The Magnetic Field and Faraday' Law

Goals and Introduction

The human experience with magnetism dates back many centuries, at least to the time of the ancient Greeks and Chinese, who were both aware of magnetic materials that had the ability to attract iron. It is around the year 1000 CE that the Chinese discovered that a steel needle rubbed with one of these magnetic materials would actually become magnetic as well. When allowed to move freely, they discovered that this needle would then always point in the same direction (assuming it was not near another magnetic material) – towards the magnetic north pole of the Earth. This early use of magnetism in the construction of the compass allowed for many discoveries, as humans were now able to navigate and explore the world more effectively in a systematic, efficient manner.

Though the discovery of the phenomenon is centuries old, it is not until much more recent times, however, that we have understood the cause of the magnetic property of materials, and of how the space around these materials is affected by their existence. Interestingly, it was our early examinations of electric current that led to these discoveries. In the early 1800's, it was Hans Oersted who discovered that a compass needle could deflect and point away from the magnetic north pole when near a current-carrying wire. Also, the amount of the deflection could be affected by the amount of current in the wire. This phenomenon could be explained by the idea that the current-carrying wire behaved like a magnetic material, and must affect the space around it in a similar way. Magnetic materials, and devices like the current-carrying wire, cause there to be a magnetic field in the surrounding space, such that if an object sensitive to this field is brought nearby, it may experience a force, or torque.

In exploring magnetic fields created by their sources, we are thus reliant on observing or measuring electric and magnetic properties. A compass needle provides us with an excellent tool for probing and observing the direction of a magnetic field at a certain location in space. We now understand, of course, that a compass will point towards the magnetic north pole because the Earth itself generates a magnetic field. Because the needle always aligns itself in a very particular way, we designate one end of the needle as the "north" end and the other as the "south", based on the alignment of the needle. The end of the magnetic needle that points to the north is called the "north pole" of the needle, and the end that points south is called the "south pole" of the needle. The needle is a magnet with both a north and a south pole. It can be shown however, by using two magnets whose poles we have determined, that opposite poles attract each other. The consequence of this is that what we call Earth's magnetic north pole (because it is in the north) is actually the south pole of a huge magnetic field, and what we call Earth's magnetic south pole (because it is in the south) is actually the north pole of a huge magnetic field!

Figure 1 (http://www.nasa.gov/sites/default/files/thumbnails/image/geomagnetic-field-orig_full.jpg) shows an example of how we might picture the shape of the magnetic field around the Earth, with each of the poles labeled. These field lines and their directions illustrate the direction the north pole of the compass needle would point if it were brought to any of these locations in the space around the Earth. Note how the direction of the magnetic field indicates that the north pole of the compass needle would point away from the magnetic south pole of the Earth in all cases. Also, while images of magnetic field lines like the one below often indicate that the lines seem to start and stop at opposite poles, this is not quite accurate. Magnetic field lines are continuous and do not start and stop at the poles, though it is helpful to imagine this in drawing the lines. In truth, the magnetic field lines shown in the image would pass through the Earth from the north magnetic pole and point directly to the south magnetic pole. Though the investigation of nature continues, we have not yet observed a magnetic monopole (an isolated south or north pole of a magnet).

