interaction between the source and medium*

Sound is the result of the interaction between the source, in this case our tuning fork, and the medium, or air. The movement of the tuning fork tines affects surrounding air molecules in exactly the same way that striking the tuning fork affects the tines. The act of striking of the tuning fork is the incident that sets the billions of air molecules around it (which are already moving according to Brownian motion) into a regular pattern of movement which we call a **tone**.

PICTURE OF TUNING FORK BEING STRUCK

By calling it a tone I'm suggesting that you can hear the movement of the tines, and you can, if you put it close to your ear. The reason why you're hearing it is because the air molecules surrounding the tines are being pushed in a way that sets off a chain reaction in the air molecules between the tuning fork and your ears. Much like a row of dominoes falling as the result of the first domino being pushed, air molecules surrounding the tuning fork push other air molecules until eventually the molecules around your ear end up moving in a similar way.

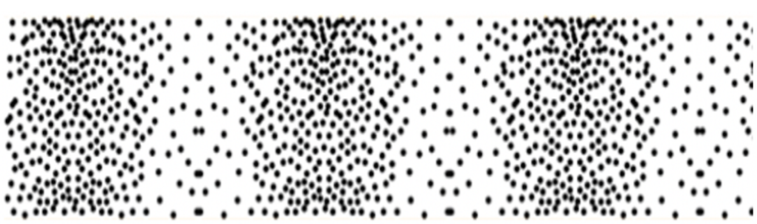
PICTURE OF A DOMINOES FALLING FROM THE TUNING FORK TO AN EAR

But the movement of these air molecules is not as simple as the dominoes in the example above. Air molecules bounce back after bumping into adjacent molecules.

Let's take a closer look at this "bouncing" behavior of air molecules. Remember that before the tuning fork is struck, the tines and the air molecules around them are in an equilibrium position. Once the fork is struck, however, the tines begin to vibrate (as a result of inertia and elasticity) and consequently push air molecules from equilibrium position. Those air molecules begin at equilibrium, reach a position of maximum displacement, return to equilibrium, overshoot equilibrium, reach a position of maximum displacement in the opposite direction, then return to equilibrium, and the back-and-forth oscillation begins again.

STEP-BY-STEP MOVEMENT OF AIR MOLECULES DISPLACED BY TUNING FORK

Air molecules have mass, and their movement occurs precisely because of the same forces we described affecting the tines of our tuning fork: elasticity and inertia. As they reach their maximum displacement position, they exert a force on adjacent molecules and set off their oscillation. This sequence of oscillations and collisions results in a wave-like movement in the mass of air, ultimately reaching your ears. That's why you can hear the tuning fork when it's struck, a guitar string when it's plucked, or a bird when it sings.



When those air molecules approach other air molecules, there is a momentary increase in density (air molecules pushed closer together), which we call **compression.** As the molecules move back towards equilibrium, density between them and adjacent molecules decreases, which we call **rarefaction.**

As the air molecules head back to their original position, having struck adjacent molecules (which are themselves set into motion), they overshoot their target to maximum displacement in the opposite direction, again causing a region of compression.

1.2.3 Patterns in air

If we were to *zoom out* from our picture of individual air molecules, oscillating back and forth and hitting adjacent molecules in a chain reaction, we'd see a more recognizable pattern--the **sound wave**. The sound wave, or the movement of a mass of air, is just regions of compression and rarefaction. The collection of compressed air molecules (dense clusters) results in momentary regions of high pressure (remember that as density increases, so does pressure). When that cluster of air molecules retreats towards their equilibrium state there is a region of rarefaction or low pressure. The regions of compression and rarefaction alternate, resulting in a movement of air called the sound wave or sometimes a *pressure wave*.

> ***Think about it!***
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> Often when we think about (or even talk about) sound we might envision it leaving the source and arriving at your ears—something like a ball being thrown from one person to another. This implies that the same air molecules surrounding the sound source are the same air molecules hitting your ears. But this is incorrect! When a sound is produced, the individual air molecules move in space but not in any appreciable way. Rather the only thing moving is the wave, which is an abstraction representing dense and less dense regions of air molecules.

