

# CNS Institute for Physics Teachers

<b>Title:</b>	<b>Physics on the Guitar</b>
<b>Original:</b> <b>Revision:</b>	13 October 2006 15 July 2010
<b>Authors:</b>	Jim Overhiser and Luke Donev
<b>Appropriate Level:</b>	Regents Physics
<b>Abstract:</b>	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.
<b>Time Required:</b>	Two 40 minute periods
<b>NY Standards Met:</b>	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. 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.
<b>Special Notes:</b>	<b>Physics on the Guitar</b> is a kit available from the CIPT Equipment Lending Library, <a href="http://www.cns.cornell.edu/cipt/">www.cns.cornell.edu/cipt/</a> .

**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/](http://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 Teacher:****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](http://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

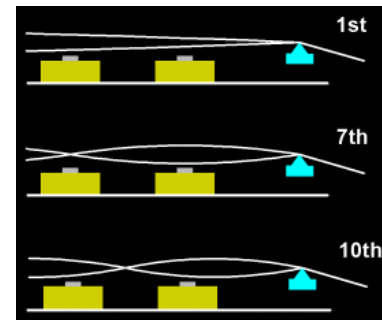
Understanding a vibrating string helps to understand how pickups sound. The diagram to the right shows a string vibrating over a pickup, viewed end-on. When you pluck a string, the string does not vibrate in a plane (red line), but in any number of planes, or circles (green), or ellipses (white). In 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. 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:** send email to [cipt\\_contact@cornell.edu](mailto:cipt_contact@cornell.edu) to request answers

## References:

- How do guitar pick-ups work? By Hank Wallace. <http://www.aqdi.com/pickups.htm>
- Smith, Monica. 2001. "The Electric Guitar: How we got from Andres Segovia to Kurt Coban." Invention and Technology, Summer 2001, Volume 20, Issue 1. [http://www.americanheritage.com/articles/magazine/it/2004/1/2004\\_1\\_12.shtml](http://www.americanheritage.com/articles/magazine/it/2004/1/2004_1_12.shtml)
- The Guitar by Sam Hokin. <http://www.bsharp.org/physics/guitar>
- Physics of the Acoustic Guitar by Ian Billington. <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. <http://www.phys.unsw.edu.au/~jw/guitarintro.html>

## Equipment List



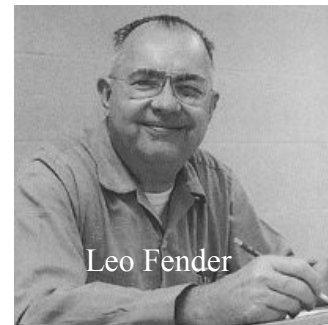
Item Number	Quantity	Item
1	1	Simple Physics Guitar
2	1	Tuner
3	1	“Pick-up Stick”
4	1	Connector, mono plug to alligator
5	1	Iron nail and aluminum nail
6	1	Paper stick and plastic stick
7	1	Galvanometer +/- 500 $\mu$ A
8	10	Paperclip
9	1	C cell battery
10	2	Ceramic magnet (1/2”)
11	1	Amplified speaker
12	1	Microscope slide
13	1	Iron fillings
14	1	CNS coil - plastic tube coiled with copper wire
15	1	Neodymium magnet (1/4” x 2”)
16	1	Styrofoam cup
17	1	Transistor radio
18	1	Compass
19	1	Storage box
20	1	(Not pictured) Auto speaker (4”)
21	1	(Not pictured) Small plastic bag

# PHYSICS ON THE 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 1940s. In this lab you will learn how a pick-up coil works and use a home-make pick-up to play the "physics guitar."



## I. What does electricity have to do with magnetism?

One of the basic pieces of an electric guitar pick-up is a simple coil of copper wire. In this activity you will see the simple connection between electric current in the copper coil and the creation of a magnetic field.

### Materials:

- CNS Coil (See illustration A)
- Compass
- C-cell battery

### Procedures:

- Place the compass next to the CNS Coil. Observe how the compass behaves as the CNS Coil is brought closer.
- Connect/hold the two bare wires to the + and - terminals of a C cell battery and observe what happens to the compass needle when the CNS Coil is placed close to the compass face. (See illustration A-2)
- Use the compass to explore the magnetic field around the CNS Coil.

