Lab 25
Faraday's Law

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Learning Objectives

- Explain electromagnetic induction as expressed in Faraday's Law
- Predict and test how changes in a magnetic field affect an electric field
- Apply Faraday's Law by building a simple motor

Introduction

The discovery that a moving charge or current generated a magnetic field came as a big surprise to scientists. What may have been an even bigger surprise is that the reverse is true. A magnetic field can induce an electric field that can induce a current (moving charge). The relationship between electric current and magnetic field has a wide range of technological applications—from electric motors to electric door locks.

Faraday's Law of Induction

Michael Faraday was the first to observe the relationship between magnetic fields and a generated current. In one of Faraday's basic science experiments he connected a loop of conducting wire to an **ammeter**, a device used to measure electric current on circuits without a battery. Without a battery, there was no current in the wire. However, when a bar magnet was moved toward the loop, there *was* a current reading on the ammeter. As soon as the bar magnet stopped moving toward the loop, the reading returned to zero amps. When the bar magnet was then pulled away from the loop, the current reading on the ammeter came back, but the current was now in the opposite direction. Faraday realized if there is a current in the wire, there must be a voltage somewhere too. From this and a few other simple experiments, Faraday discovered that changing the amount of magnetic field lines passing through a loop induces a voltage in that loop.
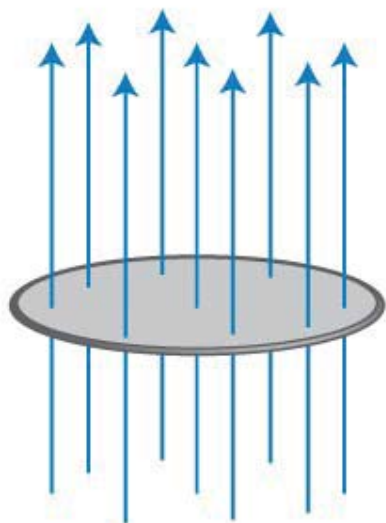

Figure 1: Magnetic field lines (blue arrows) flowing through the area of a loop (gray circle).

In order to apply Faraday's Law, the number of magnetic field lines that pass through a loop need to be calculated. The number of magnetic field lines that pass through an area (in this case, a loop of conducting wire) is called **magnetic flux**. Consider Figure 1 in which a loop is enclosing an area, *A*, and it is in a magnetic field, *B*. The standard measurement for magnetic field is the tesla, T, where $1\text{ T} = 1\text{ kg·s}^{-2}\text{·A}^{-1}$. The magnetic flux, Φ, can be calculated by:

$$\Phi = \int B \cdot dA$$

The unit for magnetic flux is a Weber, Wb, where $1\text{ Wb} = 1\text{ kg·m}^2\text{·s}^{-2}\text{·A}^{-1}$. When the magnetic field is uniform and angled perpendicular to the area of the loop, the equation reduces to:

$$\Phi = BA$$

Remember, it is the *change* in the magnetic flux that induces a voltage in the loop. This voltage has a special name called **induced electromotive force** or **induced emf** (ε). The magnitude of the induced emf in a loop is equal to the rate at which the magnetic flux, $d\Phi$, is changing over time, dt, multiplied by the number of turns or loops in the coil, N. Since induced emf opposes the change in magnetic flux, the rate is expressed as negative:

$$\varepsilon = -N \, \frac{d\Phi}{dt}$$

If the flux changes at a steady rate the induced emf is:

