Speaking of Electricity & Magnetism

Pre-Lab: Sound Waves and Their Generation by Speakers

A Bit of History

“Mr. Watson, come here! I want to see you!” These words were spoken by Alexander Graham Bell to his assistant, Thomas Watson, as the first transmission through a working telephone in 1876. This fact is something that you probably learned long ago. You may also have heard that Mr. Bell had just spilled a bunch of battery acid and needed some help. (This may or may not be true.) What you most likely didn’t learn is that in order to invent his telephone, Bell first had to invent both the speaker and the microphone. These devices allowed Bell to convert between mechanical sound signals and electrical signals, the essential trick performed by a telephone.

What Is Sound and How Do Humans Perceive It?

Before we can proceed, we need to know a bit about the propagation of sound through a medium (unlike light, sound requires a medium through which to travel). We are usually interested in how sound travels through air, and it is the propagation of sound through air that we discuss here. However, sound can travel through solids and liquids as well, and the word “air” could easily be replaced with “plastic” or “water.” Now, getting back to the point, generally a collection of air molecules are hanging out at atmospheric pressure. (See p. 10 of Unit T in Moore or Ch. 18 of Young & Freedman for a description of gas pressure.) When these molecules are in contact with a surface, they exert this atmospheric pressure on that surface. If the pressure in the air were to increase, the pressure on the surface would increase, causing the surface to be compressed. Likewise, if the pressure in the air were to decrease, the pressure on the surface would decrease, allowing the surface to expand.

Now, you might ask, “What the heck does this have to do with sound?” Well, it turns out that sound waves are a series of high and low pressure areas that travel through air (see Figure 1). So as a sound wave reaches a surface, the pressure that the air exerts on that surface varies. This series of increasing and decreasing pressure causes the surface to expand and contract, or vibrate.

![Figure 1: As a sound wave propagates through the air, it compresses and expands the gas molecules into areas of high and low pressure, respectively. The effects of this compression and expansion can be seen in the Sound Wave Animation which you can access from the Pre-Lab Links on the lab website. The amplitude of the wave is the pressure difference between the peak and the dotted line.]
The phenomenon described above is the basis for how the human ear works. When a sound wave enters the ear, it impinges on the ear drum. The ear drum responds to the alternating high and low pressures by vibrating back and forth (see the Sound Wave Animation on the lab website). This vibration is communicated to an area of the inner ear called the cochlea. Inside the cochlea, there are a series of hair cells that respond to this vibration by sending electrical pulses to the brain, thus creating the perception of sound.

**How Does a Speaker Create a Sound Wave?**

Now that we’re familiar with how a sound wave propagates, let’s investigate how a speaker creates a sound wave. To start, we must remind ourselves of the relationship between a current-carrying wire and the magnetic field it creates. Imagine that a wire carrying current $I$ is wrapped into a coil of radius $R$ that has $N$ turns. It can be shown that the strength of the magnetic field inside this coil of wire is proportional to the number of turns of wire and to the current, while it is inversely proportional to the radius of the coil (eq. E9.13 in Moore; eq. 28.17 in Young & Freedman)

$$|\vec{B}| = \frac{N \mu_0 I}{2R}$$

Eq. 1

At their heart, speakers contain a diaphragm attached to a coil of wire that partially surrounds a permanent magnet (for a pictorial representation, see Figure 2). When a current passes through the wire coil, a magnetic field is created inside the coil (this is commonly called an electromagnet). This electromagnet has north and south poles just like a permanent magnet. The electromagnet feels a force from the permanent magnet in its center. In response to this force, the electromagnet and the diaphragm move.

**Figure 2:** A speaker consists of a permanent magnet, a coil of wire, a diaphragm, and an alternating source of current. When a current is sent through the wire, an electromagnet is created. The permanent magnet inside the coil produces a force on the coil causing the coil (and the diaphragm attached to the coil) to move.

Please note that the coil is NOT in contact with the permanent magnet. If the coil were wrapped directly around the permanent magnet, the coil could not move and the speaker would not work.

When the direction of the current is switched, the magnetic field of the electromagnet also switches. This flips the direction of the force on the electromagnet and, in turn, changes the direction it and the diaphragm move. Figure 3 shows snapshots of two instants in time when the current is in opposite
directions. The back-and-forth motion of the diaphragm causes the air near the diaphragm to alternately compress and expand. This process of compressing and expanding the gas is how a sound wave is created.