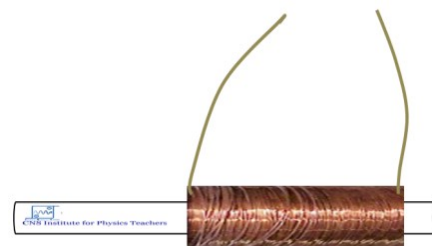


Illustration A

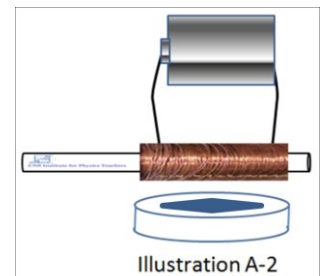


Illustration A-2

*Answer related questions on the student data sheet.*

## **II. How strong is an electromagnet?**

During this activity you will insert several materials into the CNS Coil and observe the affect on the magnetic field created when voltage is applied.

### **Materials:**

- CNS Coil
- Paperclips
- Iron nail
- Aluminum nail
- Paper sucker stick
- Plastic stirring stick



Illustration A-3

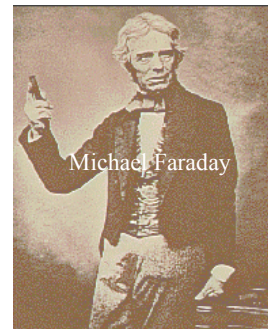
### **Procedures:**

- Without connecting the CNS Coil to the battery, see how many paperclips the CNS Coil can pick up.
- Connect the CNS Coil to the 1.5 V C battery and see how many paperclips you can pick up.
- Next, place an iron nail inside of the CNS Coil (see illustration A-3) and see how many paperclips you can pick up.
- Repeat Step #3-4 using an aluminum nail, paper stick and a plastic stick.

*Answer related questions on the student data sheet.*

## **IIIa. What did Faraday tell us?**

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.



Michael Faraday

### **Materials:**

- CNS Coil
- Small neodymium rod magnet 1/4"D x 2" long
- Mini-amplifier
- Mono-plug with alligator connectors
- Compass
- Galvanometer

### **Procedures:**

- Using the compass, determine how the poles of the neodymium magnet rod are oriented. Record your observation on the student data sheet.
- Connect the CNS Coil wires to the galvanometer using the two patch cords supplied in your kit. (See illustration B-1).

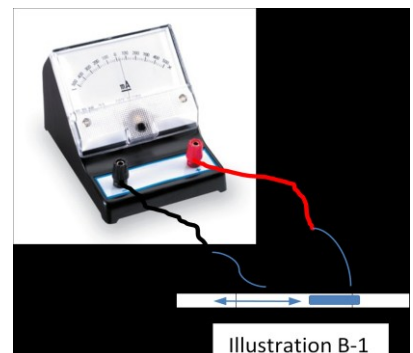
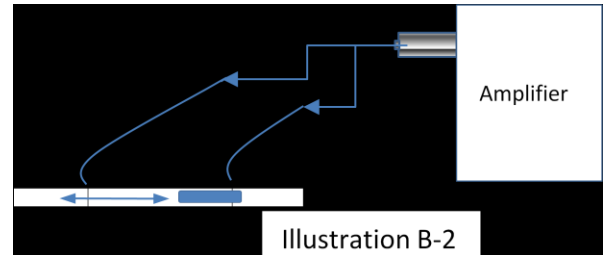


Illustration B-1

- Place a 1/4" diameter neodymium rod magnet inside the CNS Coil. With your fingers covering the two ends of the CNS Coil, move the CNS Coil so the magnet can slide back-and-forth in the CNS Coil without falling out.
  - Move the magnet inside the CNS Coil slow and fast and observe the effect.
  - Slide the magnet more quickly and observe the affect.
  - Now slide the magnet in **only one direction** and observe the galvanometer response.
  - **Flip the magnet** around and slide the opposite end in and observe the glavanometer response.
  - Now connect the CNS Coil wires to the small speaker-amplifier using the mono-to-alligator adapter. (See illustration B-2.)
  - Again, place a 1/4" diameter neodymium rod magnet inside the CNS Coil. With your fingers covering the two ends of the CNS Coil, move the CNS Coil so the magnet can slide back-and-forth in the CNS Coil without falling out.
  - Move the magnet inside the CNS Coil slow and fast and observe the effect.
  - Slide the magnet more quickly and observe the affect.
  - Remove the magnet from the CNS Coil. Holding the CNS Coil steady, move the magnet in and out of the CNS Coil and observe the affect on the mini-amplifier.
- Answer the appropriate questions on the student data sheet.*



### **IIIb. White noise, the Humbucker pickup and the Barkhausen Effect.**

In this activity you will do a simple demonstration to illustrate the effect of changing magnetic domains in an iron core.

