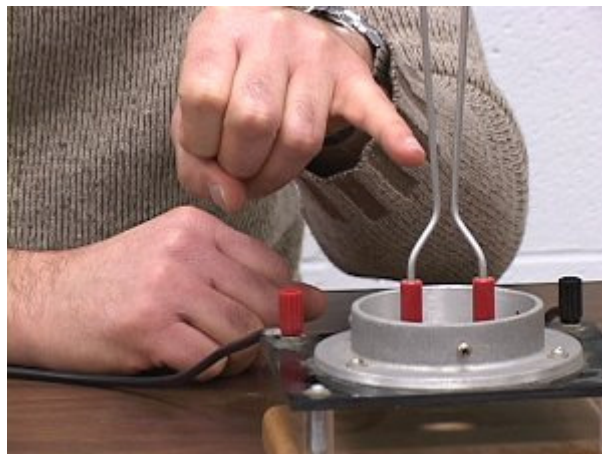
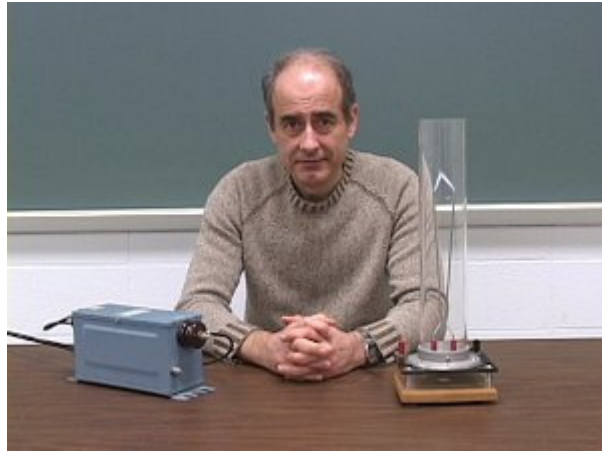


## K. The Laws of E&M



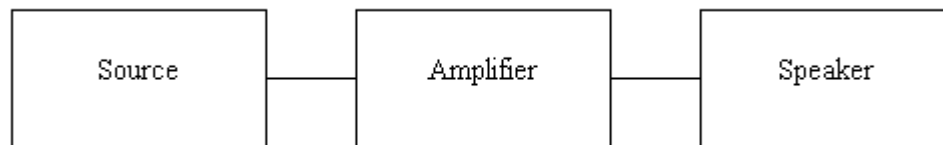
There are three basic stages of sound reproduction. These are illustrated in Fig. K-1. Dividing the challenging task of sound reproduction into modular steps is good engineering practice. We have division of labor and specialization of function. There is no duplication of jobs. Also, the source can then be interchanged. It might be a CD player, tape deck, or microphone.

The signal from any of these sources needs to be enhanced in order to drive a speaker membrane. This is accomplished in the second stage by the amplifier. In the

third stage we find the speaker so we can hear the sound. A single speaker gives *monophonic* or *monaural* sound.

Two speakers, each with a somewhat different channel of sound information, provide for a three-dimensional experience of sound. This is *stereophonic* or *stereo*, which we are very accustomed to. A set of four speakers, each with a separate channel, is called a *quadraphonic* system. Most people are pleased enough with stereo and often settle for stereo systems.

Fig. K-1. The Three Basic Stages of Sound Reproduction.



Since the time of *hi-fi* (*high-fidelity*), when sound reproduction became quite realistic, but still monophonic, serious music lovers have taken pride in carefully picking out components for their sound systems. They might buy the best record player (e.g., in the 1950s) built by one manufacturer, the amplifier built by another, and speakers from still another.

In the late 1950s, as stereo became accessible to the masses, thousands of monophonic records had to be replaced by the new stereo records. The standard setup was a turntable, amplifier, and two speakers. A tuner to pick up the new stereo radio stations was also essential. The older reel-to-reel tape recorder was handy for making good stereo tapes off the air. This would mean three source units: the turntable, tuner, and tape recorder. No one serious would dare buy a record changer

that stacked records and dropped one automatically on top of the last one when playing the next record. The turntable, which can only handle one record, offered the best protection for your fine records like the *Angel* recordings of the Schumann four symphonies. You would want a good amplifier, capable of at least 35 watts per channel and two fine speakers. Each speaker unit would contain a large speaker for long-wavelength low frequencies and a smaller one for the higher pitches. Those with systems including 15-inch bass speakers would look down on those with 12-inch speakers. If you had 8-inch speakers, you were pretty far down the list. The wattage per channel was also a measure of status. One of the author's friends in graduate school had a 200-watt system in a small apartment during the 1970s.

