UNIT H

MAGNETS, CHARGE, AND ELECTRIC MOTORS

"I am busy just now again on electro-magnetism, and think I have got hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labor, I may at last pull up."

–Michael Faraday (1791 - 1867)

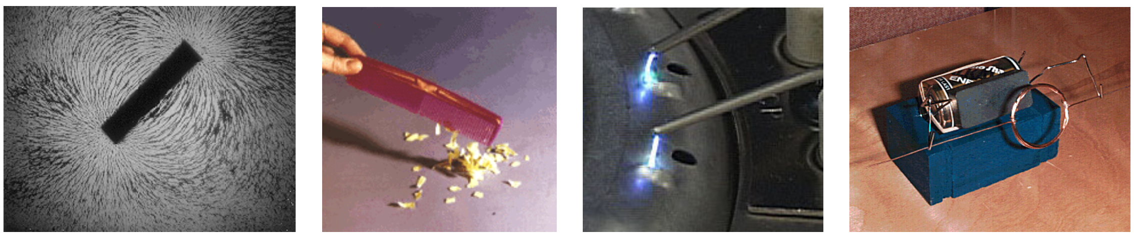
0 OBJECTIVES

1. To explore the behavior of magnets and be able to explain why magnets are attracted to certain materials.
2. To understand the operation of a compass on the surface of the Earth.
3. To observe and classify electric charges and how they interact with other charges and with insulators and conductors.
4. To construct a capacitor and observe how moving charges can perform useful work.
5. To understand the phenomenon of lightning by experimenting with charges.
6. To explore the interaction between moving charges and magnets and construct an electro-magnet from moving charges.
7. To use your understanding of charges and magnets to build a working DC electric motor.

0.1 OVERVIEW

We live in a world in which we are surrounded by electrical and magnetic devices. From computers to blenders to vacuum cleaners to telephones, we are literally surrounded by devices that make use of electrical and magnetic phenomena.

We will begin this unit by focusing our attention on magnets. This is something that most students have had some experience with. One of our goals here is to learn why some objects are attracted to a magnet. After learning about magnetic interactions, we turn our attention to charges. Students often confuse the concept of charge and magnets. We will see that they are in fact two very different phenomena. After learning about charge, we will look at what happens when charges move around. This electrical current can be used for a wide range of useful purposes. Finally, we will look at how magnets can affect moving charges and use this information to construct a working motor. The following figure provides an outline of what we will look at in this unit.



Section 1: Why are some objects attracted to a magnet?

Section 2: Why is paper attracted to a comb?

Section 3: What happens when charges move?

Section 4: How does a motor work?

Figure H-1: The main questions we will consider in this unit.

1 MAGNETS AND COMPASSES

We begin our study by investigating magnets. Most people have played around with magnets and have a basic understanding of their behavior. One of our purposes in this section is to make sure that everyone has the same experiences with magnets. Thus, whether you are reasonably familiar with magnets or not, the activities presented in this section are important because they will give us a common set of experiences from which to base our understanding.

You will need some of the following equipment for the activities in this section:

- A number of small magnets [1.1 – 1.3]
- Small metallic (magnetic and non-magnetic) objects [1.1]
- Small non-metallic objects [1.1]
- Small metal paper clips [1.1 – 1.3]
- Small containers of water (e.g. Petri dishes) [1.2 – 1.3]
- Iron filings [1-3]
- Compasses [1.3]

1.1 A FIRST LOOK AT MAGNETS

There are a wide variety of magnets that you may have seen. Bar magnets, horseshoe magnets, refrigerator magnets, etc. Do all these magnets have the same behavior or are they different in some way? In order to find out, we will begin by simply playing around with magnets and trying to understand their behavior. Rather than playing with all different kinds of magnets, we will start by focusing our attention on bar magnets. One we have an understanding of how bar magnets work, we will investigate the other kinds of magnets.

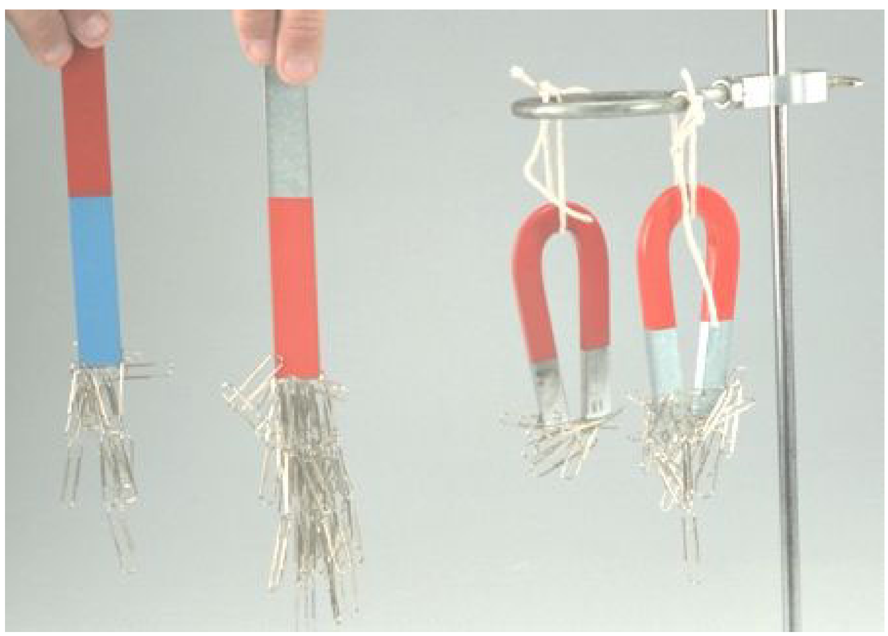


Figure H-2: Paperclips suspended from magnets. Notice that some of the paperclips are suspended without being in contact with the magnet. Why does this happen?

Activity 1.1.1 Playing with Magnets

a) Your instructor will give you three similar looking items, one of which is a magnet. Briefly describe how these objects interact with each other.

b) Now focus your attention on the two objects that attract each other. One of these objects is a magnet. By making careful observations between the interactions between these two objects, can you determine which one is the magnet? Describe your observations below and be ready to discuss your procedure with the rest of the class.

c) Now your instructor will give you a number of additional objects to explore, including another magnet. Based solely on the interactions between these objects, separate these objects into three categories. Below, *briefly* describe (a few words is fine) the interactions between the objects in the different categories (including objects in the same category).

	Category A	Category B	Category C
Category A			
Category B			
Category C			

d) Do any of the classifications above have both magnets and non-magnets in them? What words would you use to describe these three categories of objects?

Depending on your past experience with magnets, this first activity may or may not have surprised you at all. There are a couple of important things to note. First, there are many materials that do not interact with magnets at all. Some of these materials are even metallic. These are called *non-magnetic* materials. Examples include wood, cloth, aluminum and copper. Second, there is an attraction between magnets and certain materials. These are called *magnetic* materials. Examples include iron and steel. Lastly, and probably familiar to most students, is the fact that magnets can have both attractive and repulsive interactions with other magnets.

Activity 1.1.2 Taking a Closer Look at Magnets

a) You instructor will give you several different kinds of magnets. Does the force you feel depend on the distance between the magnets or the relative orientation of the magnets? Explain.

b) The places on each magnet that interact *most strongly* with other magnetic materials are called *poles*. Determine where the poles are on each magnet and explain how you found them.

c) Are there different kinds of poles or are all poles the same? Discuss this question with your group and describe how you can determine one type of pole from another.

d) To help distinguish between the two poles of the magnets, we are going to do a class activity. We will arbitrarily choose one pole and mark it with a piece of masking tape. From that "standard" magnet, you should determine which end of your magnets should have a piece of masking tape on it. We will henceforth refer to these as the taped pole and the un-taped pole.

e) State a *rule* below for how the different kinds of poles interact with each other? Try to be as clear as possible.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

The way magnets interact with each other is relatively simple and very important. Throughout this unit, we will rely on the rule you just specified above. Before moving on, be sure you have a solid understanding of how two magnets interact with each other. It should be clear from the previous activity that each magnet has two regions of strong interaction called poles and that the interaction becomes weaker as you move farther away from the poles. We often use the term *magnetic field* to describe this interaction.

The interaction is strong where the magnetic field is strong and the interaction is weak where the magnetic field is weak.

It should also be clear that the two poles on a magnet behave quite differently. In addition, you should be able to provide evidence for knowing how to distinguish one kind of pole from the other. As you are probably aware, the two poles on a magnet are called *north* and *south* poles. We will discuss where these names come from later in this section.

Note: It turns out that every single magnet in the world has both a north pole and a south pole. A *magnetic monopole*—a magnet that has only a single pole—has never been found in nature and is presumed not to exist. Of course, that does not prevent scientists from looking for one. The theoretical consequences of a magnetic monopole are very interesting and would create a sensation in physics if one were found.

1.2 THE BEHAVIOR OF MAGNETIC MATERIALS

In the last activity, we determined how two magnets interact with each other. But what exactly *is* a magnet? This is not a simple question. In this subsection, we will take a closer look at the behavior of magnetic materials[1] in the presence of a magnet. This process will allow us to describe what a magnet is, or at least how one goes about making one.

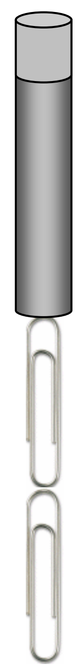
Activity 1.2.1 Magnets and Paperclips

a) Play around with a magnet and a some paperclips. Beginning with two paperclips on the table, try to figure out a way of picking up both paperclips without using your hands such that only one of the paperclips is touching the magnet. How far can you get the paperclip from the magnet and still lift it? Explain your procedure below. If it helps, draw a simple picture.

[1] There are a number of different kinds of magnetic materials, including paramagnetic, diamagnetic, ferrimagnetic and others. Most of these magnetic materials interact very weakly with permanent magnets. In this unit, we focus our attention only on *ferromagnetic* materials that interact very strongly with permanent magnets.

b) Is the paperclip (the one not touching the magnet) being attracted to the magnet or to the other paperclip? Explain briefly and be sure to support your answer with evidence. Again, feel free to draw a picture if it helps you explain your answer.

c) Now try the following experiment. Hold a magnet so that one paperclip hangs from one of the poles on the magnet. Then, gently pick up a second paperclip onto the end of the first paperclip, as shown in the figure. Then, holding onto the upper paperclip with one hand, **gently** detach the magnet from the paperclip. Describe what you observe.



A magnet with two paperclips attached.

d) Now try using the upper paperclip to pick up a different paperclip. What do you notice? What appears to have happened to the upper paperclip?

e) Now let's repeat the experiment with a slight twist. Begin by picking up two paperclips with the magnet as before. Again, hold the upper paperclip and gently detach the magnet. Then, flip the magnet over and slowly bring the opposite pole towards the top of the upper paperclip *without touching it*. Describe what you observe and explain what the magnet seems to doing to the paperclip. You might want to try this experiment a few times to make certain your results are reproducible.

The last activity is very interesting. It appears that a paperclip can be turned into a weak magnet simply by coming into contact with a magnet. This phenomenon is called *magnetization*. In fact, further experiments show that there does not need to be any physical contact between the magnet and the paperclip for this to happen. The paperclip only needs to be held close to the magnet. Of course, to verify that the paperclip has been turned into a little magnet requires us to observe that the paperclip indeed has two poles like a regular magnet. This is the topic of the next activity.

A paperclip is magnetized between two magnets.

Activity 1.2.2 The Paperclip Magnet

a) Take a paperclip and place it between opposite poles from two magnets as shown in the figure. **Remember which end of the paperclip is in contact with which pole of the magnet.** While one person holds the magnets and paperclip in this configuration (it should stay in place if you lay it down on the table), someone else can go and get a small dish filled with water (a Petri dish works well). We are going to attempt to float the paperclip on the surface of the water.