#### **Materials:**

- CNS Coil
- Small neodymium rod magnet 1/4" D x 2" long
- Mini-amplifier
- Mono-plug with alligator connectors
- Iron nail

#### **Procedures:**

- Replace the magnet and place the iron nail into the CNS Coil.
  - Connect the CNS Coil wires to the small speaker-amplifier using the mono-to-alligator adapter. (See illustration B-3.) Set the volume on the amplifier so that there is not audible hiss.
  - Move the neodymium magnet around the CNS Coil and observe the affect.
- Answer the appropriate questions on the student data sheet.*

### IIIc. The making of a magnet

In this activity you will study the interaction between a magnet and a common guitar string.

#### Materials:

- Small disk ceramic magnet
- Small sealable plastic bag
- Iron filings
- Compass

#### Procedures:

- Use the compass to detect the location of N and S poles on a ceramic disk magnet. Place the disk magnet with N poles up into a sealed plastic bag. (See Illustration E.)
- Sprinkle a small amount of iron filings on the top of the bag over the magnet. Tap the bag gently and observe the magnetic field lines shown in the filings.
- Carefully reach into the bag and reposition the magnet so that it is on its side. (See Illustration E-2.) Again, sprinkle a small amount of iron filings in the outside of the bag and observe the field lines.
- Remove the magnet from the plastic bag **being careful not to get any of the iron filings on the magnet.**
- Lay the end of a piece of guitar string from the kit on top of one of the small disk magnets and let it lay there for a few seconds. (See Illustration E-3.)
- Sprinkle a small amount of iron filings onto a separate piece of paper.
- Pick up the guitar string and dip the end that sat on the magnet into the filings. Tap it a few times, pull it out and observe the results.
- Use the compass to see if it is possible to detect the location of the North and South poles on the guitar string.

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



Illustration E

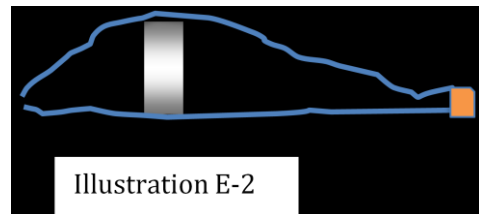


Illustration E-2

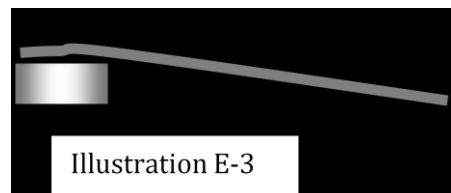


Illustration E-3

### IV. Electric guitar pick-up

In this activity you will apply what you have observed to explain how an electric Guitar pickup works.

#### Materials:

- “Pick –up stick” (See Illustration F.)

- Mini-amplifier
- Simple Physics Guitar

**Procedures:**

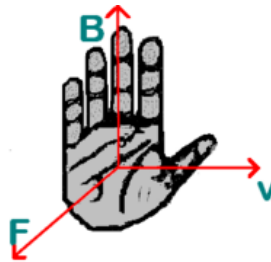
- Attach two wires on the electric “pick-up stick” to the speaker-amplifier using the mono-to-alligator adapter.
- Turn the amplifier to the on position and turn the volume knob to maximum.
- Slide the “pick-up stick” magnet under one of the strings in the region close to the bridge on the Physics Guitar. Make sure the magnet does not touch the string.
- 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.*

**Extension activity (Speakers)**

Prior to doing this activity the student needs to review the hand-rule for force on a current carrying wire.