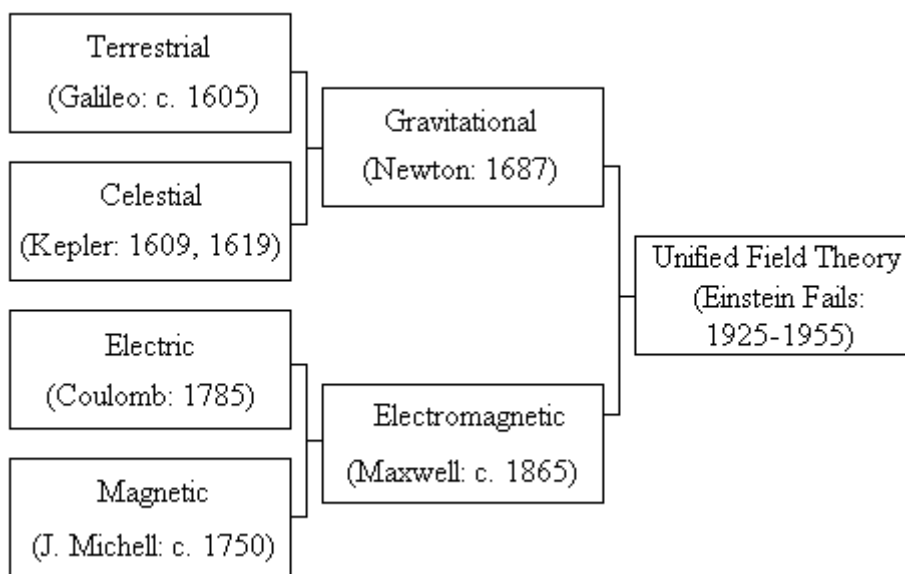
We need to understand basic concepts in electricity in order to understand the 20th-century developments in sound reproduction. Electricity involves using a fundamental force of nature, the electric force, to our advantage. Let's look at basic forces in nature before pursuing our study of the electric force in some detail. Physicists have found very few fundamental forces in nature. You might say that these basic forces are responsible for holding the world together. Physicists have been amazed to discover that forces once thought to be different and separate, were found to be related in an intrinsic way.

For example, the forces that govern heavenly motion were once thought to be different from earthly forces. Kepler (early 1600s) discovered laws describing the celestial orbits of planets while Galileo, around the same time, found what appeared to be a different law describing terrestrial motion. Newton showed that the (*celestial*) force that keeps the moon in orbit

around the Earth is the same (*terrestrial*) force that causes apples to fall to the ground. He called this the force of *universal gravitation*. Newton published this in his famous work, the *Principia*, in 1687.

Other forces under investigation, mainly in the 1700s and 1800s, were *electric* forces and *magnetic* forces. These were likewise shown to be manifestations of a single force (c. 1865), now called the *electromagnetic force*. The early historical development of discovering the unifying forces in nature is summarized in Fig. K-2. Einstein was so impressed by nature's unity of forces that he set out to search for the one force that unified all, the *unified field theory*. He failed to discover this. Also, there are two nuclear forces that need to be dealt with. There has been considerable success in unifying all the basic forces in nature except gravitation since 1967. Work is in progress now to unify all. String theory might be the answer. Of course, there is a chance that unification is impossible.

Fig. K-2. Unification of Basic Non-Nuclear Forces in Nature.



Engineering applications of gravitation and mechanical systems were made centuries before Newton presented his elegant mathematical laws in 1687. The associated inventions include the pulley, lever, and wheel-axle assembly. However, with the electromagnetic force, the engineering applications came after the theoretical laws were laid down. Mechanical systems can be seen and touched. We can handle levers and pulleys. We can experiment directly with our hands. But electricity is more subtle.

After the laws of electricity and magnetism were written down in 1865, the stage was set for inventors and engineers to develop an arena of new technological devices. A new source of power was unleashed, electrical power. Electrical engineering became a specialized profession. Electronics became an area of applied science. These developments made possible the science of sound reproduction. The laws of electricity and magnetism are essential for sound reproduction. Electronic circuits are joined with mechanical components to make microphones, tape decks, speakers, and other sound devices. At this point, we would like to learn more about this new duet of basic forces, the electric and magnetic forces, that makes all of this possible.

