# CNS Institute for Physics Teachers

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| **Title:** | **Physics on an Electric Guitar** |
| **Original:**<br>**Revision:** | 13 October 2006<br>24 June 2008 |
| **Author:** | Jim Overhiser and Luke Donev |
| **Appropriate Level:** | Regents Physics |
| **Abstract:** | The guitar is one of the most common instruments in contemporary music. There are several aspects of the guitar that can be used to teach basic physics concepts; this lab focuses on magnetic pickups in an electric guitar. Students are led through a series of explorations to build experience with basic concepts in magnetism and electromagnetism. At the end they are asked to put these concepts together to explain how an electric guitar works. |
| **Time Required:** | Two 40 minutes periods |
| **NY Standards Met:** | 4.1 j Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or space and may be converted to other forms of energy.<br>4.1 k Moving electric charges produce magnetic fields. The relative motion between a conductor and a magnetic field may produce a potential difference (voltage) in a conductor. |
| **Special Notes:** | Physics on an Electric Guitar is available as a kit from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/. |

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**Behavioral Objectives:**

Upon completion of this lab, a student should be able to:

- explain that an electric current generates a magnetic field.
- explain that a changing magnetic field induces an electric current in a nearby closed loop of wire.
- explain and demonstrate how ferromagnetic materials can become magnetized in the presence of a magnetic field.
- apply concepts of magnetism and electromagnetism to explain how a magnetic pickup on an electric guitar functions.
- explain how a loudspeaker works.

**Class Time Required:** Two 40-minute periods

**Teacher Preparation Time:** 5-10 minutes to set out kits and materials

**Materials Needed:** Kits available on loan from the CIPT lending library at www.cns.cornell.edu/cipt/. List of materials available on CIPT web site.

**Assumed Prior Knowledge of Students:**

- Basic electricity concepts
    - Definition of electrical current
    - Current flows only in a closed loop
- Basic magnetism concepts
    - Definition of N-S poles
    - Sketching magnetic fields
- Sound waves are variations in air pressure that can be caused by vibrating objects

**Background Information for Teachers:**

**How magnetic pickups work**

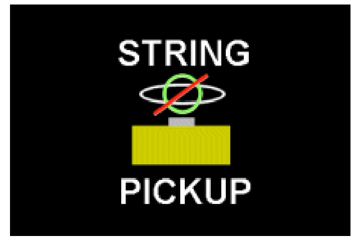
At the core of magnetic pickups are magnets. Each magnet is oriented so that an imaginary line through the north and south poles will intersect with the string above it. A thin copper wire coiled around the magnet so that the axis of the coil aligns with the N-S axis of the magnet.

The basic physics behind pickup is Faraday's Law of Induction. It states that a changing magnetic field can cause an electromotive force in a nearby wire. An electromotive force will be created as long as the wire is not parallel to the direction of the changing magnetic field. If the wire is a closed circuit or loop, then a current will flow. (See "Faraday's law of induction" in www.wikipedia.com for the full mathematical description.)

Since Faraday's Law states a changing magnetic field makes an electric current, how does the magnetic field from the fixed permanent magnets of the pickup help? That's where the guitar string comes into play. The string is made of nickel and steel (iron and carbon), materials that are ferromagnetic. The magnetic field from the permanent magnet in the pickup causes the string to become magnetized, or to become a magnet itself. When the magnetized string vibrates, it creates a changing magnetic field above the pickup coil. This, in turn, makes a current flow (in the coil) that tracks the vibration of the string, and we have a working pickup!