$$\varepsilon = -N \, \frac{d\Phi}{dt} = -N \, \frac{\Delta\Phi}{\Delta t}$$

Magnetic Force

A second **right hand rule** (Figure 2) describes the force on a charged particle moving through a uniform magnetic field that points in one direction. If you point your index finger in the direction of the moving charge with the face of your palm (or middle finger) in the direction of the magnetic field, then your thumb will point in the direction of the force on a positively charged particle (for negative charges, the force is in the opposite direction). If, instead of one charged particle, there is current traveling through a conductor (such as a length of wire), then the same rule relates the directions of the current, the magnetic field and the force on the current-carrying object.
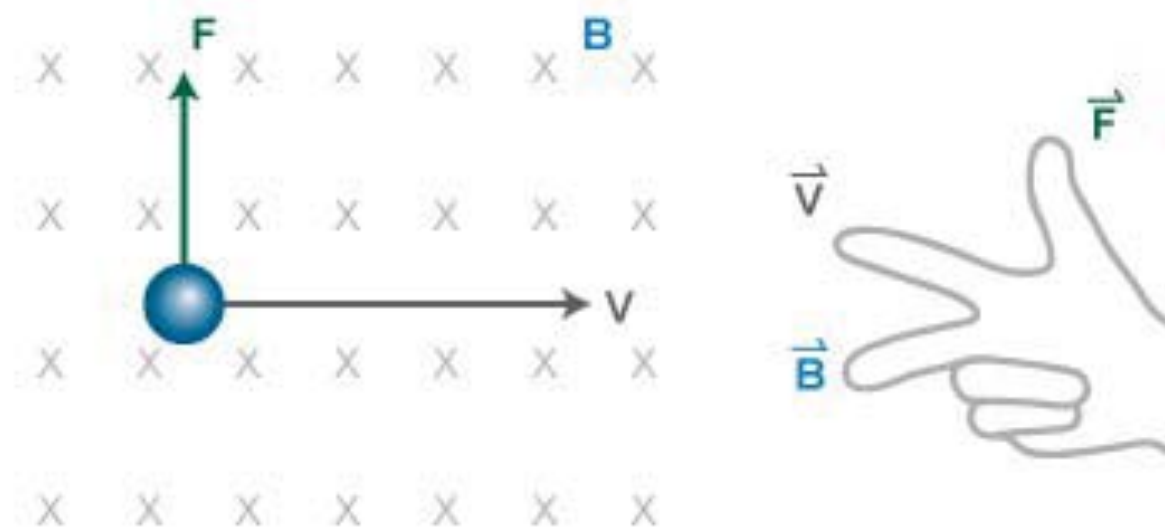

Figure 2: The series of gray X's represent a uniform magnetic field in a direction pointing into the page. Given the direction of the charge as indicated by arrows, the force on the segment of wire is in the upward direction.

In general, the force on a moving charge, *F*, is equal to the product of the magnitude of the moving charge, *q*, its velocity, *v*, and the magnetic field strength in a direction perpendicular to the velocity, *B*:

$$F = qvB$$

The force will point in the direction indicated by the right hand rule for magnetic force. If instead of one moving charge there is an electric current, the force is a product of the current, *I*, flowing through a wire section of length, *L*, and the magnetic field strength direction perpendicular to the current, *B*:

$$F = ILB$$

In cases where the angle between the current and the field is not 90°, only the vertical component of the magnetic field is considered.