The electric force can produce *electricity*, the flow of charged particles. *Charge* is similar to mass in the sense that

it is related to a fundamental force in nature. Mass is the source for gravity (or gravitation) and mass also responds to gravity. For example, the large mass of the Earth produces gravity near the surface of the Earth, and other masses, like rocks and baseballs, respond to this "force field" of gravity. The Earth and a baseball attract. We see the baseball move and not the Earth, because the baseball is light and the Earth is so huge.

Another fundamental force in nature besides gravitation, is the electric force. Charges create electric "force fields" and other charges respond to these fields. Once again, the lighter masses do more of the moving around. The electric force can be attractive or repulsive. There are two types of charges, designated as "+" and "−," making this possible. Two like charges, e.g., two plus or two minus charges, repel while unlike (a plus and a minus) attract.

The building blocks of matter are molecules and atoms. However, atoms are made up of a nucleus containing two types of particles (protons and neutrons) and a cloud of surrounding electrons. The elementary building blocks of matter are therefore the protons, neutrons, and electrons. These give us the key to understanding where charges come from. Table K-1 below lists these three elementary particles. The unit "amu" stands for *atomic mass unit*, a very small unit of mass.

Table K-1. Elementary Building Blocks of Matter.

	Proton	Neutron	Electron
Mass	1 amu	1 amu	0.0005 amu
Charge	+1	0	−1

In Table K-1 one unit of charge is taken to be the amount of charge on a proton. The masses of the proton and the neutron are about the same in value; however, both are much more massive than the electron (1836 electrons have about the same mass as 1 proton). The charges that move as electricity in wires are electrons. Electrons surround the nucleus in an atom. The number of electrons (minus charge) for any neutral atom is equal to the number of protons (positive charge) in the atom. The details of electron orbital motion and interaction with neighboring atoms are the subject of chemistry. In a metal wire, atoms are bound together forming a metallic solid. However, the outer electrons of the atoms are free to move around from one atom to another. This motion makes possible the production of electricity.

Electricity can be very dangerous. One should never play with electrical outlets at home. Electricity consists of small moving particles as we have seen. A current of these charges traveling in wires is the standard type of electricity. However, there is another kind of electricity called *static electricity*. There is no motion in this case (except for when sparks fly). To illustrate static electricity, rub a balloon against your arm and try to get it to stick on a wall (see Fig. K-3). The author stuck 100 balloons on walls in his second daughter's bedroom for her 4th birthday in 1990. Many of them stayed attached to the wall overnight. Rub a comb or ballpoint pen (plastic) against your sweater. Can you then pick up little bits of paper with the comb or pen? This is an example of the electric force at work.

Prepare two balloons by tying a string to each. Can you get the balloons to repel each other after rubbing them on your arm (see Fig. K-4). The balloons are said to be charged with static electricity. Each balloon picks up electrons (negative charges) when rubbed against your arm. Like charges

repel each other. So the balloons repel each other because they have gained electrons. Ben Franklin called these charges negative, in the 1700s, before anyone knew that the charges were electrons. The electron was not discovered until 1897. Ben Franklin's choice forced scientists later to call the protons (with opposite charge) positive.

Normally, an object such as a balloon has just as many electrons as protons. The balloon is neutral. When you rub an object against another, sometimes electrons are transferred; the protons stay where they are. Two balloons with extra electrons repel since "likes" repel ("unlikes" attract). Rubbing silk with glass removes electrons from glass. Rubbing cat's fur with plastic removes electrons from the cat.

Fig. K-3. Static Electricity.

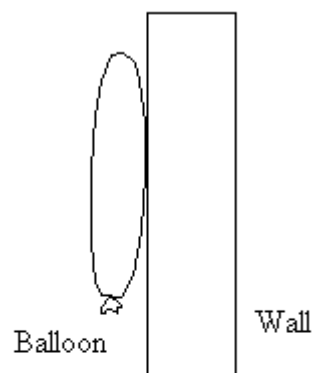
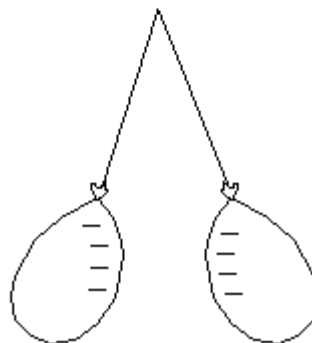


Fig. K-4. Electric Repulsion.