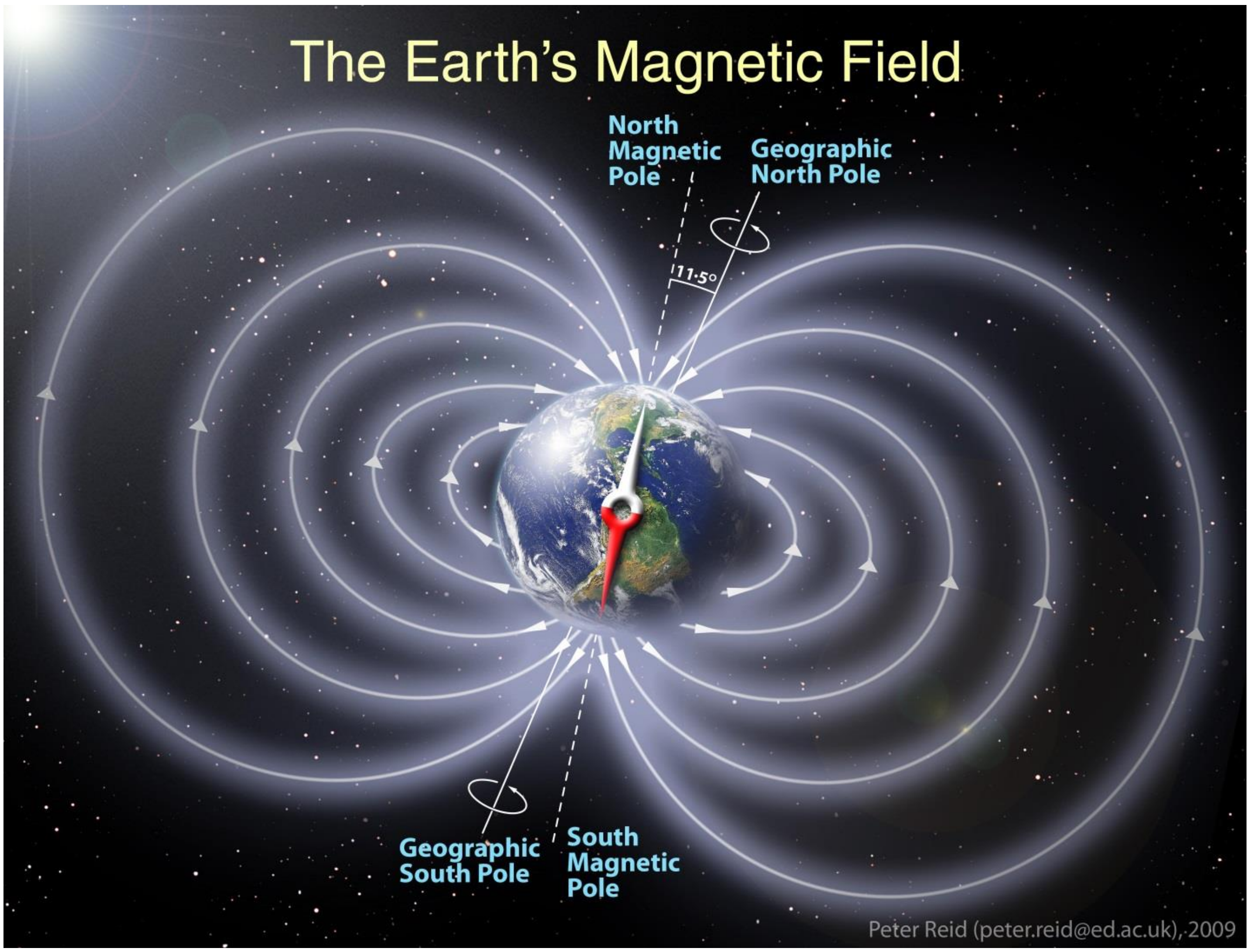

Figure 1

The end result of all this is that we can use a compass needle to sketch the magnetic field caused by a magnetic material or other source, by keeping track of which way the north pole of the needle points at each location. We, of course, will have to consider that we can't just "turn off" Earth's magnetic field when conducting this kind of examination, but as long as the field from the source is strong, we can rely on field directions measured when we are close to the source.

Shortly after the discovery that a current could create a magnetic field in the space around a wire, a curious observer would have been compelled to ask if a magnetic field could create an electric current. As it turns out, the answer is "yes", but with a twist. The existence of a magnetic field by a nearby loop of wire is not sufficient to create a current, but if the magnitude of the field near the wire is changed, or the size of the loop is altered, or if the loop is rotated in the magnetic field, a current will manifest in the wire! These three possible changes that could be made to cause a current in the loop of wire speak to one specific quantity that is changing in each of the cases – the magnetic flux, Φ_B, through the loop of wire. Magnetic flux is a measure of the amount of magnetic field through the loop, considering only the component of magnetic field perpendicular to the area of loop. This certainly seems like a strange quantity, but if you think through the three possible changes identified, we can see how the amount of magnetic flux through the loop could change in each case.