![Image of speaker and diaphragm](image)

**Figure 3:** This is a snapshot of the side of a speaker at two instances of time in which the current is going in opposite directions. The field lines of the permanent magnet loop around it from north to south (left to right in the space above the magnet).

In the upper picture, the current loop is creating an electromagnet with field lines that loop from right to left in the space above the magnet, opposite to the direction of the field lines of the permanent magnet. This causes the two magnets to repel, pushing the electromagnet and the diaphragm to the right. *(The permanent magnet is stationary.)*

In the lower picture, the current loop is creating an electromagnet with field lines that loop left to right above the magnet, parallel to the direction of the field lines of the permanent magnet. This causes the two magnets to attract, pulling the electromagnet and the diaphragm to the left.

As the current switches back and forth, the coil and the diaphragm get pushed back and forth, creating the sound wave that eventually reaches your ears.

**Characteristics of Sound Waves**

The sound wave created by our speaker has two important characteristics: frequency and amplitude. The frequency of the sound wave corresponds to the pitch of the sound wave. The frequency of the sound wave created by the speaker is dictated by the rate at which the current through the coil switches directions. High frequency switching of current means the speaker produces a high pitched sound wave and low frequency switching of current means the speaker produces a low pitched sound wave.

The second characteristic of a sound wave is its amplitude. The amplitude of the sound wave is related to what we perceive as the volume of the sound. Recall that a sound wave consists of alternating regions of relatively high and low pressure. The amplitude of the sound wave is the difference between the pressure in a high pressure region and atmospheric pressure. This is equivalent to the difference between the pressure of a low pressure region and atmospheric pressure (see Figure 1). The amplitude of the sound wave created by the speaker is dictated by the force on the diaphragm of the speaker. Large forces on the diaphragm means the speaker produces a sound wave with large amplitude (a loud sound) and small forces on the diaphragm means the speaker produces a sound wave with small amplitude (a quiet sound). More precisely, the amplitude is proportional to the force on the diaphragm. In this week's lab, you will investigate how various properties of a speaker effect the volume of the sound it emits.
Permanent Magnets and Electromagnets

Since permanent magnets and electromagnets are so important to the operation of a speaker, let’s get more comfortable with them by playing with a computer simulation.

**Do This:** Download and run the PhET simulation “Magnets and Electromagnets” which you can access using the Pre-Lab Links.

**Do This:** On the tab labeled “Bar Magnet”, play around with the compass by positioning it at various locations around the magnet. Note: the direction of the magnetic field line points from white to red on the compass.

**PL1.** Which scenario in Figure 4 depicts the correct orientation of the compass when placed below the N pole of the bar magnet?

**Do This:** Click on the box labeled “Show planet Earth”.

**PL2.** What direction would the north pole of a bar magnet point if you were to hang the bar magnet from a thin string?

**Do This:** Now move to the tab labeled “Electromagnet” and play around with the compass. Keep in mind that the moving circles are supposed to be *electrons*.

**Read This:** Use Figure 5 to answer questions PL3 - PL5.

**PL3.** Imagine that you are looking at the coil of wire from the perspective of the eye shown in Figure 5. What direction would you see the *current* moving?

**PL4.** What direction would the magnetic field created in the interior of the coil point?

**PL5.** What happens to the direction of the magnetic field when you switch the polarity (direction) of the battery?

**PL6.** Using the Field Meter at a certain point in space, I measure a field of 8 G produced by an electromagnet with four loops. Then I replace the four-loop electromagnet with a two-loop electromagnet. If I measure the field produced by the two-loop electromagnet at the same location in space, how strong will I measure the magnetic field to be?

**PL7.** What is true of the magnetic field produced by an electromagnet when the current source is AC instead of DC?

*End of Pre-Lab*
Part I: The Speaker (Qualitatively)

The Story

It’s late on a Wednesday night and your procrastination can go no further – you need to study for tomorrow’s physics exam. Preparing to head to the library for a long night, you pack all the essentials: textbook, computer, coffee, headphones….wait, your roommate has stolen your headphones again! What to do? You could study without music, but who does that?!