The best analogy for the movement of individual clusters of molecules resulting in wave movement is actually "the wave" done by fans at sporting events. Individuals stand up, one after the other, while raising their arms, which, when you observe from afar, looks like a wave travelling across the stands.

DRAWING OF INDIVIDUALS IN VARIOUS STATES OF STANDING UP, THEN FROM AFAR AS A WAVE

So, while air molecules themselves travel very minimally (in our sports wave analogy above an individual only moves up and down from her seat), the collective effect of the microscopic oscillations of air molecules is much more meaningful because it captures the essence of sound.

Summary

The story we have told so far goes something like this: we live in an environment where we are surrounded by air molecules randomly moving about. These molecules have a **mass** and are, like all objects on earth, subject to the force of gravity. The force of gravity on air exerts pressure on the environment which we call **ambient pressure** (P_{am}). Air molecules are **most dense** (or more tightly packed) at lower elevations relative to higher elevations because of the force of gravity. As the density of air increases or decreases, so too does pressure increase or decrease. **Elasticity** is what allows air to retain its original shape when its density is changed because of some disturbance.

Important definitions/concepts

Brownian motion: the free moving behaviour of air molecules in random trajectories

Pressure: the force applied perpendicularly on an area

Mass: the amount of matter in an object

Atmospheric pressure (P_{atm}): the pressure of atmospheric air typically measured at sea level, 101.33 kPa or 1033 cm of H_2O

Ambient pressure (P_{am}): atmospheric pressure at a given location

Volume: the amount of fluid or gas that a three-dimensional container can hold, typically measured in litres

Boyle's Law: states that pressure is directly proportional to volume, $P_1V_1 = P_2V_2$

Density: the amount of mass per unit volume; a measure of the compactness of a substance

Pressure differential: a difference between the pressures of two containers

Driving pressure: the pressure of air flow from a high-pressure region to a lower pressure region, the result of a pressure differential

Laminar and turbulent flow: the *way* air flows as a result of a pressure differential. Laminar flow is smooth and steady with no changes to speed and direction, while turbulent flow is fast and unsteady with changes to speed and direction resulting from obstructions in the path of air flow or the characteristics of the channel in which air is flowing

Sound source: the object that is vibrating and causing a disturbance in the air surrounding it

Equilibrium: the initial state of the air molecule before acted upon by a sound source or adjacent air molecules

Inertia: the property of matter that keeps it in rest or motion unless acted upon by an opposing force.

Elasticity: the property of matter that resists distortion and allows it to return to its original state. When air molecules are displaced, their elasticity allows them to return to a position of equilibrium

Restoring force: a force that acts to restore an object back to its original position

Compression: describes a region of high density (and pressure) of air molecules that have been displaced from equilibrium position

Rarefaction: describes a region of low density (and pressure) of air molecules as they approach the equilibrium position

Sound wave: the alternating regions of compression and rarefaction of air molecules that result from their interaction with the vibrating sound source

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Practice problems

1. Suppose you have an empty 0.3L paint can. When you put the lid on the can, the air pressure inside is the same as atmospheric pressure (101.33kPa). If you were to crush the can to half its original volume, what would be the new pressure inside?
    a. (0.3L)(101.33kPa) = (0.3/5)(P2)

        P2 = [(0.3)(101.33)]/(0.3/5) = 506.67kPa

2. Suppose you had two canisters (A and B) of air connected by a hose with valves, letting you close it off. If canister A was 1L and the air inside it was pressurized at 103kPa, and canister B had the same amount of air but was 0.9L, would you expect air to flow from canister A to B or B to A, or neither, when the valves were opened?
    a. You would expect air to flow from canister B to A because the pressure inside canister B is higher than in canister A

P_A=103kPa, V_B=1L ; P_B=x, V_B=0.9L

P_B=103/0.9 = 114.44kPa, which is greater than the pressure in canister A, so air will flow from the higher-pressure canister to the lower- pressure one.