The fact that a changing magnetic flux through a loop of wire causes a current was discovered by Michael Faraday in the mid 1800's (Eq. 1). Recall that when a current flows in a wire we will find that there is a potential difference between different points in the wire. We sometimes describe the flow of current as being due to an *electromotive force* (EMF), which is also measured in units of volts. While the term *force* is used here, we are really describing a voltage that exists in a circuit that is driving the current. Realize that in the case we are discussing, there is no battery present; there is just a magnetic flux changing in a loop of wire. Thus, it wouldn't be correct to talk about some fixed potential difference that is causing current to flow – so we speak of the electromotive force in the wire, symbolized as EMF, or with a script "E" in some cases. Interestingly enough, this EMF manifests in the space near a time changing magnetic flux whether there is a loop there or not! With a loop of wire though, we are able to sample, measure, and observe the effect.

$$\text{EMF} = -N\frac{\Delta\Phi_B}{\Delta t} \qquad \text{(Eq. 1)}$$

The EMF that arises from the changing magnetic flux through a loop of wire can be magnified by including more loops, or turns, of wire, *N*. If we take a wire and loop it around several times, we can then attach a voltmeter to each end of the wire to observe the EMF that is created when the magnetic flux changes. Note that the magnetic flux through the loop could increase or decrease, AND that magnetic field causing the flux could point through the loop in two different directions (because of the behavior of the magnetic field lines). This means that as you bring a magnet near a loop of wire, the orientation matters. It also means that as you move the magnet away from the wire, the orientation matters. In any of these cases, we will observe that the magnetic flux could be increasing or decreasing. This difference would be seen in the direction of the current flow in the loop, or in the polarity of the EMF. When using a voltmeter that can read voltages that change polarity, we would expect to read negative values of voltage in one case and positive values of voltage in the other.

In today's lab there will not be any calculation, but there will be much observation and thought required, as we seek to explore and gain a better understanding of the existence of magnetic fields, and observe Faraday's law in action. By using a 3D compass needle, you will explore the magnetic fields due to a magnetic material (a bar magnet) and several aspects of the magnetic field due to a current-carrying wire. You will then use a voltmeter with a coil of wire to observe Faraday's law in action and attempt to determine the polarity of a small unmarked magnet. Note that many of the observations for this activity are to be recorded in prose. This means you must write out your observations in words, sentences, and paragraphs.

Goals:
(1) Measure and map the magnetic field due to a magnetic material
(2) Measure and map the magnetic field due to an electric current running through several loops of wire
(3) Measure and map the magnetic field due to an electric current through an approximately straight current-carrying wire
(4) Observe Faraday's law in action for a changing magnetic flux through a loop of wire, and confirm the effects of changing the direction of the magnetic field when changing the flux through the loop
(5) Attempt to determine the polarity of an unmarked bar magnet.

Procedure

Equipment – 200-turn loop of wire, 0 – 30 V DC 1 A wall power source, a large bar magnet with marked polarity, a bar magnet with an unmarked polarity, magnaprobe 3D compass, stand and stirrup with mass to weigh down the stand, digital multimeter, 2 wires

1) Use the extra mass object provided to weigh down the base of the stand and hang the stirrup from the top of the stand. Then, place the large bar magnet with the marked polarity into the stirrup so that it hangs freely. You may need to carefully bring the stirrup to rest so that the magnet stops rotating.

2) Carefully remove the 3D compass needle (magnaprobe) from the packaging. You should observe that the probe hangs vertically when far from the other magnets. This is because the mass of the magnet is sufficient that the gravitational force on this probe is greater than the magnetic force it experiences from Earth's magnetic field. This means that when we observe deflections of this probe, we can better rely that the deflections are due to local magnetic fields and that the field lines point along the direction through the probe magnet.

3) Your first task is to determine which end of the probe magnet (red or blue) is the north pole and which end is the south pole. Consider which should be attracted to which pole of the bar magnet and **record** which color is which pole. Realize that when the probe is reacting to a nearby magnetic field we will then be able to draw a small arrow, indicating the direction of the field at that location in space, pointing from the south pole of the probe magnet to the north pole of the probe magnet, along its length.

4) Now, use the probe to determine the direction of the magnetic field in the region around the bar magnet that is hanging in the stirrup. You should **construct** at least two plots, where you use small arrows to indicate the direction of the magnetic field that you observe when you place the probe at locations near the magnet. The minimum two suggested plots are as follows:

A: Look down from above. Note the polarity of the bar magnet and use the probe at the same height of the magnet above the table to observe the field all around the magnet (this will measure the field directions in the horizontal plane, where the magnet resides). You should move the probe to different distances and different locations all around the magnet until you have sufficient recordings that you can start to connect the small arrows and see the trend to draw the magnetic field lines around the bar magnet (in the horizontal plane you are sampling). The viewpoint of the drawing should be indicated by including the bar magnet in your sketch, as shown below.