After the paperclip has been between the magnets for a few minutes, take it out and hold it between your thumb and forefinger on the long sides of the paperclip. Then, lower your hand towards the dish until your fingers come into contact with the water. When the paperclip is very nearly touching the water (within a few millimeters), gently open your fingers and let the paperclip drop very gently onto the surface of the water. If you are careful, your paperclip should be floating on the surface of the water. If it sinks, you will need to take it out and try it again with a dry paperclip.

Once you have a floating paperclip, predict how it will behave when you bring the red pole of a magnet nearby. Your prediction should be very specific.

b) Now try the experiment. Place one of the magnets on the table far away from the Petri dish and arrange it so that the taped pole is closest to the Petri dish. Then, slowly bring the magnet closer to the Petri dish until you notice an interaction. **Note:** The magnet should not be brought too close to the Petri dish. Always keep it at least a couple of inches away from the dish. Describe your observations. Was your prediction correct?

c) Check to see if your paperclip exhibits both attractive and repulsive behavior, and if so, explain which end of the paperclip is a taped pole and which end is a un-taped pole. Be sure to support your answers with evidence.

d) Now try magnetizing another paperclip with the same orientation as you did in part a). Predict what you will observe when you bring this paperclip near the floating paperclip. Be specific and make sure you write down your prediction *before* performing the experiment. After making your prediction, try the experiment and describe your observations. Do they make sense? Explain. **Note:** You can bring this paperclip quite close to the floating paperclip, but make sure they don't touch or you may sink the floater.

Prediction:

Observations:

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

It should be very clear from the last activity that a paperclip can be turned into a (weak) magnet simply by placing it near the poles of a magnet. As previously mentioned, this process goes by the descriptive term magnetization. But what exactly is *magnetization*? Before tackling this difficult question, the following activity uses the results of the previous activity to explain why certain materials are attracted to magnets.

Activity 1.2.3 Why Magnets Attract Certain Metals

a) Does the previous activity help explain why a paperclip (or some other piece of magnetic material) is attracted to both poles of a magnet? Think carefully about this and discuss it with your group. Then answer the following question. What happens to an object when it is brought close to the pole of a magnet? Your answer should clearly explain why the object is attracted to either pole of the magnet. Be specific and support your answer with experimental evidence from class.

Magnetization and Permanent Magnets

The process of magnetization is actually quite difficult to explain on a fundamental level. Quite simple, when an object made from a magnetic material (more precisely, a piece of *ferromagnetic* material) is brought near a magnet, it is itself turned into a magnet. The closer this object is brought near one of the poles of the magnet, the stronger this effect is. That is, the effect of magnetization is stronger when the object is placed in a stronger magnetic field.

But how and why does this happen? The answer to this question has to do with the *spin* of an electron. Electrons have a quantum-mechanical property called spin.[2] One of the properties of electron spin is that the electron behaves like a tiny magnet. In many materials, electrons are paired up in such a way (with opposite spin) that there is no macroscopic magnetic effects. However, some materials have unpaired electrons and in ferromagnetic materials, these unpaired electrons like to point in the same direction. The reason for this is purely quantum-mechanical, but the effect is rather remarkable. When a

[2] Although it is tempting to think of an electron as spinning around, this is not an accurate picture for what spin is. Unfortunately, we cannot give a good picture for what spin is because there is no classical analogy for spin. It is a purely quantum-mechanical effect.

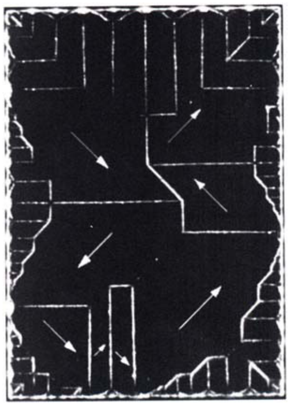


Figure H-3: A photograph of domain patterns within a single crystal of nickel; white lines reveal the boundaries of the domains. The white arrows superimposed on the photograph show the orientations of the magnetic dipoles within the domains and thus the orientations of the net magnetic dipoles of the domains. The crystal as a whole is unmagnetized if the net magnetic field (the vector sum over all the domains) is zero.

bunch of electrons have their spins pointing in the same direction, it is like a large number of tiny magnets acting together to make a stronger magnet.

So why aren't all objects made of ferromagnetic materials magnets? Well, in some sense they are. You see, although the electron spins want to point in the same direction, there are small regions called *domains* where all the electrons point in a particular direction and there are other domains where the electrons are pointing in a different directions. The macroscopic effect of all these domains pointing in different directions is to cancel each other out so the material has no net magnetic properties. However, when placed in a magnetic field (near the pole of a magnet), the domains that have the electron spins "lined up" in the magnetic field grow whereas the domains with electrons pointing in different directions shrink. This results in the material acquiring a net macroscopic magnetization.

Interestingly, if the magnetic field strength is large enough, the entire object can be coerced into having only a single domain. In this case, the object has been turned into a *permanent magnet.* In fact, what we have been calling "magnets" all along are just permanent magnets. Of course, just like the paperclip, these magnets are not truly permanent. After some time, the magnetization will wear off. This can be exacerbated in a number of different ways. One of the easiest is by dropping the magnets. This is why your instructor will tell you to be careful with the magnets and not drop them. If they are banged around enough, they will no longer be magnets until they are re-magnetized.

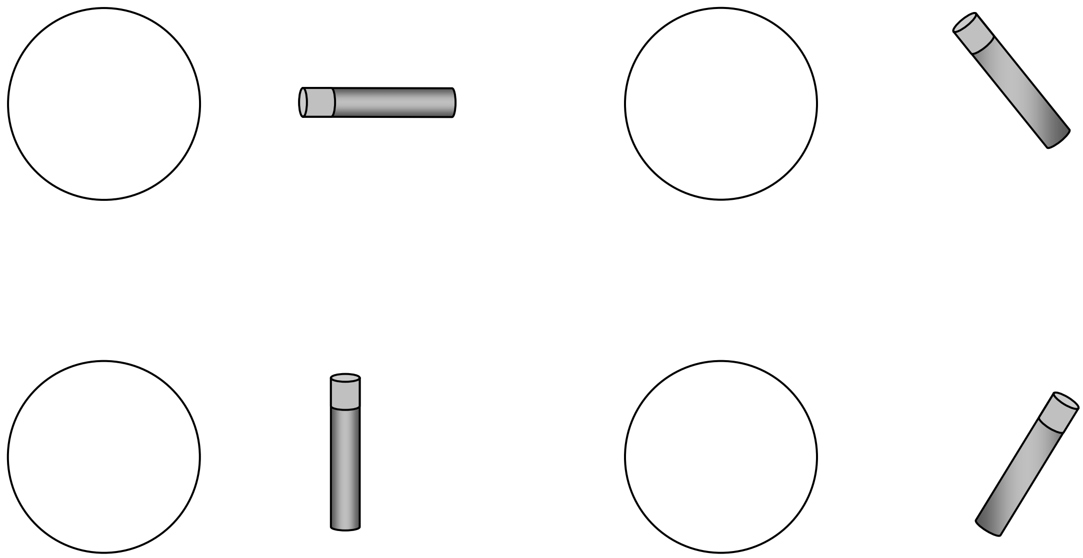
1.3 THE MAGNETIC FIELD

Earlier in this section, we loosely introduced the concept of a magnetic field. In this section, we will explore the magnetic field concept more fully. Although the magnetic field is a somewhat abstract concept, it is quite useful and very easy to visualize.

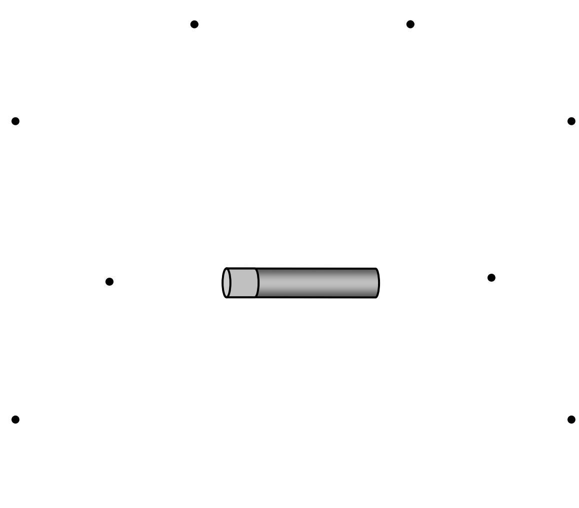
Activity 1.3.1 The Spinning Magnet

b) As you did back in Activity 1.2.2, set up a floating magnetized paperclip in a small Petri dish on your table. Remember which end of the paperclip was placed near the north pole and which was placed near the south pole (you might want to write it down). Place a magnet on the table far away from the Petri dish with the one of the poles pointing towards the floating paperclip. Then, slowly move the magnet towards the dish until you observe some interaction taking place. Now try slowly rotating the magnet so that first the north pole points towards the Petri dish, then the south pole, then the north pole again. Does the floating paperclip always point towards the magnet? Explain what you observe.

c) Shown below is a top view sketch of the magnet and the Petri dish for various orientations of the magnet. Sketch in the orientation of the floating paperclip in each of the diagrams below. Make sure to identify the two ends of the paperclip as separate.



d) Below is a picture of a magnet. By using the information from above (and by performing additional experiments if needed), sketch in what the orientation of the paperclip would be at each point marked by a dot. Instead of trying to sketch an actual paperclip, just draw an arrow with the head of the arrow representing the taped pole and the tail representing the un-taped pole.



The direction of the magnetic field is defined as the direction that a small magnet would point (which way the north pole would point) if it was placed at a particular point in space. By determining the orientation of our magnetized paperclip around a magnet, we have effectively determined what the magnetic field around a bar magnet looks like. Of course, it is difficult to determine the orientation at all points around a bar magnet by using something as large as a paperclip. However, there is a very nice method for determining the magnetic field around a bar magnet that uses the fact that iron becomes magnetized in a magnetic field. This is the topic of the following activity.

Activity 1.3.2 The Magnetic Field of a Bar Magnet

a) Begin by placing a bar magnet flat on the table and then placing two pieces of cardboard (or two notebooks) right up next to the magnet on both sides. The cardboard (or notebooks) should be about as thick as the magnet. Next, place a sheet of white paper on top of the cardboard so that the magnet is approximately under the center of the paper. Then, obtain some iron filings from your instructor and start sprinkling them on top of the white paper starting at the center (where the magnet is) and then moving outwards. Keep sprinkling until you can see a nice pattern. The iron filings are oriented along the direction of the magnetic field lines. Make a sketch of what you observe below and explain whether this pattern is consistent with the orientation of the magnetized paperclip in the last activity.

b) Explain what is happening to the iron filings to cause the pattern that you are seeing. Discuss this question with your group before writing your answer below.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

As demonstrated in the previous activity, the presence of a magnetic field is easily detected with iron filings which become magnetized by the field. In fact, this only works for reasonably strong magnetic fields because a weak magnetic field is not capable of magnetizing the iron filings. However, if one uses a weak magnet, like our magnetized floating paperclip, then one can detect much weaker magnetic fields. This is the purpose of the next activity.

Before beginning the next activity, check to see if your floating magnetized paperclip is still functional. You can do this by bringing a magnet nearby (not too close) and seeing if there is an interaction between the paperclip and the magnet. If the paperclip is no longer functional, take it out of the water, dry it off completely, then re-magnetize it and get it floating in the water once again. It is important to dry off the paperclip completely or else it is difficult to get it floating again. If needed, you can always start with a brand new paperclip.