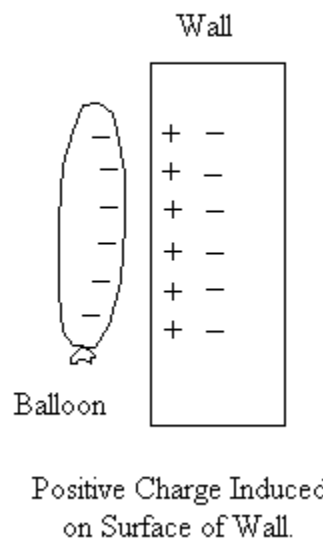
When you rub a balloon or comb against your hair, the balloon or comb picks up electrons, as we have noted. The negative charge on the balloon chases away electrons in the wall. These wall electrons are repelled by the electrons on the balloon. They move away from the edge of the wall (see Fig. K-5 at the right). The absence of electrons at the wall leaves the surface with a positive charge. The balloon's electrons are attracted to this positive charge and the balloon sticks to the wall. The electrons can't easily leave the balloon so the balloon stays stuck to the wall. If it is humid, the electrons can leave the balloon for the moist water droplets. The balloon then won't stay on the wall very long. The positive charge at the wall is induced by the balloon. This is called *electrical induction*. This also explains why a comb picks up bits of paper after you rub it on your sweater.

We can now consider magnetic forces by an analogy to electric force. Magnets attract and repel other magnets depending on the orientation of the ends of the magnets. We call one end north and one south, analogous to positive and negative. We find that "likes" repel. Two north poles won't pull together. They push each other away. Similarly two south poles repel. However, a north pole and south pole attract. See Fig. K-6 below. We have a similar rule here as the one we encountered in the electric case: "likes" repel and "unlikes" attract.

There is an important difference though. No one has ever found a magnet with one

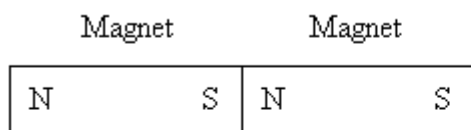
pole. All magnets have north and south poles. This is unlike charges, where we can find a sole plus charge such as the proton and a sole negative charge such as the electron.

Fig. K-5. Electrical Induction.

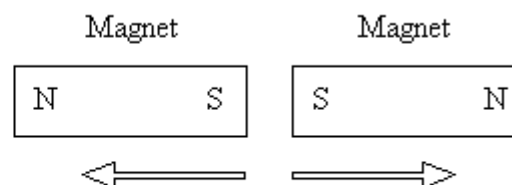


Our next experiment will shed some light on why magnets have two poles. It will also show us that electricity and magnetism are related. However, some scientists still search for a magnet with one pole, a *monopole*. So far none have been discovered. This fact has become one of the laws of electricity and magnetism: *magnetic monopoles* do not exist! So if someone discovers one, that person will probably win a Nobel prize in physics.

Fig. K-6. Magnetic Attraction and Repulsion.



"Unlikes" Attract.  
North and South Poles Stay Together.



"Likes" Repel.  
The Magnets Move Away From Each Other.

## Speakers

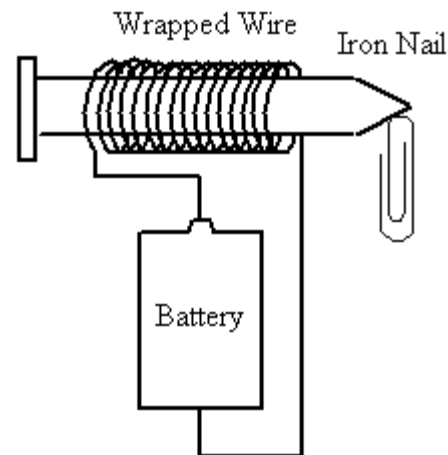
Our next experiment will show us the connection between electricity and magnetism, give us insight why magnets have two poles, and provide the groundwork for understanding speaker systems.