**V. Talking back to the speaker**

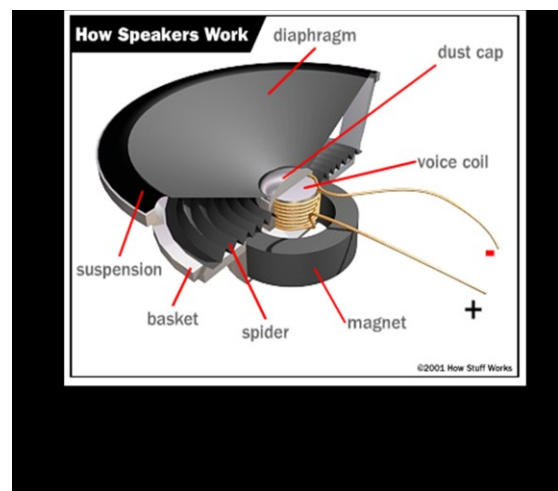
In this activity you will identify the parts of a common loud speaker (driver) and consider how it works relative to the force created by the interactions between magnets and coils of current-carrying wire.

**Materials:**

- Mini-amplifier
- Alligator to mono-plug cable
- Small loudspeaker

**Procedures:**

1. Study Illustration C to the right and find the components we have discussed to this point: the coil and the magnet.
2. Connect the mini-amplifier to the small speaker using the mono-to-alligator adapter. VERY GENTLY tap the loud speaker and observe the effect.
3. Using the same set-up, talk into the loud



speaker as if it were a microphone. Observe the effect on the amplifier.

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

## VI. **Simply speaking**

In the previous activities you observed how moving a magnet (magnetic field) perpendicular to a coil of wire can create a current in the coil of wire. Now you will reverse the process by sending a current through a coil of wire.

### **Materials:**

- CNS Coil
- Small radio
- Mono-plug with alligator connectors
- 2 small ceramic disk magnet
- 12 oz Styrofoam cup
- Iron nail
- Compass



Illustration D-1

### **Procedures:**

- Set the 2 small disk magnets to the top of the nail. (See Illustration D-1.) Position the point of the nail close to the compass and observe the interactions.
- Flip the small disk magnets on the top of the nail and, again, observe the interaction with the compass.
- Push the iron nail through the bottom of a Styrofoam cup until the head is at the bottom. Place the small ceramic disk magnets on the head. (Refer to Illustration D-2.)
- Slide your CNS Coil over the nail as pictured in the illustration to the right.
- Find a strong station on a portable radio. Connect the CNS Coil to the earphone jack on the radio using the mono-to-alligator adapter and observe the results. (Refer to Illustration D-2.)

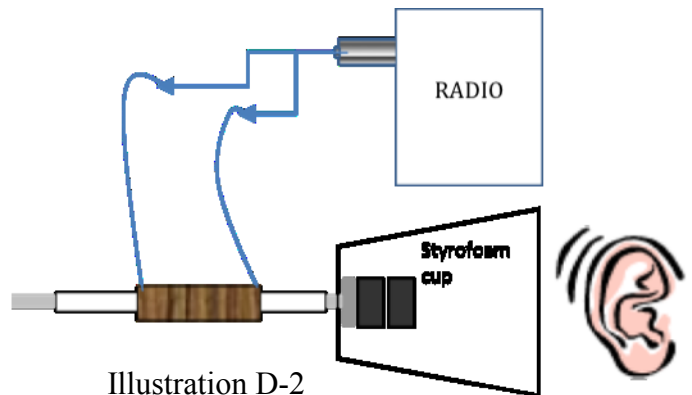


Illustration D-2

*Answer the appropriate questions on the student data sheet*

# Physics on the Guitar

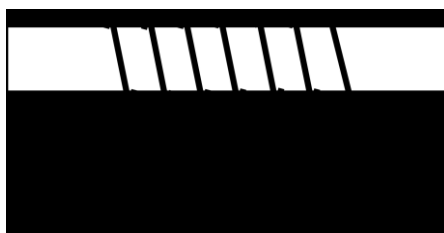
## Student Data Sheet

### I. What does electricity have to do with magnetism?

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 copper coil on the illustration below.



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 leads (+/-) by flipping the battery what happens to what you observe on the compass. Why?
5. Study the labeled illustration in #3. If the fingers on your right hand represent the current direction in the copper coil, to which compass pole is your thumb pointing?
6. Define “electromagnet” in your own words.

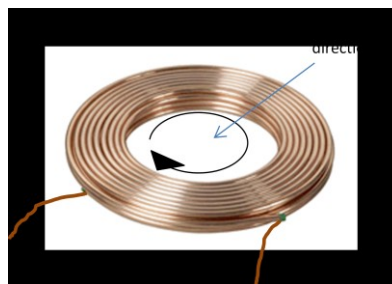
### II. How strong is an electromagnet?