Activity 1.3.3 Show me the Way

a) Once you have a floating magnetized paperclip, get it into the center of the dish and then move all magnets far away from the Petri dish. After letting the paperclip come to rest, make note of its orientation (determine which way the taped pole points). Then check the other floating paperclips in class to see how they are oriented. Comment on what you observe. **Note:** You might find it useful to tape a piece of paper to your table and draw the orientation of your paperclip on that paper.

b) Why do you think the paperclips are all oriented the way they are? Try re-orienting your floating paperclip by bringing a magnet nearby (but remember not to bring it too close or you might sink your paperclip). Now let the paperclip come to rest again and then check to see whether all the paperclips in the room are oriented in the same way again. Is this evidence that there is a magnetic field present? If so, what do you think might be the cause of this magnetic field? Explain briefly.

c) It is sometimes said that the Earth acts like a giant bar magnet. Do your observations support this claim? If so, where would the Earth's magnetic north and south poles be located? Explain briefly and draw a sketch if necessary.

d) Your instructor will provide you with a compass. Set the compass down on the table far away from any magnets or metal. Note the orientation of the needle on the compass and compare this to the orientation of the paperclip. You are probably aware that the poles of a magnet are usually referred to as "north" and "south" as opposed to taped and un-taped. Based on your observations, can you deduce why this is so? Explain.

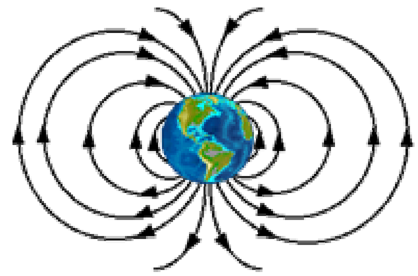


Figure H-4: The Earth has a magnetic field that can affect magnets. This makes compasses useful as navigational aids.

Compasses and the Earth

It is sometimes said that the Earth acts like a giant bar magnet. Although this statement is a bit simplistic, it is surprisingly accurate. The Earth does have a magnetic field and this magnetic field can be detected quite easily with our floating magnetized paperclips. In fact, you may have realized that our floating magnetized paperclips are nothing more than a compass. Stated another way, a compass is nothing more than a small magnet that is free to rotate.

As we have already observed, a small magnet will align itself in the direction of a magnetic field and can therefore be used as a magnetic field sensor. As the last activity just demonstrated, when no other magnets are around, all of our floating magnets point in the same direction. They were lined up north-south.[3] This has been known for a long time and compasses were designed to help people navigate when they were sailing. In fact, the (geographic) north and south poles on the Earth were common terms long before magnets were understood, so the end that pointed north was called a north pole and the end that pointed south was called a south pole. Of course, as you should now be able to explain, that means that the Earth's geographic north pole is a magnetic south pole!

[3] In fact, this is not quite true. The magnetic poles on the Earth are not quite aligned with the geographic poles determined by the axis of rotation. Note also that the magnetic field of the Earth changes so that what is now a magnetic north pole was at one point a magnetic south pole. These changes do not occur at precise times but take place on the order of 100,000 years.

2 *ELECTRICAL CHARGES*

Now that we have a fairly good understanding of magnetic behavior, we turn our attention to electric charge. It is worth mentioning that many students try to explain magnetic behavior in terms of charge. As we will see, although these two phenomena have some similarities, they also have some very different properties. You should try to be very aware of how the properties of electric charge are different from the properties of magnets.

You may need some of the following equipment for the activities in this section:

- Rubber balloons [2.1 - 2.3]
- Scotch tape [2.1 - 2.3]
- PVC pipe (1/2″ diameter, 3′ long) [2.2 - 2.3]
- Aluminum tape [2.1]
- Small plastic canister (35 mm. Film canister) [2.2]

2.1 A FIRST LOOK AT ELECTRIC CHARGE

As with magnets, most students have some familiarity with electric charge. For example, rubbing your feet on the carpet and then touching something results in a spark. Rubbing a balloon on your head allows you to "stick" the balloon to the wall. Running a comb through your hair allows the comb to pick up small pieces of paper. All of these examples demonstrate the phenomenon of electric charge, but in different ways. In this section, we will guide you through a step-by-step process that should help you understand these examples and many others as well.

Note: For many of the experiments in this section, we will be handling pieces of Scotch tape. When handling Scotch tape, it is useful to create a small "handle," by folding over a small section of the tape to itself. This will allow you to hold onto the tape without it sticking too much to your fingers. One of the things we will be looking for is whether the tape is attracted to or repelled by different objects. Thus, be careful when handling the tape so that it does not stick to anything.

Activity 2.1.1 A Piece of Tape

a) Begin by blowing up a rubber balloon and tying it off. Next, tear of a piece of Scotch tape approximately 3-4 inches long (about the length of your index finger). Affix the tape to the balloon (don't forget the handle) and make sure it is secure. Then, quickly rip off the tape from the balloon. Attach one end of the tape to a stand (or the side of your table) so that most of the tape hangs down. Slowly bring your finger towards the piece of tape and describe what you observe. Is there any interaction between the tape and your finger? Does this interaction depend on the distance between your finger and the tape?

b) Now try bringing your finger up to the front (sticky) side of the tape and see if you notice the same behavior. What do you observe?

c) Now try using the set of materials your instructor gave you in the previous section. Determine how each of these objects interacts with the piece of tape and write your observations below. If any of the interactions seem weak, you may want to use a fresh piece of tape ripped from a balloon.

d) How does a piece of tape ripped from a balloon interact with each of the categories of objects that you specified in Activity 1.1.2?

e) Can you find any object that does not attract the piece of tape? **Note:** There is at least one object that you have access to that will behave differently.

The previous activity should have demonstrated that a piece of tape ripped from a balloon appears to be attracted to almost everything. This is in stark contrast to the behavior of a magnet. You should also have noticed that there are some objects that repelled the piece of tape. In particular, another piece of tape ripped from a balloon. One question that may have come to mind is whether something has happened to the tape ripped from the balloon? This is the topic of the next activity.

Activity 2.1.2 What Happens to the Tape?

a) Begin by preparing a piece of tape from a balloon and sticking it onto stand or your table as before. Check to see that your finger attracts the piece of tape. Then prepare another piece of tape in the same way. Check to see that this piece of tape repels the first. Then, gently rub your fingers all along both sides of the second piece of tape. Then check to see how it reacts with the first piece of tape. Rub your fingers some more on the second piece of tape and again check how it interacts with the first. Write your observations below.

b) Now try bringing an object up to the each piece of tape. Describe how the object interacts with each piece of tape.

c) Now rub the first piece of tape between your fingers like you did with the second. How do objects interact with each piece of tape now? How do the two pieces of tape interact?

d) What do you think is happening when the tape is ripped from the balloon? What do you think happens when you gently rub the tape with your fingers? Explain briefly and include your observational evidence from above.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

It should be clear from the previous activity that ripping the tape from the balloon does *something* to the tape. It should also be clear that this something can be undone by gently rubbing your fingers all over it. It is reasonable to hypothesize that something is actually getting onto the tape when it is ripped from the balloon and that whatever gets onto the tape can also be removed by gently rubbing it off. For now, we will simply refer to this stuff as "stuff." Note that two objects that have no stuff on them do not interact in any way.

2.2 A MORE DETAILED INVESTIGATION OF STICKY TAPE

We have seen that when a piece of tape is ripped from the balloon, it interacts with everything. We have also seen that it interacts in a very different way with another piece of tape ripped from the balloon. It turns out that the interactions between two pieces of tape ripped from a balloon are easier to understand than the interaction between a piece of tape and an "ordinary" object. Because of this, we want to focus our attention on the interactions between various pieces of tape ripped from a balloon. We will return to discuss the interaction between a piece of tape ripped from a balloon and an ordinary object later.

Activity 2.2.1 A Closer Look at Tape-Tape Interactions

a) Begin by placing a piece of tape onto the balloon as before. Then place a second piece of tape directly on top the first. (Don't forget to include handles on your tape so that we can separate them later.) Now grab both handles together and rip off the two pieces of tape as if they were one piece of tape. We call this a *double-tape*. Observe that this double-tape attracts objects like a single piece of tape. Next, gently rub your fingers on the tape to get all the stuff off of it. Check to make sure that the stuff has been removed by looking for attraction with different objects. Now rip the two pieces of tape apart and while keeping them apart from each other, affix them to the stand or your table as before. By using ordinary objects, check to see whether there is "stuff" on these pieces of tape. State your observations and include your evidence below.

b) Where do you think this stuff is coming from? Explain briefly.

c) Now rip a single piece of tape from the balloon and check to see how it interacts with the two previous pieces of tape. Summarize your observations below.

d) Does the above experiment indicate that there is a single kind of stuff or more than one kind of stuff? Clearly state your evidence and be ready to discuss it with the rest of the class.

In the last activity, it should be clear that there is more than one kind of stuff that can be attached to the tape. We observed that the two pieces of tape ripped from each other both attracted normal objects and therefore must have had some stuff on them. We then saw that a third piece of taped ripped from the balloon was attracted to one piece of tape while it was repelled by the other. This suggests that there is at least two different kinds of stuff. Notice that this is quite different from the way magnets work. Although magnets have two different kinds of poles, these poles always occur in pairs. In the next activity, you will develop and test an hypothesis for how these different types of stuff interact.

Activity 2.2.2 Hypothesis: How Stuff Interacts

a) Working with your group, develop an hypothesis about how the two types of stuff interacts. Specifically state how your hypothesis would predict your observations in part b) of the previous activity.

b) Again, working with your group, try the following experiment to test your hypothesis. Prepare two double-tapes from the balloon, making sure to rub each one to remove any stuff. Check to make sure there is no interaction between the double-tapes. Now rip the double-tapes apart and check to see how the pieces interact with each other. Explain how your observations support or refute your hypothesis above. **Note:** Keep track of which piece of tape was on top and which was on the bottom.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

In the last activity, you developed an hypothesis regarding how the two types of stuff interact with each other and you performed an experiment to test your hypothesis. From now on, we will call this stuff *charge*. It is important to note that two pieces of tape prepared in an identical manner will acquire the same kind of charge. For instance, the pieces of tape that were on top acquired what we might call “top” charge while the pieces of tape that were on the bottom acquired what we might call “bottom” charge. There are also objects that have neither top charge nor bottom charge. We call these *neutral* objects.

Activity 2.2.3 Where Does the Charge Come From?

a) Prepare a double-tape from the balloon and rub it between your fingers to make sure that it is neutral (*neutralize* it). Now rip the two pieces of tape apart. Determine whether or not these two pieces of tape have charge. Explain how you think we can obtain two charged objects from an initially neutral object?

b) Notice that the double-tape was prepared by ripping it off the balloon. Based on our observation that the two pieces of tape acquire charge when they are ripped apart, it is reasonable to assume that the balloon acquires charge when tape is ripped from it. Predict what kind of charge (top or bottom) the balloon will acquire when tape is ripped from it. Explain your reasoning.

c) Now devise an experiment to test your prediction. Discuss your experiment with your instructor and then carry it out. Explain how you were able to determine the type of charge on the balloon. Be ready to discuss your procedure and results with the rest of the class.

WE NEED TO PUT IN A BIT OF A SUMMARY HERE

Summary of Charge Interactions

In the last several activities, you've investigated the interactions between several different kinds of objects prepared in different ways. At this point it is worth taking some time to reflect back on what we have learned so far. In the following activity, you will summarize the interactions you have observed between "top" charged, "bottom" charged, and neutral objects.

THE FOLLOWING PAGE BREAK IS ERRONEOUS.

Activity 2.2.4 Summary of Charge Interactions

a) Fill in the following table describing how each type of object interacts with each other type of object.

	"Top" charged	"Bottom" charged	Neutral
"Top" charged			
"Bottom" charged			
Neutral			

b) Are the interactions stronger or weaker when the charged objects are closer together? **Note:** If you don't remember, you might want to try a quick experiment.

In the last activity, you summarized the interactions between the different kinds of charged objects that we have observed. More than likely, you found that charges of the same type repel each other while charges of different types attract each other. You also probably noticed that both kinds of charged objects are attracted to neutral objects, but that neutral objects don't attract or repel other neutral objects. At this point, you probably feel like you've got a pretty good handle on how charged objects behave, but neutral objects are still a bit tricky because they are attracted to both kinds of charged objects. In the next sub-section we will take a closer look at these neutral objects.