If materials are available, take an iron nail and wrap thin insulated wire around it many times. Then connect each end of the wire to the ends of a battery, being careful not to touch the bare-wire ends or battery terminals. The wire and nail can get quite hot. If the insulated wire gets too warm, stop. Wrap more windings. Try to pick up a paper clip. The nail now acts like a magnet. See Fig. K-7 at the right. You have an *electromagnet*. You may find that a residual magnet remains after disconnecting the battery.

Our experiment shows that we can make a magnet using electricity. This suggests a unifying relationship between electricity and magnetism. It explains why scientists consider electric and magnetic forces as one fundamental (electromagnetic) force rather than two. Now reflect on Einstein's struggle to look deeper into nature and find a similar relationship between gravitation and electromagnetism. If you don't see a connection, don't feel bad

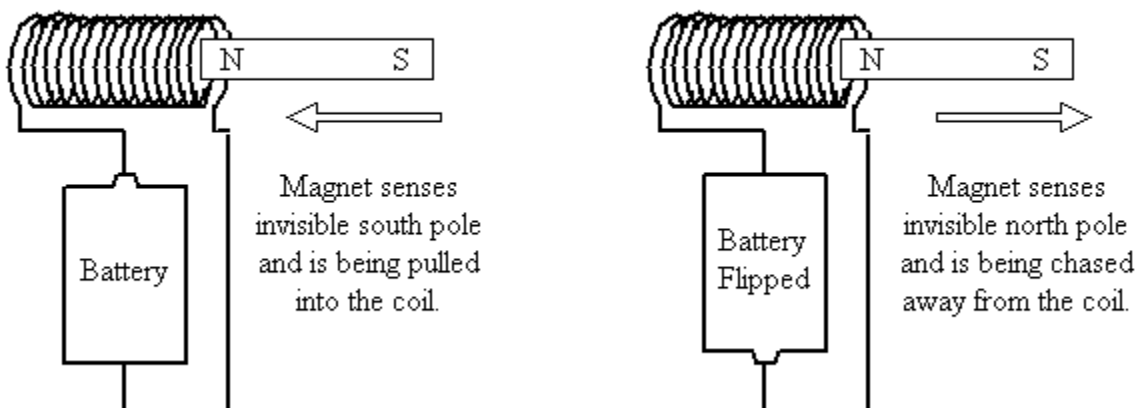
- neither did Einstein. And he studied the problem for the last 30 years of his life before he died in 1955.

Fig. K-7. Electromagnet.



Now comes the real magic. We remove the nail and find that a compass responds in the vicinity of the ends of the wrapped wire. A force field exists although there is no magnet per se. We call this force field a *magnetic field*. We find that we can make a "ghost magnet" of the polarity of our choice by the way we attach the battery. See Fig. K-8 below.

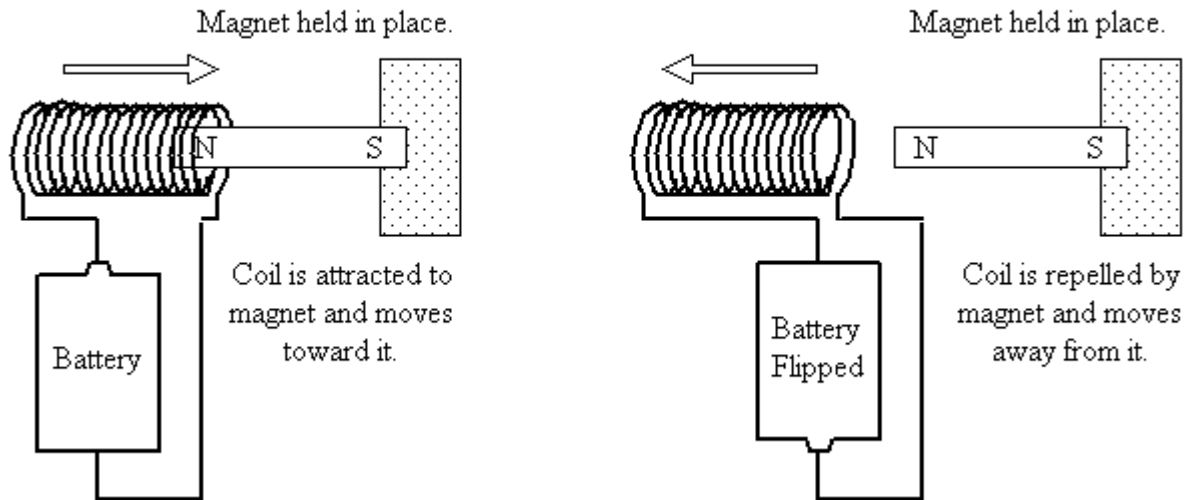
Fig. K-8. Magnetic Fields.