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

In the copper coil	Number of paperclips picked up
Nothing	
Iron nail	
Paper stick	
Plastic stick	



8. Some materials become “magnetized” when exposed to a magnetic field. This is called induced magnetism. Which materials were magnetically induced when placed in the core of the electromagnet?
9. Describe what you think happens on an atomic level when something becomes magnetized.
10. Why do you think electromagnets often have iron cores?
11. The picture to the right is a junkyard magnet that is capable of lifting an entire car. They are all large round disk of iron (steel) and powered by electricity. Below is a picture of the coil that might be on the inside of one of these large electromagnets. Draw the rest of the disk showing the current direction and the correctly labeled magnetic poles.



**IIIa. What did Faraday tell us?**

12. What does a galvanometer measure?
13. Below are three illustrations of the activity you did sliding the magnet inside of the coil. On each of the illustrations draw set of magnetic field lines around the cylindrical magnet.



14. The two illustrations here show a copper coil and a set of arrows showing the direction of the coil winding. On both illustrations draw an arrow showing the general direction for the magnetic field as the magnet slides through the coil.



15. Describe the orientation of the magnetic field relative to the coil of wire when the current is created.
16. How did changing the speed of the magnet affect the current?
17. What happens to the current direction when you flipped the poles of the magnet and slide it through the coil?
18. No current is produced when the magnet is not moving. Describe why you think a non moving magnet does not create the current.
19. In the space below, describe why you think you heard a noise in the amplifier when you moved the magnet inside of the coil.
20. Write Faraday's Law in your own words.

### **IIIb. White noise, the Humbucker pickup and the Barkhausen Effect**

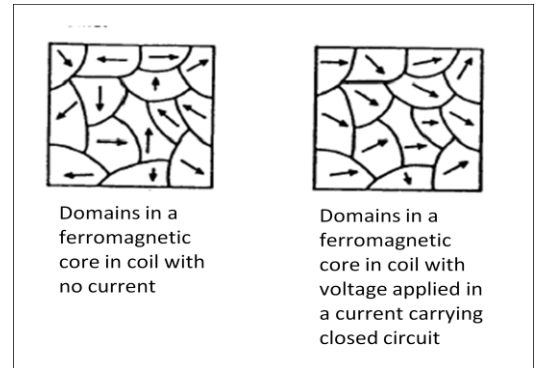
#### Read the following:

Barkhausen noise: A coil of wire wound on the ferromagnetic material can demonstrate the sudden, discontinuous jumps in magnetization. The sudden transitions in the magnetization of the material produce current pulses in the coil. These can be amplified to produce a series of clicks in a loudspeaker. Discovered by German physicist Heinrich Barkhausen in 1919, it is caused by rapid changes of size of magnetic domains in the core.

21. Describe what you observed when the magnet was moved near the iron core/coil set-up.

22. What caused the affect you described in #19?

23. Study the following illustrations of ‘domains’ in a ferromagnetic core. The arrows represent the direction of average electron spin in the region. Based on these illustrations, answer the following questions.



- What does magnetism mean?

- What effect does putting current in the coil have on the atomic level of the iron nail?

- Why did moving a magnet close to the core create a sound in the amplifier? (Barkhausen effect)

24. (Research) A Humbucker electric guitar pickup is designed to eliminate the hum (white noise) that may occur when a guitar player is performing. This is preventing the Barkhausen effect! What might be a source of magnetic interference on a performing stage?



### IIIc. The making of a magnet

25. Draw your observation when you sprinkled the iron filings on to the magnet in the following position. Record the North and South pole orientation on the illustration.



26. Draw your observation when you sprinkled the iron filings on to the magnet in the following position.



27. Describe the effect of touching the guitar string to the iron filings after holding it close to the magnet. Did the guitar string get magnetized?