Using the knowledge gained in class, you know you can make your own headphones out of materials you have lying around your dorm room. Given one more chance to delay your studying, your procrastinating spirit wins and you decide to take advantage of this opportunity.

Equipment

- Wire (6-meter section)
- PVC Pipe
- Two magnets
- Piece of plastic bag
- Duct tape
- Multimeter
- Headphone jack
- Music source (i.e. lab computer, phone, Walkman, etc.)
- Function generator with amplifier

1. Constructing and Understanding the Speaker

**Do This:** Go to the In-Lab Links page of the website and find the Speaker Construction Slideshow. Follow the steps to create a speaker from scratch. **Don’t forget to count the number of times you loop the wire around the pipe. This may be important when analyzing your data in Section 2.** Keep in mind that when you are winding the wire you should make the windings as tight as possible. After you have wound the wire around the bottle, connect each end of the wire to one clip of the headphone jack.

**Checkpoint 1.1:** How many turns of wire are in your coil?

**Checkpoint 1.2:** After plugging the headphone jack into the music source, hold the pipe to your ear as shown in Figure 6. What do you hear? (If your TA begins to dance, don’t be alarmed!)

**Keep in Mind:** You are about to connect your speaker to an amplified function generator so that you will have greater control over the sound produced by your speaker. There are about 15 speakers in this room. Please keep your speaker at a reasonable volume. Treat your speaker like headphones rather than a boom box. You should only be able to hear it if your ear is at the end of the pipe.

**Read This:** There are a couple of knobs that will control the volume of your speaker: one on the function generator and one on the amplifier. The following instructions will explain how to adjust these knobs.

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STOP

Figure 6: Wrap your fingers around the end of the pipe. Then press your thumb and fore finger against your ear. The pipe itself should not touch your ear.
Do This: First, find the knob on the function generator (the big box) that reads AMPL. It’s at the far-right of the function generator. Pull this knob toward you and turn it to 9 o’clock. You won’t need to touch it again.

Do This: The large knob on the amplifier (the little box) reads VOLUME. This is the knob that you will use for the rest of the lab in order to change the amplitude of the current through your speaker. Begin by turning the current all the way down by turning the VOLUME knob counter-clockwise.

Read This: If your speaker ever stops working, your amplifier may be to blame. If your amplifier (the little box) is making a clicking sound, it is trying to supply more current than it actually can. Turn the volume down until the clicking stops.

Do This: Disconnect your speaker from the headphone jack and connect it to the white leads coming from the amplifier using some combination of test leads and alligator clips.

Do This: See Appendix A for detailed instructions on the use of the function generator. The paragraph on the FREQUENCY and RANGE knobs is indispensible.

Do This: Play with the speaker! Adjust the amplitude of the current using the VOLUME knob. Remember to keep the volume at a reasonable level. Adjust the frequency using the FREQUENCY and RANGE knobs on the function generator. Pay attention to how the sound changes as you turn the knobs.

Read This: Now that you have a working speaker that you have total control over, let’s run a little experiment.

Do This: Set the function generator on a low frequency (~1 Hz). You should be able to see how this speaker is working. You may have to increase the volume significantly. Reduce the volume when you are done watching the speaker.

Checkpoint 1.3: What exactly did you see?

Read This: In case you were wondering, most people can hear sounds that are within the range of 20 Hz to 20 kHz. Sound below 20 Hz (like your speaker was producing during the most recent Do This) is called infrasound. Sound with a frequency higher than 20 kHz is known as ultrasound. Professor Miller leads a group in the Wash U physics department that studies ultrasound. See the lab website for links to details.

Synthesis Question 1 (20 points): You have heard a sound coming from your speaker. You have also seen how your speaker functions. Describe the major difference between how your speaker functions and how the speaker shown in Figure 2 functions. The answer relates to how the three main components are connected and which components move. (Do not tell your TA that commercial speakers are not made out of plastic bags. Do not tell your TA that your speaker is quiet. These are obvious and uninteresting differences.)
Part II: The Speaker (Quantitatively)

Equipment

- Speaker from Part I
- Function generator and amplifier
- Vernier microphone
- Multimeter and test leads

What Are We Quantifying?