2.3 NEUTRAL OBJECTS: THE SWITZERLAND OF CHARGES

It is worth taking a moment to reflect upon an interesting observation. We have seen in previous activities that neutral objects exhibit the interesting behavior that they are attracted to both top charged objects and bottom charged objects. Isn't it strange that you've lived your whole life without realizing this? On the other hand, maybe this isn't so strange. After all, almost all objects that you deal with in your daily life are neutral objects and neutral objects don't interact with other neutral objects. It takes a charged object to bring out the attractive behavior of neutral objects, and as we have seen, we have to do something special to make an object charged.

Activity 2.3.1 Putting it Back Together Again

a) In this activity, you are going to produce top charged and bottom charged pieces of tape in the usual manner. Predict what will happen if you put these two pieces of tape back together again with exactly the same orientation they had before ripping them apart. That is, predict how this "recombined double-tape" will interact with a top charged object, a bottom charged object, and a neutral object.

b) You need to be careful when performing this experiment because it is not easy to put the double-tape back together in the correct orientation. You should only handle the tape on the ends since we know that rubbing our fingers all over the tape will neutralize it. A good technique is to have one person hold one piece of tape by the two ends and another person hold the other piece of tape by the two ends. Then, keeping your fingers out of the way, the two pieces of tape should be carefully aligned and gently pressed together. One person should then grab the entire double-tape by both ends and stretch it gently (this will help the two pieces of tape adhere to each other). Remember, it is important that the orientation is the same as when the double-tape was ripped apart. Describe how recombined double-tape interacts with a top-charged object, a bottom-charged object, and a neutral object.

c) Was the recombined object charged or neutral? Cite evidence to support your claim.

d) Does this help you learn anything about neutral objects? That is, do you think neutral objects have charges on them? Explain briefly.

This last activity is an important one. We saw that we could take a neutral object such as a piece of double tape and rip it apart to get two charged objects that have different types of charge on them (top and bottom). Then, when we bring these two charged objects back together, we end up with a neutral object once again. This suggests that top and bottom charge are in some sense opposites of one another, or that one kind of charge can counteract the effects of the other. In fact, one can hypothesize that a neutral object contains equal amounts of the two kinds of charge.

Note: Since we can produce top and bottom charges by ripping apart a neutral double tape, it is not necessary to begin by placing the double tape on a balloon. Since we neutralize the double tape before ripping it apart, the double tape can begin on any surface. The important thing is that there is good contact between the top and bottom pieces of tape. One easy way of doing this is by preparing your double tape on the surface of your table.

Top and Bottom: Positive or Negative?

This peculiar behavior was noticed hundreds of years ago and the two kinds of charge were given the names positive (+) and negative (-). This was done mainly for mathematical convenience so that when you add equal amounts of positive and negative charge you get zero total charge. This terminology, although standard, is somewhat arbitrary. You may have wondered why we have avoided this standard terminology thus far. The reason for this avoidance is because there is no easy way to tell whether top charge is positive or negative. Therefore, we will continue to call charge on the top piece of tape top charge and charge on the bottom piece of tape bottom charge.

Now, so far, most of our charged objects have been pieces of sticky tape. Is that the only thing that we can get charged? Well, in a previous activity, we saw that ripping a piece of tape from a balloon not only gave the piece of tape a charge, it also left the balloon with some charge as well (the opposite kind of charge, of course). Thus, it is worth taking a few moments to see what other objects can easily become charged.

Activity 2.3.2 Other Charged Objects

a) Blow up a balloon and tie it off. Tear off some tiny pieces of paper (about 10) and make a small pile. The pieces of paper should be about ¼ inch by ¼ inch. Then, take the balloon and rub it vigorously in your hair. Then try placing the part of the balloon that you rubbed in your hair near the tiny pieces of paper. Describe what you observe. **Note:** You should also try holding the balloon near some tiny pieces of paper.

b) Do you think the balloon is charged? Do you think the small pieces of paper are charged? Do you think everything is charged? Explain briefly.

c) By preparing a double tape and then ripping it apart, determine whether the balloon has charge, and if so, determine whether this charge is top or bottom.

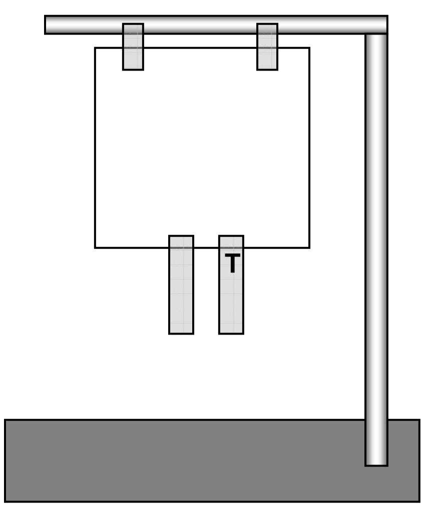
d) Now try rubbing a piece of PVC pipe with cotton. (Your instructor might have some other objects for you to rub together.) Is the PVC pipe able to pick up the small pieces of paper? If so, determine what kind of charge is on the PVC pipe. Explain your procedure and record your observations below.

It should be clear that it is not very difficult to cause other objects to become charged. It is worth noting that in every case so far, we have had to invoke some kind of "rubbing" or "ripping" type of behavior in order to get the objects charged. One of the easiest and therefore the most useful ways of getting charge is to rub a balloon vigorously in your hair. We will make use of this over and over again.

We would now like to turn our attention back to the fact that neutral objects are attracted to both top charged and bottom charged objects. Is it possible to explain this behavior using the idea that neutral objects contain equal amounts of top and bottom charge? In the next activity, you will construct a simple physical model to explore this possibility.

Activity 2.3.3 The Attraction of Neutrality

a) Tape a piece of paper to your stand or your table so that it hangs down. Now prepare a neutral double tape, about 4-6 inches long, being sure to label the top piece with a T. Rip apart the double tape and affix the two charged pieces of tape to the bottom of the paper (about 1-2nch apart) so that they are hanging down but not touching. Predict what you will observe if you slowly bring a top charged object towards the two charged pieces of tape. That is, what will happen to each piece of tape and what (if anything) will happen to the piece of paper. Will anything different happen if you bring up a bottom charged object?



b) Now rub a balloon vigorously in your hair and slowly bring the balloon towards the two pieces of tape. You should begin about 2 feet away and do not get any closer than about 5 inches. Describe what happens to the two pieces of tape and also what happens to the combined paper/tape system.

c) Explain why the paper moves in the direction that it does. **Hint**: You might want to refer back to part b) of Activity 2.2.4.

d) What would be different if you brought up an object with the opposite kind of charge? Would the paper move in the same direction? Explain briefly.

e) Now try bringing up a neutral object to the two pieces of tape. Again, you should begin about 2 feet away and do not get closer than about 5 inches. Record your observations below.

f) Is this system a reasonable model for a neutral object. Explain briefly.

g) Based only these observations, can you develop a microscopic model (possibly similar to the microscopic magnet model) for neutral objects. Your model should explain why a neutral object is attracted to both types of charged objects and why neutral objects are not attracted to other neutral objects.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

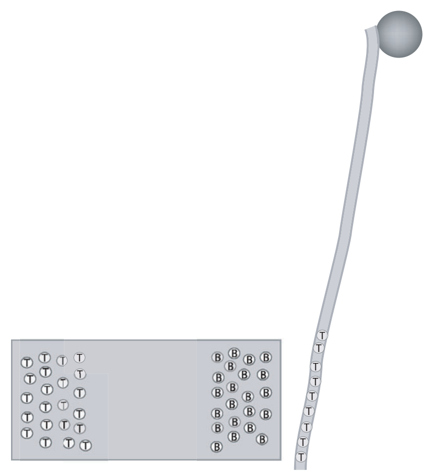
Don’t be discouraged if you had some difficulties with the last activity. Trying to understand why neutral objects are attracted to both kinds of charged objects is not a simple matter. On the other hand, we observed in the last activity that a piece of paper with two pieces of tape that came from a neutral object does in fact have the properties of a neutral object.

First, it is important to notice that the piece of paper in the previous activity was neutral to begin with. Then, we attached two pieces of tape with opposite charge on them. In fact, these two piece of tape were produced from a neutral double tape so we know that the charge on each of them will in effect cancel each other out. Thus, the paper/tape system has an equal amount of top charge and an equal amount of bottom charge. Next, we brought up a charged balloon towards the two pieces of tape. What did we observe? Well, as you probably expected, one of the pieces of tape was attracted to the balloon and the other one was repelled. However, what you may not have expected was that the paper itself will move slightly towards the balloon. The reason for this is that the tape that is attracted to the balloon feels a stronger force than the tape that is repelled. This is not because attractive forces are stronger than repulsive forces, but because both attractive and repulsive forces are stronger when the objects are closer than when the objects are further away.

Trying to put these observations into a microscopic model is challenging and in fact there are numerous ways of doing it. We will discuss the two most useful models, both of which are quite similar to the microscopic magnet model.

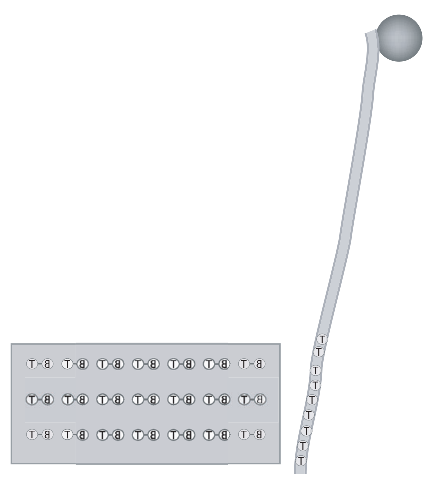
Free Charge Model

In the free charge model, we assume that a neutral object is made up from equal amounts of top and bottom charge, but that these charges are free to move around in the material. Thus, when a object with top charge is brought close to this neutral object, the microscopic top charges are repelled and the microscopic bottom charges are attracted. Since these charges are free to move around in the material, the top charges will move far away from the charged object and the bottom charges will move closer. This means that there will be more bottom charges near the object with top charge which will result in a larger attractive force (since the force of attraction or repulsion is stronger when the distance is smaller). The exact same kind of behavior will take place if an object with bottom charge is brought close to the neutral object except it will be the microscopic bottom charges that are repelled and the top charges that are attracted.



Bound Charge Model

In the bound charge model, we again assume that a neutral object is made up of the same amounts of top and bottom charge, but this time the charges are not completely free to move around in the material. Instead, each top charge is stuck next to a bottom charge, but this pair of charges is free to rotate around without changing its location. Now when an object with top charge is brought near this neutral object, the microscopic pairs of charge can swivel around so that the bottom charge is slightly closer to the charged object and the top charge is slightly further away. Again, because of the closer charges have a stronger interaction, there will be more attraction than repulsion so the neutral object will be attracted to the charged object. A similar discussion holds if the charged object has bottom charge instead of top charge.



Both of these models correctly predict the fact that neutral objects will be attracted to a top charged object and a bottom charged object. A natural question that most students will ask is which of the two models is correct? Well, at this point we can't really tell. Since both models can account for the observed behavior, they are both equally valid. In fact, it is even possible that they may both apply in different scenarios.

The fact that two different theories can both explain a particular phenomenon is a situation that occurs not infrequently in science. When faced with two theories that can both account for the observations, scientists typically choose the theory that is simpler. The reason for doing so is simply because it is easier to deal with a simple theory than it is to deal with a more complicated theory. This principle is known as Occam's Razor.

In the present case, it is not obvious which of the two models is "simpler" than the other. They are both fairly simple ideas. To try to determine whether we should adopt one of these models over the other will require further experimentation.

2.4 PROPERTIES OF MATERIALS

So far, we have seen that neutral objects all seem to behave the same way. That is, all neutral objects seem to be attracted to both kinds of charged objects. The next few activities highlights some of the differences between different types of neutral objects.

Notice that each time we put charge on an object, we either have to rub it in some way. Either rubbing a balloon in your hair or ripping two pieces of tape apart, it seems like we have to put some effort into getting something charged. The following activity will focus on trying to charge different types of objects.