**Vibrating Strings**

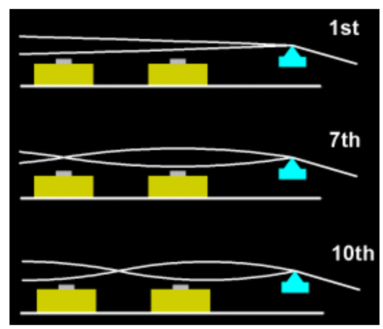
Understanding a vibrating string helps to understand how pickups sound. The diagram to the right shows a string vibrating over a pickup, viewed end-on. When you pluck a string, the string does not vibrate in a plane (red line), but in any number of planes, or circles (green), or ellipses (white). In fact, the ellipses can even rotate around their center as the note decays. This means that what you hear depends on how you pick the string, a phenomenon familiar to guitarists.




**Harmonics**

When you pluck a string it vibrates in the fundamental, second harmonic, third, fourth, etc., all at the same time. However, the pickup only detects string vibration when the string is vibrating near the pickup. It ignores the tones that have a node where the pickup is positioned. This has the effect of filtering the tones on the string.

On many electric guitars, two pickups are used on each string (see diagram to the right). Pickups are usually mounted close to the bridge, so each one is seeing the fundamental in some measure. That is, the string is moving either toward or away from all the pickups at the same time. When the signals coming out of the two pickups are added together, the fundamental has a strong signal.




For the seventh harmonic, the pickup on the right is at an antinode, getting a lot of signal, and the pickup on the left is at a node, putting out little signal. When the signals are added together, this harmonic comes across relatively strong.

For the tenth harmonic, the pickup on the right has the string moving away from it when the other pickup has the string moving toward it. This causes the signals from the pickups to cancel, so this harmonic is reduced in volume.

The distance between the pickups affects which harmonics will add and which will cancel. For example, humbucking pickups filter out higher frequencies because the two pickup coils are relatively close together. That is partly why humbuckers have a more mellow sound with less high end than single coil pickups -- the higher harmonics are canceling. The Stratocaster® sound is produced by a different spacing of the pickups. The coils can even be connected “out of phase” to produce an entirely different sound.

**Magnet Type**

There are many types of magnets in common use. Ceramic magnets are inexpensive, but brittle and do not produce a very strong field. These are commonly used in crafts and as refrigerator door magnets.

Other common types of magnets are:

- aluminum nickel cobalt [AlNiCo] (inexpensive)
- samarium cobalt (strong but expensive)
- neodymium boron iron (strongest and expensive)

There are some trade offs involved in pickup design. First, a stronger magnet means that fewer turns of wire are needed for a certain audio output. That means that the pickup can be smaller. If the pickup is made in some standard size, a stronger magnet produces more audio output.

However, the stronger magnet types are much more expensive. That's why most pickups use less expensive AlNiCo magnets. Also, stronger magnets are not the cure-all for electric guitar. Since the guitar strings are ferromagnetic and are attracted to the magnets, the pickups can affect the vibrations of the strings, which is bad since the pickups are only there to sense the vibrations, not change them.

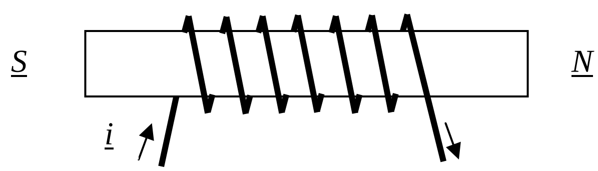
**Designer Sounds**

When considering all the variations on pickup construction (magnet type, magnet position, magnet strength, wire size, number of turns on the coil, pickup position in the guitar), it is apparent that a nearly infinite variety of sounds are available. The first electric guitarists built their own pickups, and some aficionados still do.

(The above was adapted from "How do guitar pick-ups work?" By Hank Wallace available at http://www.aqdi.com/pickups.htm. Some of the basic physics in the original document is incorrect, but it contains a lot of information and is quite readable.)