In Fig. K-9 we perform a slight variation of our previous experiment. We fix the magnet by cementing the south pole into a wall. Now when the magnet is attracted to the "ghost magnet," it can't go toward it. So

the coil comes to the magnet. The "ghost magnet" is free to move because the wires are not sturdy. When the battery polarity is reversed, the "ghost magnet" is repelled and moves away from the fixed magnet.

Fig. K-9. Magnetic Fields.



Newton discovered that for every action there is a reaction. When a force is applied, we can consider this the action, e.g., the "ghost magnet" pulls on the magnet. Then immediately there is a reaction force, the magnet pulls on the "ghost magnet." They both want to move. It's like the sun and Earth pulling on each other due to gravity. They both want to move. But the sun, which is more massive, resists moving (almost completely), while the Earth moves.

In our example, the fixed magnet cannot move, so the coil with its "ghost magnet" moves toward the magnet if the "ghost magnet's" south pole is facing the real magnet's north pole ("unlikes" attract). When the battery is flipped, the coil's north pole repels the magnet's north pole and the

coil moves away. Our "ghost magnet" also suggests that a magnet should have two poles. The "ghost" does so because each end of the coil supports one pole. You can't have just one end of a coil.

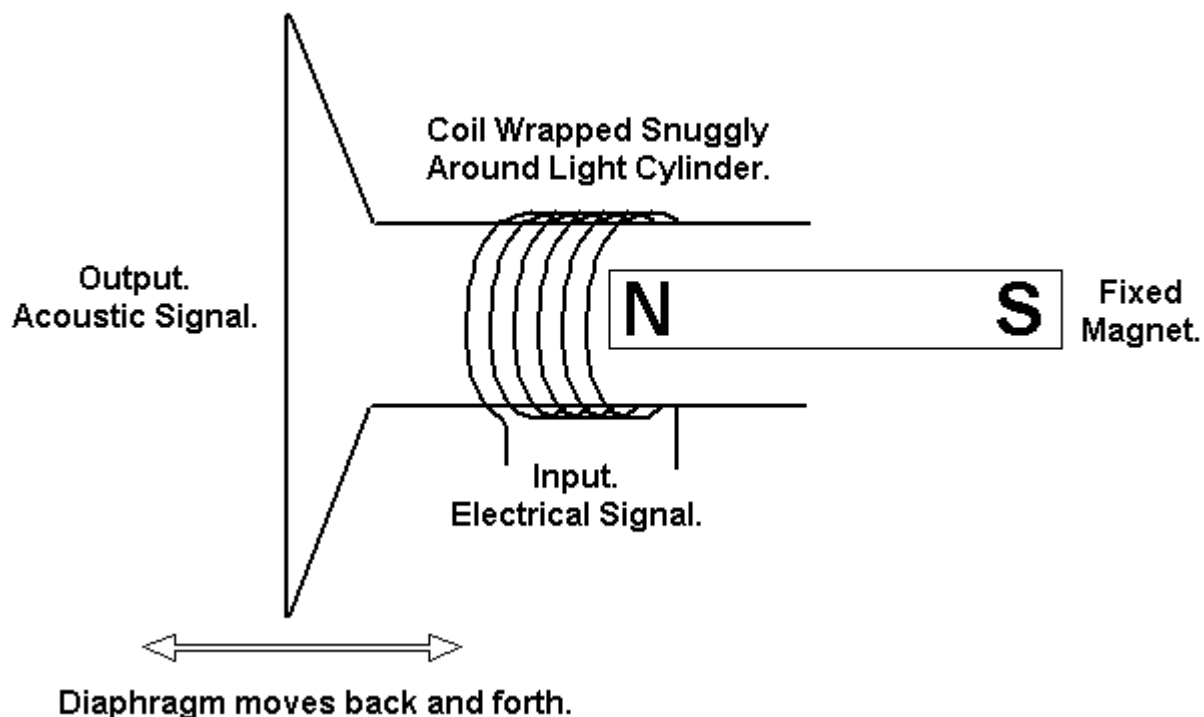
Now imagine flipping the battery from right-side-up to upside-down back and forth 100 times a second. The coil would move left and right 100 times a second. Now attach a delicate membrane to the left end of the coil. This membrane will shake the air molecules 100 times per second and we will hear a 100-Hz bass tone. We have a *speaker*. We can't flip the battery that fast, but we can attach a pair of wires carrying electrical oscillations to the coil. We then convert an electrical signal to sound. That's what a speaker does!