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



### IV. Electric guitar pick-up

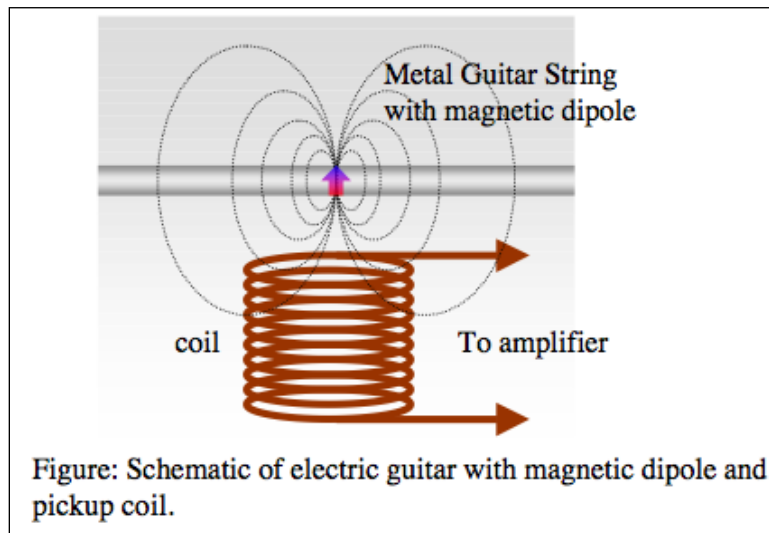
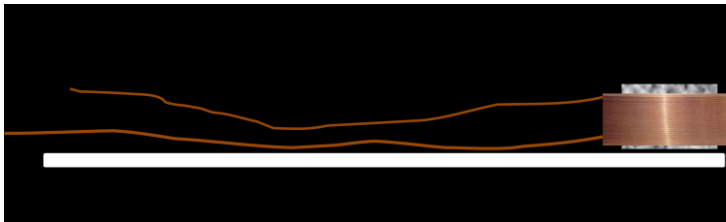
29. On the diagram of the pickup coil below, draw the magnetic field lines of the magnet inside the coil.



30. What is the purpose of the magnet inside the pickup coil?
31. The magnet inside the pick-up coil is not moving--why does the coil still get a signal?
32. Why won't nylon guitar strings work on an electric guitar?

33. **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:

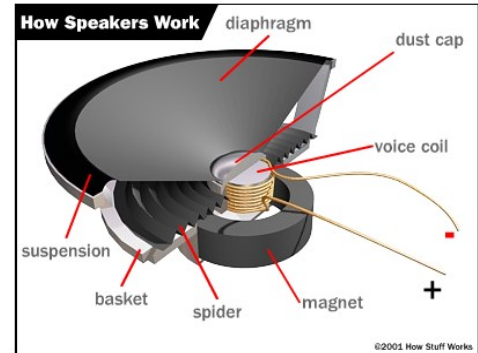
- Indicate the location of the N-S poles in the string
- Draw the magnetic field lines for both the string and the pick-up
- In your explanation, use the following terms: *magnetic field*, *magnetize*, *current*, and *Faraday's Law*.



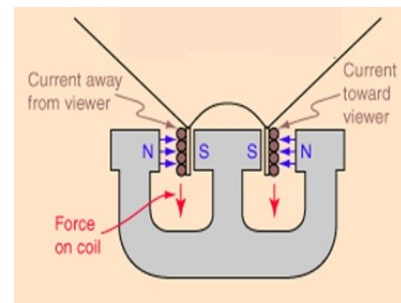
## Extension Activity (The Speaker)

### V. Talking back to the speaker

34. Complete the following sentence: Sending current through a wire that is placed in a magnetic field creates a \_\_\_\_\_ on the wire.
35. Circle the coil, the magnet, and all magnetized materials (including plates and pole piece) in the illustration to the right.
36. When you talk into the speaker and vibrate the cone, what happens to the voice coil?



37. Study the picture to the right showing the cross-sectional view of a speaker magnet. This magnet is often described as being similar to setting two (2) horseshoe magnets next to each other. Draw two horseshoe magnets on the illustration to show what they mean.
38. What will happen to the 'force on the coil' arrow if the current is reversed from the direction shown in the illustration?



39. When you tap on the speaker it moves the coil back and forth over the central magnetic core. What is the result of this action? (Be specific!)

### VI. Simply Speaking

40. What affect did flipping the disk magnet have on the induced magnetism in the nail?
41. Were you able to hear the radio station from the simple speaker? What was vibrating to produce the sound?

42. The magnet on the head of the iron nail magnetized the nail. What caused the magnetized nail to move when it was plugged into the radio?
43. The earphone jack of the radio produces a changing (alternating) electrical current that encodes the signal from the radio station. What was the purpose of plugging the coil into the earphone jack?
44. In your own words, describe how the simple speaker works.