**Answers to Questions:**

1. Describe the effect on the compass when a current passes through the coil. *The compass needle deflects.*
2. Using the compass reading, label the north and south end of your straw coil. *Answers will vary. The north end is the one the compass needle points to.*
3. On the diagram of the coil below, indicate the direction of the current flowing in the coil and the direction of the magnetic field caused by the current. *Answers will vary. One possible answer is shown below:*



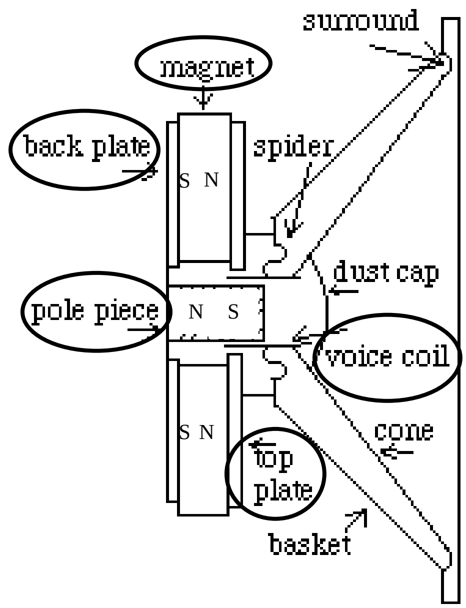
4. If you reversed the poles (+/-) by flipping the battery what happens to what you observe on the compass. Why? *The needle flips to indicate the north pole is at the opposite end of the coil as before. The opposite current creates the opposite magnetic field.*
5. Define "electromagnet" in your own words. *An electromagnet is a coil of wire with a current that creates a magnetic field.*
6. Fill-in the following table relative to the number of paperclips. *Typical answers shown below. Answers will vary depending on the number of turns in the coil and other factors.*

| In the straw coil | Number of paperclips picked up |
|---|---|
| Nothing | *0* |
| Iron nail | *4* |
| Paper stick | *0* |
| Plastic stick | *0* |

7. When were you able to pick up the most paperclips with the iron nail, in or out of the coil? *The most paperclips were picked up by the iron nail inside the coil.*
8. Some materials become "magnetized" when exposed to a magnetic field—in other words they become a magnet. Which materials were magnetized by the electromagnet? *Iron was magnetized by the electromagnet.*
9. Why do you think electromagnets often have iron cores? *The iron core greatly increases the strength of the electromagnet.*
10. What does a galvanometer measure? *The galvanometer measures current.*
11. What happened to the current when the magnet entered the coil? *There was a surge of current when the magnet entered the coil.*
12. What happens to the current if you flip the poles of the magnet and put it in the coil? *The current changes its sign, indicating a change in direction.*
13. How did changing the speed of the magnet affect the current? *The magnitude of the current decreased when the speed of the magnet decreased.*
14. What happens to the current when the magnet is not moving? *The current becomes zero.*
15. Write Faraday's Law in your own words. *Faraday's Law states that a changing magnetic field inside of a loop of wire creates a current in that wire.*
16. Were you able to hear the radio station from the simple speaker? What was vibrating to produce the sound? *The bottom of the Styrofoam cup was vibrating to produce the sound waves.*
17. The magnet on the head of the iron nail magnetized the nail. What caused the magnetized nail to move? *A changing magnetic field produced by the coil caused the magnetized nail to move.*

18. The earphone jack of the radio produces a changing electrical current that encodes the signal from the radio station. What was the purpose of plugging the coil into the earphone jack? *The changing electrical current passed through the coil to convert the signal to a changing magnetic field.*

19. In your own words, describe how the simple speaker works. *The electromagnet converted the changing electrical current from the radio into a changing magnetic field inside the coil. As the magnetic field inside the coil changed, it created a changing magnetic force on the magnetized iron nail. The motion of the iron nail caused the cup to vibrate and generate sound waves*

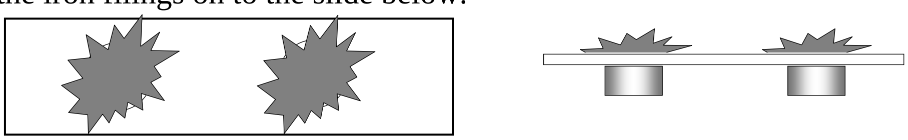



20. Circle the coil, the magnet, and all magnetized materials (including plates and pole piece) in the illustration to the right. *See diagram.*