Activity 2.4.1 The Bouncing Ball

a) Take a small piece of Styrofoam (about half the size of a Styrofoam peanut) and attach it to the end of a piece of string. You should not use tape to attach the Styrofoam. Instead, poke a small hole through the Styrofoam and pass the string through the hole and then tie a small knot so that the Styrofoam doesn't fall off. Next, take a balloon and rub it on your hair to get it charged. Then, holding the string, move the Styrofoam close to the balloon. Is the Styrofoam attracted to all parts of the balloon or only certain parts. Explain what this tells you about the charge on the balloon.

b) Now try to get some charge from the balloon onto the piece of Styrofoam by rubbing the Styrofoam against the balloon. You should not touch the Styrofoam with your fingers since we have seen that your fingers can be used to remove charge from objects. Instead, just hold the string and rub the balloon against the Styrofoam as best you can. Were you able to charge up the Styrofoam? Explain how you can tell.

c) Now make a small ball out of aluminum foil and attach it to a different piece of string. Again, you should not use tape to attach the ball to the string. Again, charge up the balloon by rubbing it in your hair and then bring it close to the aluminum ball (while you are holding onto the string). Is the aluminum ball attracted to the balloon. Next, try to get some charge from the balloon onto the aluminum ball using the same technique you used with the Styrofoam. Record your observations below. Were you able to get charge onto the aluminum ball? Explain how you can tell.

The previous activity demonstrated that some materials interact with charge very differently than other materials. In particular, it is pretty easy to get charge onto a small ball of aluminum and it is very difficult to get charge onto a small ball of Styrofoam. It is interesting to note that both the Styrofoam ball and the aluminum ball were neutral to begin with. Thus, both objects were attracted to the charged balloon when it was brought close by. You should have seen that no matter how much you rubbed the balloon onto the Styrofoam ball, it was still attracted to the balloon. This indicates that the Styrofoam ball is remaining neutral. That is, charge is not getting transferred to the Styrofoam (or at least, not very much charge). On the other hand, you only need to touch the aluminum ball to the balloon (or possibly touch it a few times) and immediately the aluminum ball jumps away from the balloon. This indicates that some charge was transferred to the aluminum ball from the balloon, and since it now had the same kind of charge as the balloon, it was therefore repelled. This behavior is very striking and you should try it a few times to make sure you understand that there is indeed a difference between these two materials.

In addition to the fact that charge is easily transferred to some materials and not so easily transferred to others, there is another big difference in the way certain materials interact with charge. This is the topic of the next activity.

Activity 2.4.2 Charging From a Distance

a) Now that we know it is relatively easy to charge up an aluminum ball, let us try to charge the ball without touching it directly. Take a piece of insulated wire with stripped ends and attach one end to the aluminum ball. This is easily done by poking the end straight into the aluminum ball. The other end of the wire is going to be held against a piece of charged PVC pipe. To get the PVC pipe charged, begin by holding one end of the pipe with your right hand. Then wrap a piece of fur around the PVC pipe and hold it with your left hand about six inches below your right hand. While holding your left hand still (it helps to hold this hand against a table or your leg), pull the PVC pipe with your right hand being careful to stop pulling before the pipe comes completely out of your left hand. This upward motion will put charge onto the PVC pipe. Now, you want to repeat this motion several times while someone holds the end of the wire in contact with the PVC pipe as it is drawn out of the fur. After a number of strokes with the PVC pipe, pull the wire out of the aluminum ball being careful not to touch the actual wire or the ball itself. Then, check to see whether the ball has any charge on it. You can do this by stroking the PVC pipe and then holding it up to the ball. Describe what you observed in this experiment.

b) Explain how you think the charge is getting from the PVC pipe to the aluminum ball.

c) What do you think would happen if you were to try this experiment again using a material like rubber to connect the PVC pipe to the ball? Explain your answer and use evidence from class to support your claim.

d) If possible, try the experiment again but use some electrical tape to cover the ends of the wire. This basically tests to see if the coating on the wire behaves the same way as the wire itself. Record your observations below.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

It should be clear from the previous activity that some of the charge from the PVC pipe ended up on the aluminum ball. Since the only connection between these two objects was the wire, it is reasonable to assume that the charge moved along the wire and ended up on the ball. If the wire is covered with electrical tape, then this charge transfer does not take place.

The last two activities have demonstrated two very important features that are only seen in certain kinds of materials. This is addressed in the following activity.

Activity 2.4.3 Two Kinds of Materials

a) Briefly describe how the aluminum ball behaves differently than the Styrofoam ball in Activity 2.4.1.

b) Briefly describe how the wire behaves differently than the wire coating in Activity 2.4.2.

c) Do you think the free charge model or the bound charge model are better at explaining the behavior of the wire? What about the wire coating? How about the aluminum ball or the Styrofoam ball? Explain.

Hopefully, the previous activities have convinced you that there are two basic kinds of materials that differ in the way they interact with charged objects. As we have already seen, all neutral objects are attracted to charged objects, regardless of the type of charge on the object. Thus, one might be tempted to lump all neutral objects together into one category. This is fine, and it is often useful to look at things this way. However, we have also seen that neutral objects can behave quite differently and it is sometimes useful to categorize neutral objects into separate categories.

Conductors and Insulators

The past few activities have demonstrated that it is quite easy to transfer charge to an aluminum ball and very difficult to transfer charge to a Styrofoam ball. We have also seen that charge can be transferred to the aluminum ball through a wire, but not through the wire covering. If we look back at our two models of neutral objects, it seems pretty clear that the free charge model seems to be a pretty good description of the wire. That is, the charge from the PVC pipe is transferred from the pipe to the ball very easily. The charges seem to move freely along the wire. On the other hand, the on the PVC pipe did not move freely along the wire coating. Thus, the bound charge model seems like it might be a better description of this kind of material.

In fact, we can even explain the behavior of the aluminum ball and the Styrofoam ball using the free charge and bound charge models. If an object with charge comes into contact with an object that obeys the free charge model, the charge that actually touches the object can freely move all over the object, thereby making more room for more charge to be transferred to the object. On the other hand, if an object obeys the bound charge model, then these charges will not be free to move and therefore there will not be room for any extra charge. Of course, if we "rub" the object over and over, we may be able to transfer charge to the object, but it will not be as easy as for an object that obeys the free charge model.

So we come to a very interesting conclusion. Both the free charge model and the bound charge model seem to be necessary to explain everything we have observed. Materials that obey the free charge model are called conductors and materials that obey the bound charge model are called insulators. Metals, including copper, aluminum, iron, gold, silver, and many others are all examples of conductors. Examples of insulators are rubber, glass, paper, wood, and plastic. Knowing how the behavior of conductors and insulators are different allows us to build interesting devices that take advantage of the special properties. We will actually build one of these devices, the so-called "sparking capacitor," in the following section.

3 *MOVING, STORING, AND USING CHARGE*

In the last section, you explored the properties of charged objects and how they interacted. You also investigated how different neutral materials behave and developed two different models for how they might behave. In this section, we will begin to explore how charges can be stored in devices called capacitors and also explore how moving charges can be coerced into doing useful work.

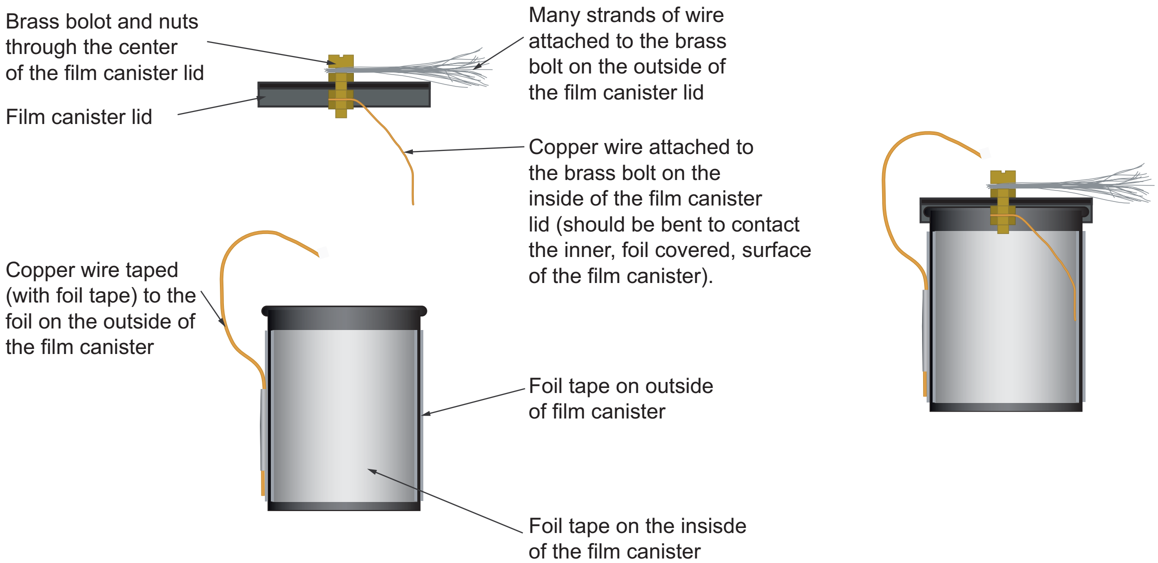
You may need some of the following equipment for the activities in this section:

- Film canisters [3]
- Aluminum Foil [3]
- Foil Tape used for duct work (found at hardware stores) [3]
- Wire (Stiff single strand and multistrand (braided shielding works well) [3]
- Brass nuts, bolts, and washers [3]
- Tools (pliers, screwdrivers, scissors, wire cutters and wire strippers)
- A 4 ft. length of ¾ in. PVC pipe
- Fur, Polyester, or Cotton cloth (Fur works best)
- Small pieces of clay, plastic, wire, steel and aluminum

3.1 MAKING LIGHTNING

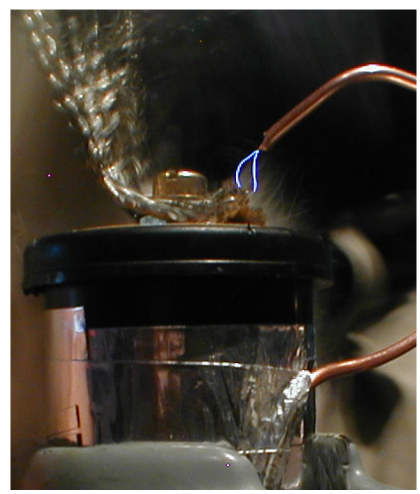
For the next few activities, you will use a device for storing charge. Before you begin these activities, you need to build your charge storage device. To do so, follow the instructions below.

1. Cover the inside and outside of a film canister with foil tape or aluminum foil. The device works much better if the foil tape lies smoothly against the sides of the film canister.
2. Poke a hole in the lid of the film canister big enough to tightly fit a bolt
3. Attach a short section of multi-strand wire or wire mesh (braided wire shielding works well) to the bolt with a nut and a washer. Spread out the strands of this wire to make a little metal brush.
4. Press the bolt through the lid so that the multi-strand wire is on the outside.
5. Use two nuts to attach a small length of wire to this bolt on the inside of the lid. Bend the wire so that it will touch the foil tape on the inside of the canister.
6. Now attach a 3-4 inch length of copper wire to the outside foil tape and bend it as shown in the diagram below.
7. Put the lid on the film canister

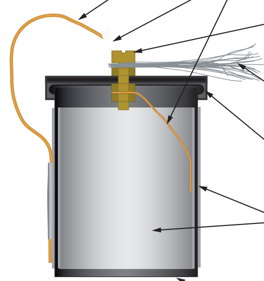


Activity 3.1.1 Making Tiny Lightning

d) To make lightening with your lightening machine, clamp it down and orient the brush so that is easily accessible. Adjust the copper wire attached to the outside foil so that it's end is about ¼" away from the bolt in the lid of the film canister. Now, take a 4 ft. length of ¾" PVC pipe in one hand and grip it with a piece of fur in using your other hand. Position the hand with the fur in it so that it is just below the brush and the PVC pipe lays across the wires of the brush. Using your other hand pull the PVC pipe upward quickly across the wires of the brush while holding the fur stationary. **Note:** It may help to brace your stationary (fur) hand against the table or the clamp. You may have to try this several times until you see a spark. You may also find it useful to attach the copper wire on the outside foil to ground with a wire. Describe your observations below.



e) Identify each component of your “lightening machine” as either a conductor (free charge model) or an insulator (bound charge model).



f) Explain how you think the lightening machine works. What is happening with the PVC pipe and fur? What is the role of each component (brushes, foil tape, film canister, wire…)?

g) Explain the role of charge in the phenomenon you observed in part a). What happens to charges on the PVC pipe/fur as you pull the pipe across the fur and wire brush?