The beauty of building your own instrument is that you can tweak the components, allowing you to customize your instrument or use your instrument for an experiment. In this part of the lab, you should explore the magnetic field produced by the electromagnet in your speaker. In class you learned that the magnetic field at the center of a current \( I \) carrying coil of wire of \( N \) turns and radius \( R \) is given by

\[
|\vec{B}| = \frac{N \mu_0 I}{2R}.
\]  

Eq. 1

Any experiment requires an instrument to record data. Your instrument for this recording will be a microphone that is connected to LoggerPro.

Choose Your Own Adventure

Your lab group must complete one of the following two Synthesis Questions. That is, you must complete either Synthesis Question 2A or Synthesis Questions 2B. If you complete both questions, only the first one that appears in your report will be graded. It would be wise to read both questions before completing either experiment.

2. How the Magnetic Field Depends on Current or Number of Loops

Checkpoint 2.1: Discuss how you can use your speaker and microphone to test the relationship between the magnetic field and the current that produces it. Think about how the magnetic field will affect the volume of the sound coming from your speaker (i.e., the amplitude of the sound wave). Rereading the “Characteristics of Sound Waves” section on page 3 of the Pre-Lab might be helpful in facilitating this discussion.

Checkpoint 2.2: Discuss with your lab partner how you could tweak your instrument to test how the number of turns, \( N \), in the electromagnet affects the magnetic field that it produces. It’s possible you will want to add turns to your coil. Does it matter if added turns are in the same orientation (clockwise or counterclockwise) as the original turns? How might you add the turns to the wire? By connecting another wire in series? By connecting another wire in parallel?

Checkpoint 2.3: How would adding wire to your speaker affect the value of the \( R \) in Equation 1? How would removing wire affect this value?
**Checkpoint 2.4:** Does an ammeter need to be connected to a circuit element in series or in parallel?

**Read This:** Note that what we are trying to test should be independent of the frequency of the sound wave, so in theory we could use any frequency we wish. However, experience has shown that using a frequency of 840 Hz will yield the best data for this type of experiment since that is a resonant frequency of your pipe.

**Do This:** Set the frequency of the function generator to about 840 Hz. The FREQUENCY knob is not especially precise, though, so it will be necessary to use your multimeter to read the frequency using the “Hz %” setting. Connect one white lead from the amplifier directly to the COM input jack. Connect the other white lead from the amplifier to the Hz input jack. Then turn the knob on the multimeter to the “Hz %” setting. Finally, turn the VOLUME knob on the amplifier to 12 o’clock. At this point you should be able to read a frequency off of the multimeter. (“Should” is a key word there. You might need to fiddle around a little bit more.) Adjust the function generator until the frequency is 840 Hz.

**Do This:** Connect your speaker, the function generator, and the multimeter such that you can measure the current through the speaker coil. As is the rule in this course, make sure to use the 10 A setting on the multimeter. You will also need to set your multimeter to measure AC current instead of DC current. Change from DC to AC by pressing the Mode button on the multimeter.

**Read This:** Do not use currents greater than 800 mA in any of your experiments. Larger currents cause the coil of wire to become dangerously hot.

**Synthesis Question 2A (80 Points):** Devise, perform, and analyze an experiment that uses your speaker, along with a Vernier microphone, to test the relationship between the magnetic field and **THE CURRENT** that produces it. Discuss whether or not your results are consistent with Equation 1. An excellent response will contain the following:

- A useful diagram of your experimental setup and description of your procedure
- One plot that you use to show how you found the amplitude of the wave recorded using Logger Pro.
- Table of raw data. The independent variable should have as wide a range in values as possible. (Remember that currents should not exceed 800 mA.)
- An estimate of the uncertainty in the dependent variable by considering how repeatable the sound wave is at a given current.
- A second plot that shows the data in the table, along with an appropriate curve fit
- Discussion of whether or not your results (i.e. the plot with the fit) are consistent with Equation 1. You are not directly measuring the magnetic field. That should be part of your discussion. Further, be sure to include Equation 1. Please see Appendix B before writing your response.
Synthesis Question 2B (80 points): Devise, perform, and analyze an experiment that uses your speaker, along with a Vernier microphone, to test the relationship between the magnetic field produced by a coil and THE NUMBER OF LOOPS in the coil. Discuss whether or not your results are consistent with Equation 1. An excellent response will contain the following:

- A useful diagram of your experimental setup and description of your procedure
- One plot that you use to show how you found the amplitude of the wave recorded using Logger Pro.
- Table of raw data. The independent variable should have as wide a range in values as possible. (Remember that currents should not exceed 800 mA.)
- An estimate of the uncertainty in the dependent variable by considering how repeatable the sound wave is at a given current.
- A second plot that shows the data in the table, along with an appropriate curve fit
- Discussion of whether or not your results (i.e. the plot with the fit) are consistent with Equation 1. You are not directly measuring the magnetic field. That should be part of your discussion. Further, be sure to include Equation 1. Please see Appendix B before writing your response.

Time to Clean Up!

Please clean up your station according to the Cleanup! Slideshow found on the lab website.
Appendix A: The Function Generator

This appendix will tell you everything you need to know about the function generator and even a little more. First, a function generator is used to produce a time-varying voltage (AC). Many features of the waveform can be varied, including: the amplitude, frequency, shape, and offset. The knobs on the function generator help to control these features of the waveform. Let’s go through all of the knobs on the function generator to understand how.

FREQUENCY and RANGE

These two knobs are used as a team to determine the frequency of the function generator’s output. To find the frequency of the output, all you have to do is multiply the number that the FREQUENCY knob points to by the value that the RANGE knob points to. (Then put Hz behind the result.)

For example, to produce a voltage with a frequency of 1 Hz, you should turn the FREQUENCY knob to 0.1 and set the RANGE knob to 10. As a second example, to produce a frequency of 20,000 Hz, turn the FREQUENCY knob to 2 and the RANGE knob to 10K.

Care should be taken when you change the range. If you are playing with a speaker at a sub-audible frequency, changing the range without lowering the amplitude or volume can result in a very loud sound that nobody wants to hear. When in doubt, lower the volume all the way before changing the range. Also, keep in mind that loud sounds above 20 kHz can hurt your ears even if you can’t hear them.

AMPL

That’s short for amplitude. You will be instructed to pull the AMPL knob and turn it to 9 o’clock. All of the amplitude adjustments will be done using the amplifier (not the function generator). Actually, we need the amplifier because this function generator alone cannot produce a large enough current for us. The amplifier can increase the amplitude of the function generator’s output while keeping the frequency unchanged.

FUNCTION

Feel free to play around with this knob. It changes the shape of the function generator’s output. The different shapes sound different even if the frequency remains fixed. You might understand why after completing the Spectra Lab later in the semester. When taking measurements, make sure the FUNCTION is set to the sine wave.

OFFSET

This shifts the whole wave up or down by some fixed number of volts. That’s something that we don’t need to do. Always keep this pushed in and pointed at 12 o’clock.

SWEEP Knobs

Don’t worry about what these do. Just make sure they are pushed in.
Appendix B: Data Analysis, Briefly

To a scientist, data is everything. When we have data, our job is to analyze it to see what patterns it reveals and how certain we can be about those patterns. Controlling for all other variables, we change our independent variable and record the effect on the dependent variable and then create a scatter plot.

We’re interested in two main aspects of this data: the **shape** of the data (what does the curve tell us about how our variables interact?), and the **uncertainty** of the data (how accurately can we repeat a single data point?).

**Shape**

The **shape** of the graph can be unclear when we have too few data points, so we always must be sure to take data with the **maximum reasonable range** of the independent variable. Often we will compare the shape of our data to the shape of an equation by fitting a curve to the data. If we have too little data (either too few points or too narrow a range), too many different equations will fit the data well.

**Uncertainty**

To decide whether or not a curve “fits the data well,” we must delve into the **uncertainty** of the data. We can get a good approximation of the uncertainty by testing the **repeatability** of our data. That is, we can take data for a single value of the independent variable several times and look at the range of dependent variable results.

**What Makes a Good Fit**

After estimating the uncertainty, we can say that the curve fits the data well if the difference between each data point and the curve is less than the estimated uncertainty in the data point. If more than one curve fits the data well, we might need to take more data or find a way to reduce the uncertainty in order to strengthen the conclusion.

**What If the Fit Is Bad?**

And what if the curve doesn’t fit the data well? If the data and the equation disagree, look at the **data** and the **experiment** for answers.