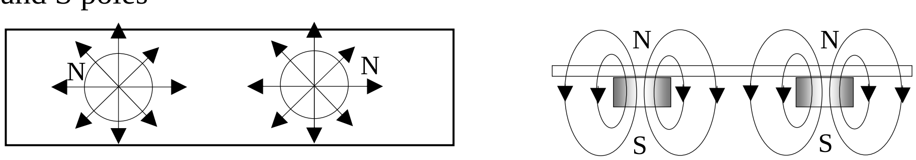
21. What you talk into the speaker and vibrate the cone, what happens to the voice coil? *The voice coil moves because it is attached to the cone.*

22. How does the motion of the voice coil produce an electrical signal that can be heard with an amplifier? *The voice coil moves causing the magnetic field inside to change and this creates an electrical current in the coil that flows to the amplifier.*

23. Draw a top view and side view illustration of your observation when you sprinkled the iron filings on to the slide below.

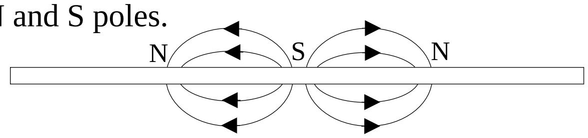


24. Draw a top view and side view of the magnetic field lines of the magnets. Label N and S poles

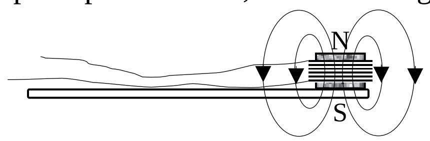



25. Describe the effect of moving the guitar string close to the iron filings after touching it to the magnet. Did the guitar string get magnetized? *Some iron filings are attracted to the guitar string, indicating that it has become magnetized.*

26. Draw the magnetic field of the guitar string, based on your observation of the iron filings. Label N and S poles.



27. On the diagram of the pickup coil below, draw the magnetic field lines of the magnet inside the coil.

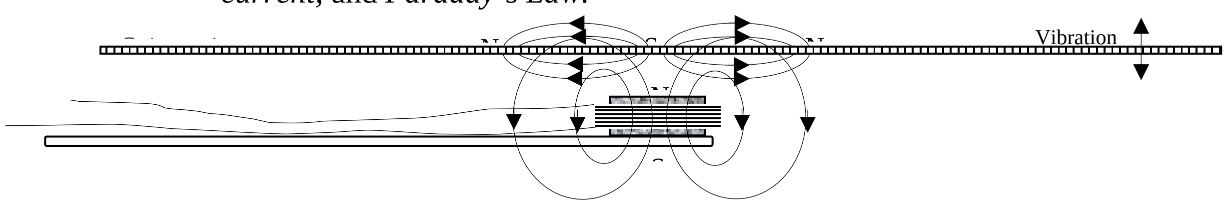



28. What is the purpose of the magnet inside the pickup coil? *The purpose of the magnet inside the pickup coil is to magnetize the string above it.*

29. The magnet inside the pick-up coil is not moving--why does the coil still get a signal? *The magnetized string vibrates and creates a changing magnetic field inside the coil. This causes the electric current in the coil.*

30. Why won't acoustic guitar strings work on an electric guitar? *Acoustic strings do not have ferromagnetic material, so they cannot be magnetized.*

31. ***See what you have learned.*** Study the illustration below of the magnetic pick-up with a guitar string positioned above it. Use this illustration to describe how a vibrating guitar string creates current in the pick-up coil, which can be turned into sound at a speaker. As part of your explanation, do the following:
    - Indicate the location of the N-S poles in the string
    - Draw the magnetic field lines for both the string and the pick-up
    - In your explanation, use the following terms: *magnetic field, magnetize, current*, and *Faraday's Law.*