The following experiment is designed to help you learn more about what might be causing the spark in the lightning machine.

Activity 3.1.2 What is Happening to the Charge?

a) Move the arm of your spark chamber so that it is relatively far away from the brass bolts that attaches to the center of the lid. Next, attach a long wire (such as the one used in Activity 2.4.2) to these brass bolts (or more easily to the wire strands that are connected to the brass bolts). Attach the other end of this wire to the small aluminum foil ball that was used in Activity 2.4.2 (it should still be connected to a string). Now, using the PVC pipe and fur, carry out the stroking procedure that led to the spark earlier in this section. You should not see a spark this time. After making a number of strokes with the PVC pipe, pull the aluminum ball off the wire using the string (don't touch it with your fingers) use the PVC pipe to check to see if it has charge on it. You may need to give the PVC a fresh stroke with the fur. Record your observation below and state what other parts of the lightning machine have charge on them.

b) Now try the same experiment again. Reconnect the aluminum ball to the wire and make a number of strokes with the PVC pipe. But this time, before removing the ball from the wire, use your hand to move the copper wire taped to the outside of the film canister close to the brass bolts in the center of the lid. What happens when you do this?

c) Now remove the aluminum ball from the wire (again, without touching it with your fingers) and check to see if the ball has charge on it. Again, you might need to give the PVC pipe a fresh stroke with the fur. Record your observations below. **Note:** Be careful not to touch the aluminum ball with the PVC pipe because as we have already seen, that will cause charge to be transferred to the ball.

d) Explain what is happening in this activity. That is, in the first experiment, we see that there is charge on the aluminum ball and portions of the lightning machine, but in the second experiment, we see that there is none. Explain what has happened to the charge.

e) There is something interesting to notice in the last experiment. After stroking the PVC pipe with fur, we can wait a few seconds and still see a spark from our lightning machine. Try doing this again (without using the aluminum ball) and seeing how long you can wait before causing a spark.

It should be clear from the previous activity that charge can be placed on the inner portion of the lightning machine and that charge will stay there for a while. Thus, our lightning machine is actually a charge storage device, sometimes referred to as a *capacitor* or a *condenser*.

Not only is our lightning machine a useful charge storage device, we can also use it as a device to distinguish between conductors and insulators. The following activity explores this procedure.

Activity 3.1.3 Conductors and Insulators

a) Set the gap in your lightning machine so that it is very easy to make it spark over and over again. Now, while one person is stroking the PVC pipe, another person should take a known conductor (like a wire) and hold it so that it makes contact across the gap. That is, it should make contact with both the copper wire (connected to the outside of the film canister) and the wire mesh that the PVC pipe is in contact with. Comment on what you observe and explain why you think this is happening.

b) Now repeat the experiment but this time use a known insulator (like rubber) and place it across the gap. Now stroke the PVC pipe and record your observations. Explain why you think this is happening.

c) Now try testing a number of different materials to see if they are insulators or conductors. You should try many different objects such as coins, paper, wood, Plexiglas, plastic, paperclips, etc. Record your observations below.

d) Now try stroking the PVC pipe with no material across the gap in our lightning machine. Well, although it looks like there is no material between the gap, there is. That material is air. As you stroke the PVC pipe, are there nonstop sparks or are the sparks somewhat intermittent? Does this tell you anything about whether air is a conductor or an insulator? Explain your answer below.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

In the past few activities, you have investigated one method for storing charge and you've made several observations of moving charges. We've even seen that when charges move through the air they may create a spark. What exactly is going on here? The previous activity should have demonstrated that air is sometimes an insulator and sometimes a conductor. Normally, air acts more or less like a insulator, but as we have seen, charge is transferred when there is a spark. This means that the charges are actually traveling through the air. But how is this possible? In the context of the bound charge model of insulators, how can charges suddenly start freely moving? That is a good question. In the bound charge model, each top charge is paired up with a bottom charge. Now, when a charged object is brought nearby, one of these bound charges will be attracted and the other will be repelled. If the strength of the attractive and repulsive forces are large enough, these bound charges can be ripped apart so that they are no longer bound together. Thus, these bound charges become essentially free charges. This explains how the charges are suddenly free to move in the air. But what exactly is the spark? The spark that you see is a result of the free charges coming back together to form bound charges. When charges recombine, they emit light.

3.2 CHARGES AND ELECTRICITY

While the phenomena we have been studying are interesting, do they relate to the electricity we use in our daily lives? Think, for a moment, about how you use electricity in your daily life. From electric lights, washing machines, and car ignitions to televisions, computers, and hybrid-electric cars, how are these phenomena associated with the ideas we've been learning about charge? In each of these applications, electricity is somehow making something happen. In the next activity, we will investigate how electricity can make something happen.

Activity 3.2.1 Making Charges Do Something

a) Affix one wire from a neon bulb to the brush part of the capacitor using an alligator clip. Adjust the copper wire attached to the outside foil of your capacitor so that it will not spark (make sure it is at least ½" away from the bolt), and then charge up your capacitor in the usual manner. Now, carefully watch the bulb as you touch the other wire to the copper wire on the outside foil of your capacitor. State your observations below. **Note:** You may want to try this several times to make sure your observations are consistent.

b) Did you see or hear anything when you touched the second wire to the outer copper wire of you capacitor? Do you think the capacitor is still charged after you touch the second wire to the outer copper wire of the capacitor? Explain.

c) What do you think happened to the charge on the capacitor when you touched the second wire of the neon bulb to the outer copper wire?

d) Now try connecting one end of the bulb to the wire mesh and the other end of the bulb to the large copper wire while you stroke the PVC pipe over and over. What do you notice now?

e) What do you think made the neon bulb light up? Why don't you think it stayed lit very long? Explain briefly.

Voltage and Current

The last activity should have demonstrated that charges can be made to light a light bulb. Unfortunately, it didn't stay lit for very long. This is our first example of charges doing something useful. We way that the charges are doing work. Note that charges do not have to do *useful* work. They can do useless work just as easily. It is important to note that it is the *moving charges* that are causing the light bulb to light up. This moving charge is called electrical *current*. Specifically, electrical current tells you how much charge is passing by in a specific amount of time (like one second). To make charges do something useful, there needs to be some kind of force that will cause the charges to move. This force typically comes from the attraction or repulsion these charges feel do to the presence of other charges nearby. The larger this force, the more potential the charges will have to do work. We say that the charges have a larger *potential energy*. When charges have a large potential for doing work, we say the charges are at a high *voltage*.

Note: In the next few activities, you will be experimenting with a battery. It is important to follow the instructions carefully in these activities. In particular, it is not a good idea to connect a wire from one end of a battery to the other end and hold it there for an extended period of time. This will cause the battery to run down very rapidly. In addition, the temperature of the battery can increase and possibly cause the battery to rupture, exposing you to potentially harmful chemicals. It is fine to connect the wire for a short period of time.

Activity 3.2.2 Exploring a Battery

a) Your instructor will give you a battery and some wire. Connect one end of the wire to one end of the battery and then bring the other end of the wire close to the other end of the battery and try to create a spark. You may need to dim the lights and touch the wire to the end of the battery. Describe your observations below and compare this with the spark created using the lightning machine.

b) Explain whether the battery acts like a charge storage device. Cite evidence to support your claim.

c) Is the battery able to make more than one spark? How is this similar to or different from the lightning machine? Does this give you any insight into the total amount of charge in these devices? Explain briefly.

d) Does the size of the spark suggest anything about which system is doing more work? Explain briefly. **Hint:** What is happening to the air when there is a spark?

Although it is not as impressive as the lightning machine, you should have been able to produce a small spark with the battery. The ability of the battery to produce a spark suggests that the battery acts like some kind of charge storage device. Although a bit simplistic, this is a pretty good way of thinking about a battery. However, are a number of differences between a battery and our capacitor. The most obvious is that we have to manually place charges on our capacitor while the battery somehow accomplishes this task on its own. The way this works is that there is an internal chemical reaction taking place whenever one end of the battery is connected to the other end via a conductor. This chemical reaction results in opposite charges being supplied to the ends of the battery.

Activity 3.2.3 Doing Useful Work

a) Your instructor will give you a small light bulb that has two wires attached. Take this light bulb and connect the two wires to the two ends of your battery. Describe what you observe. How is this similar to your observations when a bulb was connected to the lightning machine? How is it different? Explain briefly.

b) Explain how the battery is similar to and different from the lightning machine.

c) Does the battery or the lightning machine supply a more steady current? Explain your reasoning.

d) Does this give you any insight into which device stores more total charge? Explain briefly.

4 ELECTROMAGNETISM AND ELECTRIC MOTORS

For the activities in this section, each group will need:

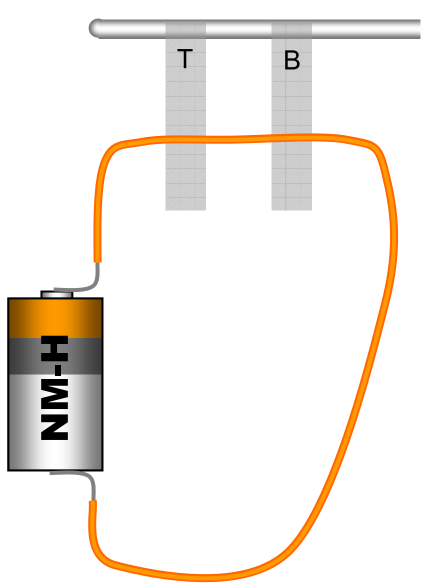
- 2-3 D sized batteries
- 1 piece of insulated wire about 3-4 ft long
- Magic Tape
- A small compass (preferably liquid filled)
- A Petri dish
- A paperclip
- Two small bar magnets

4.1 HOW DO CURRENTS INTERACT WITH CHARGE

You know from your experiments in the previous section that charges can move through a wire (or any conductor for that matter). When charges move through a conductor, we say that the conductor carries a current. It seems plausible that, since charges are moving through a current carrying wire, that the wire might become charged. In the next activity, you will explore this hypothesis.

Activity 4.1.1 Is a Current Carrying Wire Charged?

a) Given that charges are moving through a current carrying wire, do you think that a current carrying wire will be charged? Explain your reasoning.



b) Now, test your prediction. Prepare a top and a bottom charged piece of sticky tape and affix them to your stand. Using a piece of wire (about 0.5 m long), connect the ends of your battery. Now hold the middle of this wire up to the top and bottom charged pieces of tape. Describe your observations. Do they agree with your prediction? **CAUTION:** The battery and wire will get warm when you use them in this fashion. Throughout the following activities, when the battery becomes fairly warm (well before it becomes hot), you should set it aside to cool and use another battery for awhile.