B: Look at the magnet from the side. Note the polarity of the bar magnet and use the probe at the different heights, directly above and below, the magnet to observe the field all around the magnet (this will measure the field directions in the vertical plane, where the magnet resides). You should move the probe to different distances and different locations all around the magnet until you have sufficient recordings that you can start to connect the small arrows and see the trend to draw the magnetic field lines around the bar magnet (in the vertical plane you are sampling). The viewpoint of the drawing should be indicated by including the bar magnet in your sketch, as shown below.

5) Move the probe around to other places near magnet and observe the direction of the magnetic field in three dimensions. **Record** your observations of the field behavior in prose, detailing any notable features of the field.

Question 1: How does the shape of the magnetic field around the bar magnet compare to that of the magnetic field of the Earth? Explain your answer.

6) Use the large bar magnet to determine the magnetic polarity of the unmarked bar magnet. **Record and explain** the process you used to determine which end is which pole. DO NOT mark the unmarked bar magnet. Once determined, place it off to the side, away from the other magnet and equipment, in such a manner that you can recall which end is which later in the experiment.

7) Connect the 200-turn loop of wire to the 0 – 30 V DC 1 A wall power source by connecting the red port on the wall to one of the white posts on the loop and the black port on the wall to the other white post on the loop. Be sure that the knob on the wall power supply is turned all the way counter clockwise before turning on the power. Then, turn on the wall power supply and adjust the knob until the meter on the wall reads 10 V.

8) Perform step 4 from earlier for the loop of wire now. **Construct** your plots looking down from above at a horizontal plane, and looking from the side at a vertical plane. Also, not that in this case you can follow the field lines right through the loop! Be sure that you use a sketch of the loop in your viewpoint in each case (like we did with the bar magnet.

9) Explore and move the probe around to other places near the coil and observe the direction of the magnetic field in three dimensions. **Record** your observations of the field behavior in prose, detailing any notable features of the field.

Question 2: How is the magnetic field from the current-carrying coil similar to or different from that of the bar magnet? How is the magnetic field from the current-carrying coil similar to or different from the magnetic field of the Earth? Is there a north pole and south pole for the magnetic field due to the current loop? Label which side each pole is on in your field plots. Explain your answers.

10) We can approximate that the wire near the top of the loop is a straight, current-carrying wire, if we measure the field behavior very near it. In this step, we seek to determine the behavior of the field around the wire in this approximation. Use the probe very near the loop at the top of the loop and move it in a circle around the wire at the top. **Record** your observations of the field, and **construct** a single sketch of the magnetic field around the straight wire. You can draw the field by imagining the wire coming out of the page (as if you are looking down the wire), as shown below. Note that the current has been flowing in a particular direction in all of these cases.

11) Now, turn off the wall power supply. Flip the wires at the white posts on the loop of wire only, so that each white post is connected to a different wall port than before. Turn the power supply back on and adjust the knob until the meter on the wall reads 10 V. Note that the current will now flow through the loop in the opposite direction from before.

12) Repeat steps 8-10 for the current-carrying loop. When you are finished with this step, turn the knob on the wall power supply all the way counterclockwise and turn off the wall power supply.

Question 3: How is the magnetic field different now that the current is flowing in the opposite direction? Explain your answer.

Question 4: How is the magnetic field different around the straight-current carrying wire approximation in each case? Considering that each small part of the loop could be thought of as a small current-carrying wire, is there a connection between the magnetic field caused by each small portion of wire and the magnetic field we measure in the center of the loop, for example? Consider the principle of superposition and explain your response.

13) Plug one wire into the “COM” port on the multimeter and another into the “V- - -” port. Connect the free ends of these wires to the two white posts on the loop of wire. Turn the dial on the meter so that it points to “200m” in the section labeled as “V- - -” on the outer edge of the meter. Note that when you are on a setting with a “m”, the meter is reading in thousandths of volts, or millivolts. Also, recall that the meter can read both positive and negative voltages as we create an EMF in the wire loop. This will indicate the current flowing one way or the other.

14) Hold the large bar magnet very still and away from the center of the loop (about 1 ft away should work). Orient the magnet so the north pole points toward the center of the loop. Then, move the magnet towards the loop at a slow, constant speed until it is in the middle of the loop, while observing the meter reading throughout the process. **Record** your observations in prose. Repeat this several times to be sure of your results.

15) Now, repeat step 14 but move the magnet at a faster, constant speed toward the loop. **Record** your observations in prose. Repeat this several times to be sure of your results.