*The magnetic field from the magnet in the pick-up interacts with the guitar string and magnetizes it. When the magnetized guitar string is plucked it vibrates up and down, moving closer and farther from the pick-up coil. This creates a changing magnetic field in the coil, which by Faraday's Law, generates a current in the coil.*

**References:**

How do guitar pick-ups works? By Hank Wallace (website)
http://www.aqdi.com/pickups.htm

Smith, Monica. 2001. "The Electric Guitar: How we got from Andres Sergovia to Kurt Coban". Invention and Technology, Summer 2001, Volume 20, Issue 1 (online article)
http://www.americanheritage.com/articles/magazine/it/2004/1/2004_1_12.shtml

The Guitar by Sam Hokin (website)
http://www.bsharp.org/physics/stuff/guitar.html

Physics of the Acoustic Guitar by Ian Billington (website)
http://ffden-2.phys.uaf.edu/211.web.stuff/billington/main.htm

How does a guitar work? By Joe Wolfe, University of South Wales, Department of Physics, Sydney, Australia (website)
http://www.phys.unsw.edu.au/~jw/guitarintro.html

# Equipment

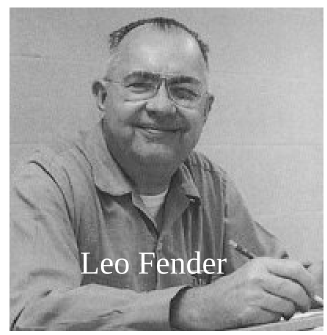

| Item Number | Quantity | Item |
|---|---|---|
| 1 | 1 | Guitar |
| 2 | 1 | Tuner |
| 3 | 1 | “Pick-up Stick” |
| 4 | 1 | Connector, mono plug to alligator |
| 5 | 1 | Iron nail and aluminum nail |
| 6 | 1 | Paper stick and plastic stick |
| 7 | 1 | Galvanometer +/- 500 $\mu$A |
| 8 | 10 | Paperclip |
| 9 | 1 | C cell battery |
| 10 | 2 | Ceramic magnet (1/2”) |
| 11 | 1 | Amplified speaker |
| 12 | 1 | Microscope slide |
| 13 | 1 | Iron fillings |
| 14 | 1 | Plastic straw coiled with copper |
| 15 | 2 | Neodymium magnet (1/8”) |
| 16 | 1 | Styrofoam cup |
| 17 | 1 | Pocket radio |
| 18 | 1 | Compass |
| 19 | 1 | Storage box |
| 20 | 1 | (Not pictured) Auto speaker (4”) |

# Physics on an Electric Guitar

Electromagnetic Induction is the process of using magnetic fields to produce voltage, and in a complete circuit, a current. Michael Faraday first discovered it, using some of the works of Hans Christian Oersted. His work started at first using different combinations of wires and magnetic strengths and currents, but it wasn't until he tried moving the wires that he got any success. It turns out that electromagnetic induction is created by just that - the moving of a conductive substance through a magnetic field (or the moving of a magnetic field past a conductor).

An obvious use for electromagnetic induction is to generate electrical power. Any device that does this is known as a generator. Most generators work with a small loop of wire inside a magnetic field, oriented so that it may spin and move the wire through the magnetic field lines. This wire is connected to a turbine or some other spinning wheel, which is driven by steam, moving water, wind, or some other source of energy.

Electric guitars also make use of Faraday's discovery. Pick-up coils, consisting of a small magnet wound with wire, allow a stringed instrument to be "electrified" and amplify its sound output. Credit for the discovery/invention of the electric guitar is somewhat controversial, but most historians give credit to Leo Fender in the 1940's. In this lab you will learn how a pick-up coil works and use a home-make pick-up to play the "physics guitar."




**<u>Procedure:</u>**

I. <u>What does electricity have to do with magnetism?</u>

1. Take a 2 m length of magnet wire and wrap it around a short length of drinking straw. Leave 1-2 cm on each end of the straw without any wire. Leave 5 cm of magnet wire at the beginning and end. See illustration A.