We give the sketch for the speaker in Fig. K-10 below. It is the design for the common *dynamic speaker*. The input signal is electrical. Consider a periodic wave such as a sine wave. The electrical current oscillates in step with the crests and troughs of a sine wave. The crests push current in one direction, the troughs pull current in the opposite direction. The coil

changes the magnetic field it produces in step with the crests and troughs. The changing magnetic polarity (north-south to south-north) results in pushes and pulls as the magnetic field interacts with the fixed magnet. The coil and cylinder vibrate back and forth. The diaphragm at the left vibrates the air and produces acoustic waves. We hear the sound of the sine wave.

Fig. K-10. Speaker Schematic.



Before we leave this section, we would like to point out that the physicist Ampère (1825) expressed in mathematical form how a current through a coil produces a magnetic field, a phenomenon first

observed by Oersted in 1820. This is called *Ampère's Law*. It is the basic law of electricity and magnetism that is applied in the invention of the speaker.

**Ampère's Law:**

**Current produces a magnetic field.**

## Microphones

Here we consider the invention of the *dynamic microphone*, the common microphone we encounter. There is a beautiful symmetry in nature that makes possible the invention of the microphone. The microphone is simply a speaker used in reverse. The laws of electricity and magnetism express this symmetry in nature. This means that if you talk into the diaphragm part of a speaker, the vibrating diaphragm will result in the production of an oscillating electrical signal. By this symmetry in nature, we mean that the cause-effect relationship, seen in the speaker, works backwards.

This counterpart law that says the reverse will work, was announced by Faraday in 1831 (Henry, an American, failed to publish his discovery in 1830). It is known as *Faraday's Law*. When you force the cylindrical coil to move back and forth near the fixed magnet, the coil "sees" the north pole of the magnet come toward it and then away from it. It "senses" a changing magnetic field. When the coil is

away from the magnet, it "senses" little or no magnetic field. As it is suddenly brought over to the magnet, the coil envelops the magnetic field. The coil "experiences" a changing magnetic field inside itself. The result is a surge of current through the coil each time there is a change. When the coil leaves the magnet (decreasing magnetic field inside the coil), the current flows one way. When the coil envelops the magnet (increasing magnetic field inside the coil), the current generated in the coil flows the other way.

We can summarize Faraday's Law by saying that a changing magnetic field creates electricity in the surrounding coil. We are careful in the statement of Faraday's Law below to say "produces an electric field" because if there is no coil around, there is no electricity. There is the potential to produce electricity, a potential to push charges. A "ghost battery" is in the surrounding space, the electric field. Put that wire in place, and the "ghost battery" works on the charges in the wire to get them moving. You then get electricity.