Question 5: Explain the differences you saw when moving the magnet faster versus when it was moved more slowly. Consider Faraday's law in your explanation.

16) Repeat steps 14 and 15 but begin with the south pole of the magnet pointing toward the loop. Note that you should start with the magnet on the same side of the loop as before. Remember to **record** your observations in prose.

Question 6: How are the results different when the south pole was pointing toward the loop versus when the north pole was pointing toward the loop? Consider the shape of the magnetic field around the bar magnet and how it will affect the loop as it is moved towards the loop in both cases. Does the change in magnetic flux explain the differences you see in the orientation of the bar magnet during this part of the experiment? Consider Faraday's law in answering this question.

17) Now, begin again with the magnet on the same initial side of the loop with the north pole pointing toward the loop. Move the magnet at a constant speed through the center of the loop and past it to the other side. you could use both hands, but the loop is really big enough that you can just move the magnet straight through to the other side. **Record** your observations in prose. Repeat this several times to be sure of your results. You may also want to consider starting the magnet in the loop and confirming what happens as it is pulled one way or the other under a given orientation. There is a lot to explore here, so explore! Develop your own set of steps and record what you did, so that you can assess the results.

Question 7: Explain your observations when moving the magnet through the loop to the other side. Does the EMF flip polarity? How would this affect the current that flows due to the EMF? Consider Faraday's law in explaining these observations.

18) Hold magnet still while it is in the middle of the loop and **record** your observations.

Question 8: Is there a current, or EMF generated when the magnet is held motionless in the loop? Why or why not? Explain your answer using Faraday's law.

19) Place the large bar magnet off to the side and get the unmarked bar magnet. Orient what you determined to be the north pole of that magnet so that it points toward the center of the loop and move the magnet at a constant speed toward the loop. **Record** your observations in prose.

Question 9: Do your results for the unmarked magnet confirm that you identified the north pole correctly? Why or why not? Consider your results with the large bar magnet and the loop in answering this question.

As always, be sure to organize your data records for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

There is no Data Analysis for this lab activity.

Error Analysis

There is no Error Analysis for this lab activity, though you should always consider and discuss sources of error as part of your conclusion (per the instruction that is always in the conclusion section).

Questions and Conclusions

Be sure to address Questions 1 through 9 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for “The Magnetic Field and Faraday’s Law,” and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) Consider the discussion of the Earth’s magnetic field and its north magnetic pole. If we imagine the Earth as a big bar magnet, considering the behavior of the magnetic field lines, the north pole of the magnet would be at

A) the Earth’s south magnetic pole.

B) the Earth’s north magnetic pole.

C) the equator.

D) the center of the Earth.

PL-2) A compass needle is a small bar magnet that is used to determine the direction of the magnetic field in a region of space. If you are near a magnetic material and the north pole of the needle points to the right, the direction of the magnetic field in that region of space is actually

A) to the right.

B) to the left.

C) up.

D) down.

PL-3) Javier and Flora are conducting this lab activity and determine that the red side of their 3D compass probe is actually the north pole of the probe magnet and that the blue side is the south pole of the probe magnet. When they bring the probe near the north pole of the bar magnet, the probe magnet should

A) orient itself so that the red side points toward the bar magnet.

B) orient itself so that the blue side points toward the bar magnet.

C) orient itself so that neither side points toward the bar magnet.

D) spin wildly out of control.

PL-4) An EMF and current can be induced in a loop of wire if the magnetic flux through the loop is changing. Which of the following is NOT a means by which the magnetic flux through a loop would change?

A) Increase the magnitude of a magnetic field that has a component perpendicular to the area of the loop.

B) Rotate the loop while it is in a magnet field in such a way that sometimes there is a component of the field perpendicular to the area of the loop.

C) Arrange a magnetic field with a component perpendicular to the area of the loop and wait a really long time.

D) Arrange a magnetic field with a component perpendicular to the area of the loop and increase or decrease the area of the loop.

PL-5) Javier and Flora observe that when they move the south pole of the bar magnet toward the loop, the reading on the voltmeter is negative, whereas when they moved the north end of the bar magnet toward the loop the reading was positive. While this only measures the EMF generated in the loop, this means that the current that is flowing in the loop in each case must be

A) nonexistent because nothing is really happening.

B) in the same direction.

C) zero, because they will cancel each other out.

D) in opposite directions.