   *(Note: A small piece of cellophane tape may be used to help hold magnet wire on the straw.)*
2. Remove the enamel coating from the two wire ends.
3. Place the compass next to the coil.
4. Connect the two bare wires to the + and – terminals of a C cell battery and observe what happens to the compass needle.
5. Use the compass to explore the magnetic field around the coil.

*Answer related questions on the student data sheet.*

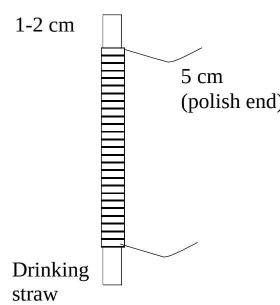



Illustration A

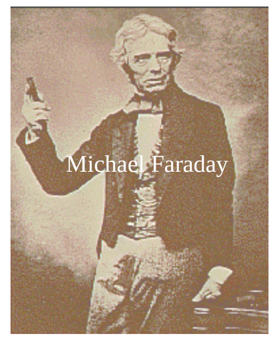
II. <u>How strong is an electromagnet?</u>

1. Without connecting the coil to the battery, see how many paperclips the coil can pick up.
2. Connect the coil to the 1.5 V battery and see how many paperclips you can pick up.
3. Take an iron nail and see how many paperclips you can pick up.
4. Slide the iron nail into the straw and connect the battery to the coil. See how many paperclips the coil can pick up.
5. Repeat Step #3-4 using an aluminum nail, paper stick and a plastic stick.

*Answer related questions on the student data sheet.*

III. <u>What did Faraday tell us?</u>

Faraday's Law of Induction states that *a changing magnetic field causes an electric field to be set up in a nearby wire, causing a current to flow if the wire is part of a closed circuit (a loop of wire for example).*




1. Attach the wires of the coil to a galvanometer.
2. Place a 1/8" diameter rod magnet in the straw/coil. With your fingers covering the two ends of the straw, move the straw so the magnet slides back-and-forth in the straw and watch the effect on the galvanometer. See illustration B.
3. Insert the magnet into the coil more slowly and observe the effect.
4. Connect the coil wires to the small speaker-amplifier using the mono-to-alligator adapter. Repeat step #2 and observe the effect.

*Answer the appropriate questions on the student data sheet.*

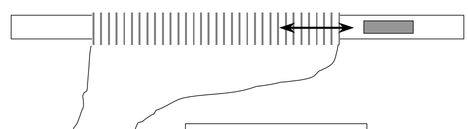


Illustration B

IV. <u>Simply speaking</u>

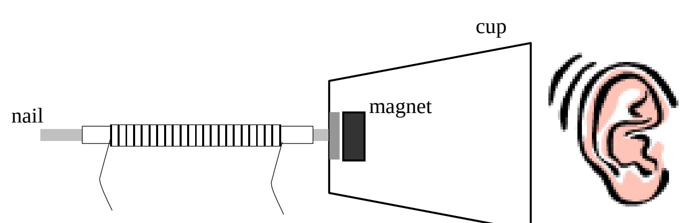



Illustration C

1. Push the iron nail through the bottom of a Styrofoam cup until the head is at the bottom. Place a small ceramic disk magnet on the head as pictured in the illustration to the right. (Refer to Illustration C.)
2. Slide your straw coil over the nail as pictured in the illustration to the right. (Refer to Illustration C.)
3. Find a strong station on a portable radio. Connect the coil to the earphone jack on the radio using the mono-to-alligator adapter and observe the results.

*Answer the appropriate questions on the student data sheet.*

## V. Talking back to the speaker

1. Study Illustration D to the right and find the components we have discussed to this point: the coil and the magnet.
2. *Answer the appropriate questions on the student data sheet.*
3. Connect the small speaker-amplifier to the small speaker using the mono-to-alligator adapter. VERY GENTLY tap the speaker and observe the effect.
4. Using the same set-up, talk into the speaker as if it were a microphone. Observe the effect on the small amplifier.