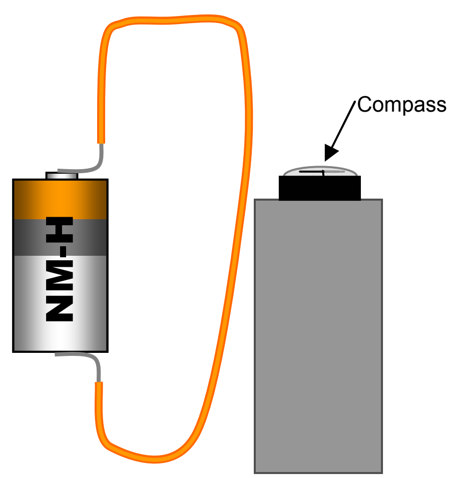
c) Try to explain your observations. Propose a model to explain how charges can be moving through the wire, even though the wire itself remains neutral. Describe your model below.

In the previous activity, you observed that a current carrying wire attracts both top and bottom charged pieces of tape. This implies that the current carrying wire is neutral. Even though we have found in the past that magnets and charges always attract, i.e. magnets are neutral, lets see if a magnet will interact with a current carrying wire. In the next activity, you will use a compass (which contains a little magnet) to see if the current carrying wire interacts with a magnet.

Activity 4.1.2 Do Currents Interact with Magnets?

a) What kind of interaction do you expect to observe between the magnet in the compass and the current carrying wire? Explain your reasoning.

b) Set your compass on a small stand as shown. Now, connect the ends of the wire to the terminals of the battery and hold the wire close to the compass. Since, the interactions between magnets depends strongly on their relative orientations, it makes sense to try several orientations and positions for the wire. Describe your observations.



Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Surprisingly, the magnet in the compass interacts with the current carrying wire. This result is almost unbelievable for two reasons. First, magnets behave like neutral objects in their interactions with charged objects. Second, you observed in Activity 4.1.1 that a current carrying wire behaves like a neutral object in it's interaction with charged objects. Clearly, our understanding of this phenomenon is incomplete. In the next subsection we will investigate in more detail how currents and magnets interact.

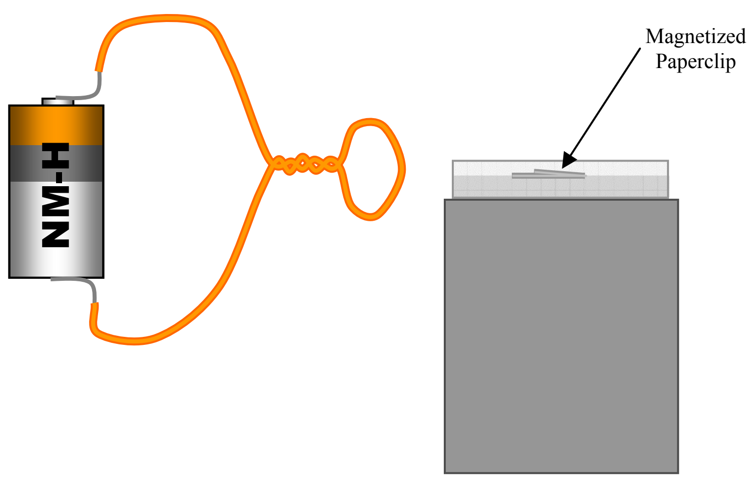
4.2 THE INTERACTION BETWEEN CURRENTS AND MAGNETS

In the next few activities, we'll explore this interaction in more detail. Although the compass is a good indicator that some magnetic phenomenon is going on, its movement is restricted so that it can only rotate. You'll recall however, that the movement of a magnetized paperclip floating on the surface of water is much less restricted. For the next few activities, we'll use a setup similar to that used in many of the activities in Section 1.

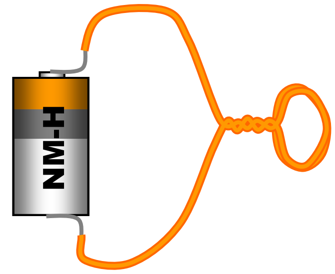
You probably noticed in the last activity that it is very difficult to determine how the compass interacts with a straight piece of current carrying wire. It turns out that the interaction between a current carrying loop and a magnet is somewhat easier to explore. In the next activity, you will explore the interaction between a current carrying loop and a magnetized floating paperclip.

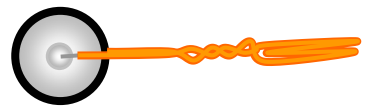
Activity 4.2.1 A Current Loop and a Magnet

a) Magnetize a paperclip and float it in a Petri dish as you did in Activity 1.2.2. Now, make a loop of wire as shown (wrapping the wire around two fingers should make a good sized loop). Next, connect the ends to the terminals of the battery. Hold the loop close to the Petri dish and observe what happens to the paperclip. You should try a variety of orientations. Describe your observations below. .**Note:** Be patient and don't' bump the table, things may happen very slowly in this activity.

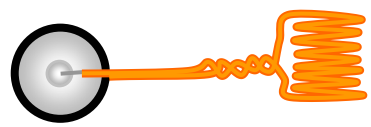


b) Try a similar observation, except, this time, make a double loop of wire. Describe your observation. Does the interaction between the paperclip and the double loop seem weaker or stronger than the interaction between the single loop and the paperclip?





c) Now try a similar observation, but this time make many loops in the wire. Describe your observations. Compare the strengths of the interaction for one loop, two loops and many loops.



d) What generalization can you make about the relationship between the strength of the interaction and the number of loops

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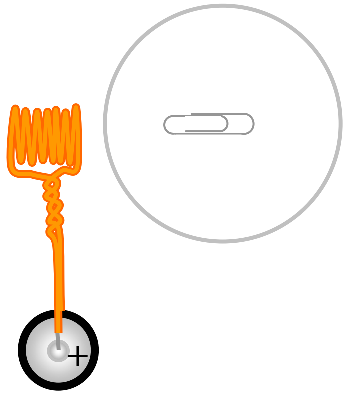
In the last activity you observed that a loop of wire interacts with the magnetized paperclip in a manner similar to the way a magnet interacted with the paperclip, but that this interaction was very weak. You also observed that by making more loops the strength of the interaction was much stronger.

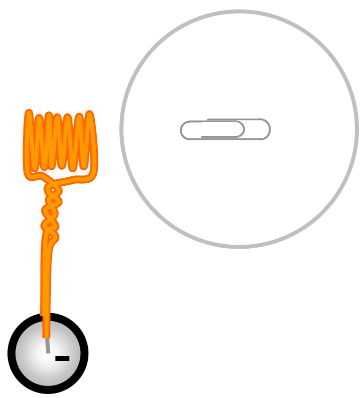
In the next activity, you will explore how the orientation of the loop of wire affects the interaction between the loops of current and the paperclip magnet.

Activity 4.2.2 Does the Orientation of the Loop Matter?



a) Using the multi-loop wire you made in the last activity, connect the wire to the terminals of the battery and hold the loops up to the Petri dish as shown. Describe what happens to the paperclip.

b) Now, flip the coils and battery over as shown and describe what happens to the paperclip.



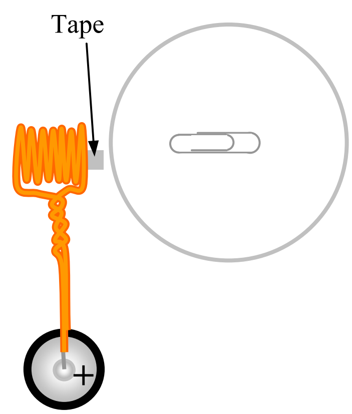
c) Position the coils in a variety of orientations with respect to the paperclip and describe how the paperclip moves. Can you make any generalizations about how the current carrying coil of wire interacts with the magnetized paperclip.

d) Recall the categories you devised in **Error! Reference source not found.**. Which of these categories best characterizes a current carrying coil of wire? Support your answer based on observations from the last couple of activities.

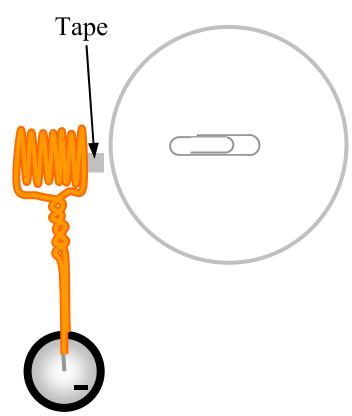
In the last activity, you found out that a coil of current carrying wire interacts like a magnet with another magnet. That is, when oriented one way, it attracts the magnet, and when oriented the opposite way, it repels the magnet. This implies that a coil of current carrying wire has poles just like a magnet. In the next activity, you will attempt to determine which part of your coil corresponds to the "taped" pole of the magnet and which part corresponds to the "untapped" pole.

Activity 4.2.3 Poles of a Current Carrying Wire (Part 1)

a) Using your coil of wire and floating paperclip, determine which part of your coil constitutes the taped pole and which part constitutes the untapped pole. Mark the "taped" pole with a small piece of tape. Describe how you determined which pole was the taped pole.



b) Now, hold your coil next to the Petri-dish as shown. Predict what will happen if you keep the coil fixed in place, but flip the battery so that the positive terminal is in contact with the lower wire and the negative terminal is in contact with the upper wire.



c) Perform the experiment. What do you observe? What do you think happens to the "poles" of the coil of wire when you flip the battery? Support your answer with observations. **Note:** You may want to do observations with several different orientations of the coil to be sure.

d) What changes in the wire when you flip the battery over?

Clearly, determining the poles of a coil of wire is not quite as simple as determining the poles of a magnet. You noticed in the last activity that by flipping the battery, you can flip the poles of the coil. What changes in the wire when the battery is flipped?

Current Flow and a Better Model for Conductors

In order to answer this question, we need to reexamine our model for current flow in a conductor. Based on our "free charge" model for a conductor, we know that charges can move freely throughout a conductor. Our simple model allowed both positive and negative (top and bottom) charges to move. It turns out, however, that only one type of charge moves in a real conductor. While we cannot determine which charges move with a simple experiment, it has been determined that the negative charges (electrons) are free to move while the positive charges remain stationary. Figure illustrates a more accurate model for describing the behavior of conductors.

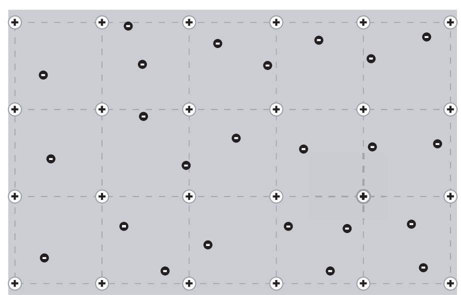


Figure 5: In this model for a conductor, the positive charges are held in a stationary lattice, while the negative charges (electrons) are able to move freely throughout the metal. Even though only negative charges are able to move in this model, it explains all the phenomena described by the "free charge" model introduced in Section **Error! Reference source not found.**.

Unfortunately, the convention indicating the direction of current flow was decided upon before we knew which type of charge was free to move in a conductor. As a result, the convention is a bit counter-intuitive. The convention was set so that positive current flow was in the direction of the motion of positive charges. Now that we are aware that negative charges move, the convention is that positive current flow is opposite the direction of the motion of the negative charges.

For our purposes, it does not matter which type of charges is moving which direction. The important thing for us is that only one type of charge flows. Thus, we can define a direction for current flow.

Direction of Current Flow: Current flows from the positive (+) terminal of a battery to the negative (-) terminal of a battery.

Based on this definition, it is clear that the direction of the current changed when we flipped the battery in the last activity. In the next activity, we well explore the relationship between the direction of current flow and the poles of a coil of wire in more detail.

Activity 4.2.4 Poles of a Current Carrying Wire (Part 2)

a) Figure out which direction the current flows in your wire. Draw a sketch below to indicate what direction the current flows. If you flip the battery over, how will the direction of the current change.

b) Devise a method for determining which side of the loop will be the taped pole based on the direction of current flow in the loop. Describe your method below.

In the previous activity, you figured out how to determine the “taped” pole of a loop of wire based on the direction current flowed through the wire. Physicists often use the “right hand rule” to help them remember which side of a current loop will be the north pole. The “right hand rule” is quite simple. Given a current carrying loop of wire. If you curl the fingers of your right hand in the direction of the current, your thumb will point toward the north pole of the current loop.