### Faraday's Law:

**A changing magnetic field produces an electric field.**

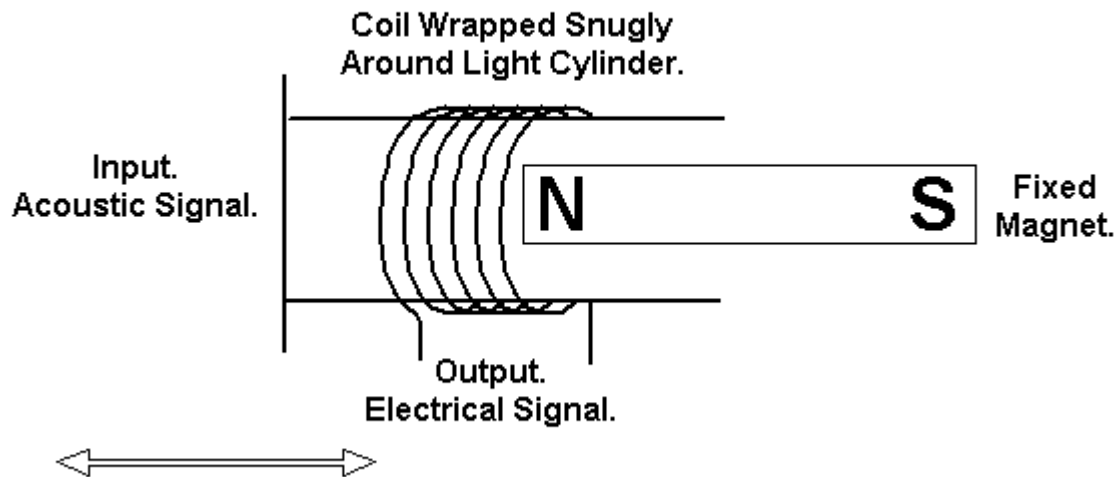
Faraday's Law got you to school today if you came in a car, truck, bus, cab, or motorcycle. Magnetic fields are created in a coil by your 12-volt car battery. Then, the magnetic field is rapidly turned on and off by a switch. A second coil surrounding the first coil "experiences" the sudden collapsing of the magnetic field. This extremely quick collapse generates electricity at 20,000 volts!

This voltage is distributed to your spark plugs according to the firing order for your car; and the 20,000 volts produce a spark across the small gap of the plug. The spark ignites the gas, which gas expands, pushing a piston that turns the mechanism that will eventually get your wheels turning. Faraday's Law enables you to go from 12 volts to the 20,000 volts.

Fig. K-11 below gives the schematic for the dynamic microphone. It is essentially the speaker diagram interpreted backwards. Someone speaks into the diaphragm. The diaphragm vibrates in step

with the sound waves from the voice. The moving coil around the magnet produces a corresponding electrical output signal in the coil wires.

Fig. K-11. Microphone Schematic.



**Diaphragm moves back and forth in response to external sound.**

We leave this chapter by pointing out a further underlying beauty in nature. The stricter statement of Faraday's Law says that a "changing magnetic field produces an electric field." This electric field can give us electricity if a wire coil is brought nearby. Someone observed that Ampère's Law is not really the strict opposite. Ampère's Law states that a "current produces a magnetic field."

The strict opposite to Faraday's Law is that "a changing electric field produces a

magnetic field." The physicist Maxwell observed this and combined this additional law with Ampère's Law around 1865. This completed the puzzle. The laws of electromagnetic theory were now complete. And we received a bonus! The fact that changing magnetic fields produce electric fields, which if changing, in turn produce magnetic fields has great consequence. It predicts the existence of electromagnetic waves. These waves include radio waves and visible light.

Table K-2 below summarizes the laws of electricity and magnetism. The four basic laws of electromagnetism are referred to as *Maxwell's Equations*. The Maxwell Equations predict the existence of electromagnetic waves. These are defined by their wavelength or frequency.

We have the familiar wave relation  $\lambda f = c$ , where  $c$  now stands for the incredible velocity of light (300,000 km/s or 186,000 mi/s). The electromagnetic (EM) spectrum of waves is broken into seven regions.

From short to long wavelengths, these are gamma rays, x-rays, ultraviolet light, visible light, infrared light, microwaves, and radio waves.

For our study of sound reproduction, we are mostly interested in the radio end of the spectrum. The wavelengths of radio waves range from a few centimeters (microwaves) to hundreds of meters (AM Radio). Table K-3 lists the rich variety of radio waves and their frequencies.

Table K-2. Maxwell's Equations of Electromagnetism.

1. Coulomb's Law	Like Charges Repel, Unlike Charges Attract.
2. (No Name)	There are no Magnetic Monopoles.
3. Ampère's Law Maxwell's Addition	Currents Produce Magnetic Fields. Changing Electric Fields Produce Magnetic Fields.
4. Faraday's Law	Changing Magnetic Fields Produce Electric Fields.

Table K-3. Types of Radio Waves.

EM Radio Wave	Frequency Range
AM Radio	550 - 1600 kHz
CB (Citizen's Band)	26 - 27 MHz
International Short Wave	28 - 53 MHz
VHF Channels 1 - 6	54 - 88 MHz
FM Radio	88 - 108 MHz
VHF Channels 7 - 13	174 - 216 MHz
Ham Operators	216 - 469 MHz
UHF Channels 14 - 88	470 - 890 MHz
RADAR	300 - 30,000 MHz

--- End of Chapter K ---