*Answer the appropriate questions on the student data sheet.*

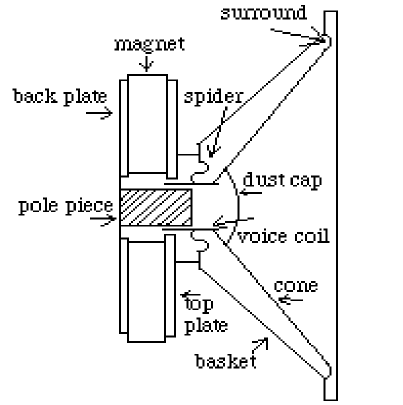



Illustration D

## VI. The making of a magnet

1. Use the compass to detect the location of N and S poles on a ceramic disk magnet. Place one or two disk magnets with N poles up under a glass microscope slide (see Illustration E).
2. Sprinkle a small amount of iron filings on the top of the slide, tap it gently and observe the magnetic field lines shown in the filings.
3. Lay a guitar string across the flat side of one magnet.
4. Sprinkle a small amount of iron filings on a sheet of paper. Lay the guitar string in the filings, tap it a few times, pull it out and observe the results.
5. Use the compass to detect the location of N and S poles on the guitar string.

*Answer the appropriate questions on the student data sheet.*


Illustration E

## VII. Electric guitar pick-up

1. Attach two wires on the electric “pick-up stick” (Illustration F) to the small speaker-amplifier using the mono-to-alligator adapter.
2. Turn the amplifier to the on position and turn the volume knob to maximum.
3. Slide the “pick-up stick” magnet under one of the strings in the region close to the bridge on The Physics Guitar. Make sure the magnet does not touch the string.
4. Pluck the string. Move the magnet in and out from under the string while it is vibrating and observe what happens.

*Answer the appropriate questions on the student data sheet.*

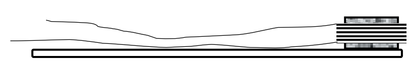
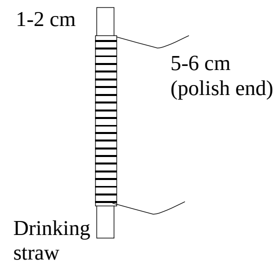


Illustration F

# Physics on the Guitar

Student Data Sheet

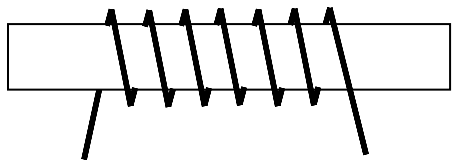
I. <u>What does electricity have to do with magnetism?</u>




1. Describe the effect on the compass when a current passes through the coil.

2. Using the compass reading, label the north and south end of your straw coil.

3. On the diagram of the coil below, indicate the direction of the current flowing in the coil and the direction of the magnetic field caused by the current.



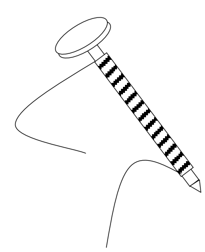
4. If you reversed the poles (+/-) by flipping the battery what happens to what you observe on the compass. Why?

5. Define “electromagnet” in your own words.

II. <u>How strong is an electromagnet?</u>

a. Fill-in the following table relative to the number of paperclips.

| In the straw coil | Number of paperclips picked up |
|---|---|
| Nothing | |
| Iron nail | |
| Paper stick | |
| Plastic stick | |



b. When were you able to pick up the most paperclips with the iron nail, in or out of the coil?

c. Some materials become “magnetized” when exposed to a magnetic field—in other words they become a magnet. Which materials were magnetized by the electromagnet?

d. Why do you think electromagnets often have iron cores?