Enhancing the Magnetism of a Current Carrying Coil

In the first section of this unit, we learned that a magnetic field surrounds a magnet that this magnetic field can affect other magnets. A good example of this was how the Earth's magnetic field causes the small magnet in a compass to orient itself pointing north-south. During the last few activities, we have seen that a current-carrying wire can have an effect on a small magnet. Thus, it is reasonable to assert that a current carrying wire also produces a magnetic field. In fact, we have seen that a small loop of wire acts just like a small magnet, with a taped pole and an un-taped pole. In addition, the more coils of wire there are, the stronger is this magnet. Since this magnet is made from a current carrying wire, it is called an *electromagnet*. The following activity explores the effect of introducing a material inside the loops of the wire (called a "core").

Activity 4.2.5 Introducing a Core

a) Based on the previous experiments with coils of wire, where do you think the magnetic field is the strongest? That is, where does the interaction with a small magnet seem to be the strongest?

b) What do you think would happen if you were to place a small piece of material inside the loops of wire? Do you think the type of material would make a difference? Explain briefly.

c) Now try placing different materials inside the loops of wire. First try wood, then Plexiglas, then aluminum or copper. Is the behavior of the current-carrying loops any different from when there is no material inside?

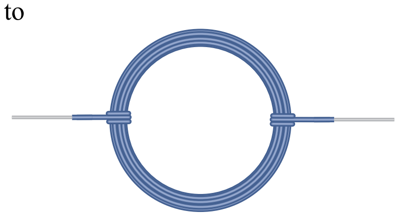
d) Now try placing a piece of iron inside the loops. What do you observe now? Explain what you think is responsible for this behavior and why it was not observed when the other materials were placed inside the coils.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

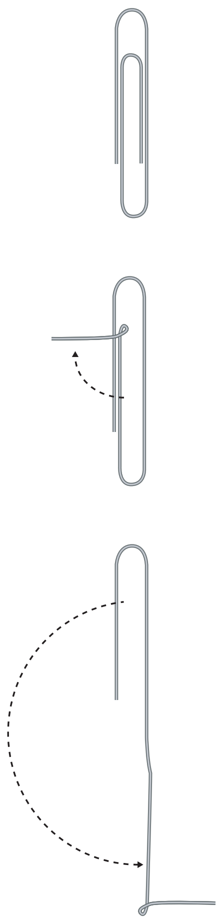
The previous activity demonstrates that the strength of an electromagnet can be increased substantially by including an *iron core*. In fact, any non-magnet attractable material would work just as well as iron. As we learned earlier, a paperclip can be magnetized (and thus act like a small magnet) when it is placed in the magnetic field of a magnet. Here, the iron core is being placed inside the coils of wire and this is where the magnetic field is the strongest. The iron core is becoming magnetized which adds to the magnetic field of the coils of wire. Interestingly, if the current in the wire is large enough, the magnetic field can be strong enough to create a permanent magnet out of the piece of iron. This is how "magnetizers" are made. Your instructor may be able to demonstrate this process for you.

4.3 AN ELECTRIC MOTOR

In the last subsection, we saw that a coil of wire will act like a magnet if there is a current flowing in the wire. We also saw that the poles of this "magnet" depend on the direction of the current flow in the coil of wire. We would now like to use the fact that a coil of wire behaves like a magnet to construct a device known as an electric motor. In order to build this motor, we will need to prepare a few items.



1. We first need to construct a good coil of wire. Take a piece of wire and wrap it around the PVC pipe 10 or more times to make a nice tight coil about an inch in diameter. Wrap the ends of the wire tightly around opposite ends of the coil



once or twice so that the stripped ends stick straight out of the coils as shown in the figure. Then place the two stripped ends of your coil on your finger and thumb so that the coil is free to rotate. Make small adjustments to your coil so that it is well *balanced*. Ideally, this would mean that you could rotate the coil to any orientation and it would stay there if you let it go. In reality, this is very difficult to accomplish. The coil will always have a slight tendency to rotate to a particular orientation, but you should try to eliminate this preference as much as possible. Have your instructor check out your coil when you think it is well balanced.

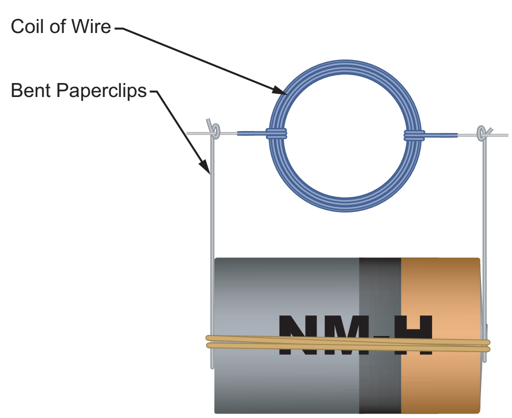
2. Next, we need two supports that will hold our coil. Take a paperclip and bend the inner end of the paperclip by ninety degrees to make a small loop as shown. Then straighten out the smaller of the two bends while leaving the larger bend alone (see figure). Make two of these supports.

3. Now take a rubber band and attach the two supports to the two ends of a battery so that the "j" ends are in contact with the battery terminals.

When you are finished, have your instructor check your construction before moving on. ***Do not put your coil of wire into the supports at this time!***

Activity 4.3.1 Magnet-Coil Interactions

a) Imagine that you place your coil of wire into the supports that are connected to the battery as shown. This will allow current to flow through the coil. Predict what will happen if you bring the pole of a magnet up close to the coil of wire. What do you think will happen if you flip the magnet over while it is still held close to the coil?



b) Now try the experiment. It is important not to leave the coil of wire connected to the battery for too long or else the battery will no longer provide a current. Thus, as soon as you are done making your observations, disconnect the coil by taking it out of the supports or by sliding it so that the stripped end of the wire is no longer in contact with the support. Record your observations below.

c) Explain the observations you just made by treating the coil of wire as a magnet.

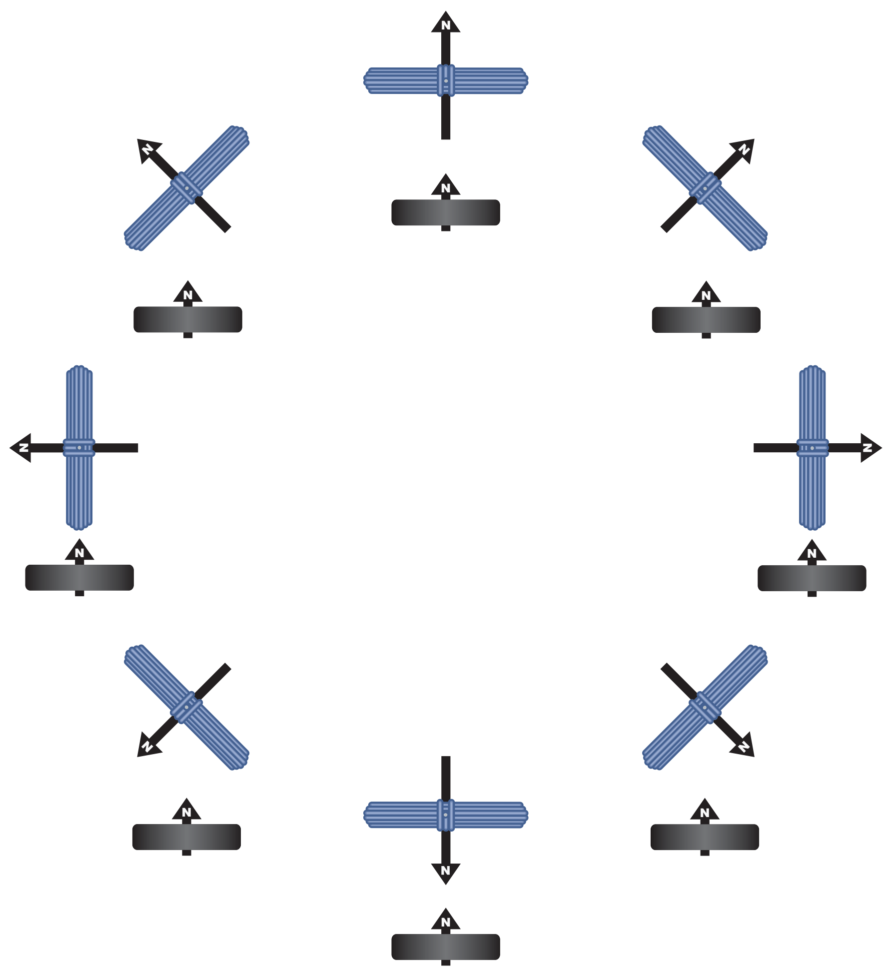
Because of the attraction of unlike poles and the repulsion of like poles, the coil of wire can be made to rotate when a magnet is brought nearby. This interesting behavior suggests the possibility that a magnet can be used to cause a coil of wire to continually rotate. The following activity explores this possibility.

Activity 4.3.2 Analyzing a Rotating Coil

a) Imagine that the coil is placed into the supports on the battery so that current is flowing in the coil but there are no magnets around. Now suppose you start the coil spinning by tapping one end with your finger. Would the coil continue to spin or would it stop at some point. Explain briefly.

b) Suppose you want the coil to keep rotating. What would you need to do with your finger to accomplish this? Explain briefly.

c) Now let's consider whether a magnet might be capable of keeping the coil rotating. Shown below is a series of diagrams that show a magnet and a coil of wire in different orientations. Assuming the coil is initially stationary, indicate what direction the coil would begin to rotate in each figure. Do you think the strength of the interaction would be the same or different in each of these orientations? Explain briefly.



d) Now imagine the coil spins through one complete rotation. Do you think the net effect of the magnet on the loop would be to provide a tendency to rotate clockwise, counterclockwise, or neither? Discuss this with your group carefully before answering and explain your reasoning below.

e) Based on this analysis above, do you think the current-carrying coil would continue to spin or would it stop after a while in the presence of a magnet? Explain.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

By treating the current-carrying coil as a magnet (which we know is valid), it is not difficult to understand why the coil has a tendency to rotate in the presence of a magnet. Since like poles repel and unlike poles attract, the coil of wire will rotate so that there are unlike poles facing each other. This is a stable position. If the coil is rotated slightly in either direction, there will be a magnetic force that tries to return it to the stable position. That is, if you rotate the coil slightly clockwise, there will be a "counter-clockwise force" from the magnet that will tend to return the coil to its stable position. Similarly, if you rotate the coils slightly counter-clockwise, there will be a "clockwise force" that will tend to return the coil to its stable position. (Incidentally, these "rotational forces" are called *torques*.) Thus, there are just as many orientations of the coil that lead to a clockwise force as there are leading to a counter-clockwise force. This means that if the coil goes through a complete rotation, the magnet will provide equal amount of clockwise force and counter-clockwise force. Thus, there will be no extra "kick" from the magnet in either direction and therefore the coil should slow down and stop at some point because of friction.

Activity 4.3.3 Getting the Coil to Spin

a) Unfortunately, the analysis of the previous activity demonstrates that the current-carrying coil will not continue spinning in the presence of a stationary magnet. But perhaps all is not lost. Maybe there is something we could do to make this system work. Discuss with your group what you might be able to do so that the coil would continue to rotate without any extra pushing from your hand. Explain your idea below. **Hint:** Consider what you could do to the current to make this happen.

b) Now try the following experiment. Place a magnet on the battery and then place the coil of wire in the supports as shown. Tap the coil with your finger to start it spinning and describe what you observe.

c) What is going on here!? We just did an analysis that demonstrated that the coil of wire should *not* continue to rotate in the presence of a stationary magnet. However, when we do the experiment, we see that the coil does continue to rotate. How can this be? Discuss this with your group and try to determine what *must* be happening in this system. Explain your ideas below. **Hint:** Again, consider the current in the coil.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

The device you have just built is called a motor. Charges from the battery are doing work that results in the spinning of the coil. A purely electrical phenomenon (current flow) is being turned into a mechanical phenomenon (spinning coil).