III. <u>What did Faraday tell us?</u>

1. What does a galvanometer measure?

2. What happened to the current when the magnet entered the coil?

3. What happens to the current if you flip the poles of the magnet and put it in the coil?

4. How did changing the speed of the magnet affect the current?

5. What happens to the current when the magnet is not moving?

6. Write Faraday's Law in your own words.

IV. <u>Simply Speaking</u>

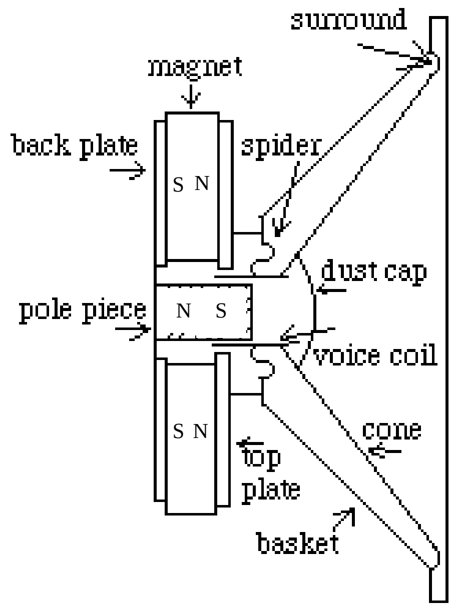
1. Were you able to hear the radio station from the simple speaker? What was vibrating to produce the sound?

2. The magnet on the head of the iron nail magnetized the nail. What caused the magnetized nail to move?

3. The earphone jack of the radio produces a changing electrical current that encodes the signal from the radio station. What was the purpose of plugging the coil into the earphone jack?

4. In your own words, describe how the simple speaker works.

## V. Talking back to the speaker



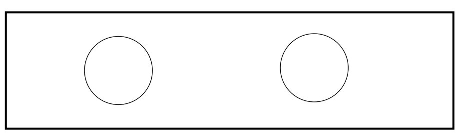

1. Circle the coil, the magnet, and all magnetized materials (including plates and pole piece) in the illustration to the right.

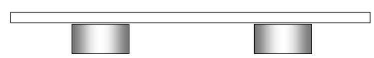
2. What you talk into the speaker and vibrate the cone, what happens to the voice coil?

3. How does the motion of the voice coil produce an electrical signal that can be heard with an amplifier?

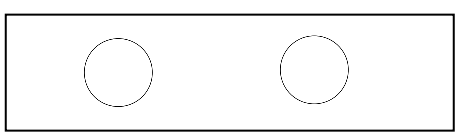
## VI. The making of a magnet

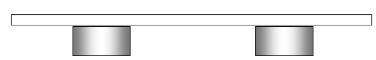
1. Draw a top view and side view illustration of your observation when you sprinkled the iron filings on to the slide below.





2. Draw a top view and side view of the magnetic field lines of the magnets. Label N and S poles.



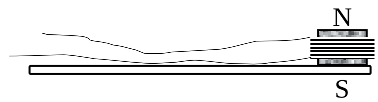


3. Describe the effect of touching the guitar string to the iron filings <u>after</u> holding it close to the magnet. Did the guitar string get magnetized?

4. Draw the magnetic field of the guitar string, based on your observation of the iron filings. Label N and S poles.

VII. <u>Electric guitar pick-up</u>

1. On the diagram of the pickup coil below, draw the magnetic field lines of the magnet inside the coil.




2. What is the purpose of the magnet inside the pickup coil?

3. The magnet inside the pick-up coil is not moving--why does the coil still get a signal?

4. Why won't acoustic guitar strings work on an electric guitar?

5. ***See what you have learned.*** Study the illustration below of the magnetic pick-up with a guitar string positioned above it. Use this illustration to describe how a vibrating guitar string creates current in the pick-up coil, which can be turned into sound at a speaker. As part of your explanation, do the following:

   - Indicate the location of the N-S poles in the string
   - Draw the magnetic field lines for both the string and the pick-up
   - In your explanation, use the following terms: *magnetic field, magnetize, current,* and *Faraday's Law.*