Application of Faraday's Law

One of the most useful inventions within the last 150 years is the electric motor (Figure 3), which takes advantage of the relationship between electric current and magnetic field. An **electric motor** consists of a coil of wire (called the *armature*) situated within a magnetic field (created by either permanent magnets or electromagnets). When electric current passes through the coil, the parts of the coil perpendicular to the field experience a force that rotates the armature. If the current is engineered to reverse at just the right moment, the armature will continue to rotate, drive a shaft, and turn electric current into mechanical work.
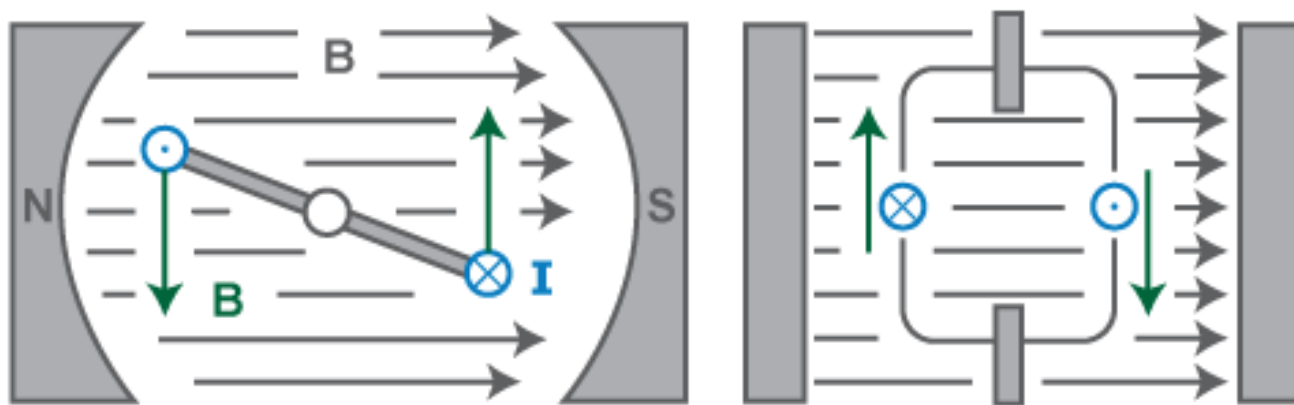

Figure 3: A side view (left) and top view (right) of a motor armature rotating between two magnets (gray). A circle with a cross signifies a direction into the page, and a circle with a dot represents a direction out of the page. When viewed from above with current traveling in the clockwise direction, an upward force is experienced by the right side, and a downward force on the left side. These forces create a torque that turns the armature in a counterclockwise direction (shown in left figure). Once the armature reaches the vertical position the current must be reversed to prevent it from getting stuck.

A **generator** uses similar principles as the motor, but the process is reversed: mechanical work is converted into electrical energy. According to the right hand rule, when a coil of wire is forced to rotate within a magnetic field, a current in the wire will be induced. For example, if you were to manually rotate the armature in Figure 3, a current would be induced in the wires in a direction that would alternate every half turn. For this reason, generators that produce alternating current (AC) are fairly simple to build.

Transformers (Figure 4) convert high voltages to low voltages by utilizing changing magnetic fields and currents. Without a transformer, the circuits in simple home appliances would have to be built to withstand the high voltage electricity that the electric company sends to houses. Transformers are used in almost every electronic device that plugs into a wall socket.

Transformers are also helpful for efficiently transferring electricity over long distance power lines, reducing the amount of power lost due to heat. By increasing the transmission voltage significantly, the drops in current (according to the equation $V = IR$) and power loss ($P = I^2R$) are much less. Unfortunately, the high voltage difference between two wires is very dangerous, as is the voltage drop between a single power line and the ground. This is why power lines are often placed high above or far below ground.
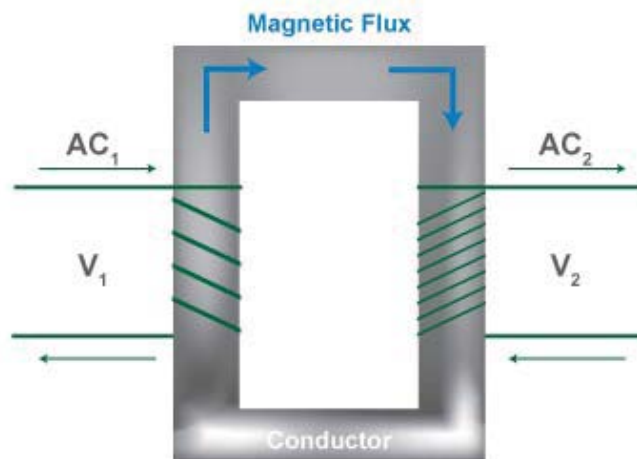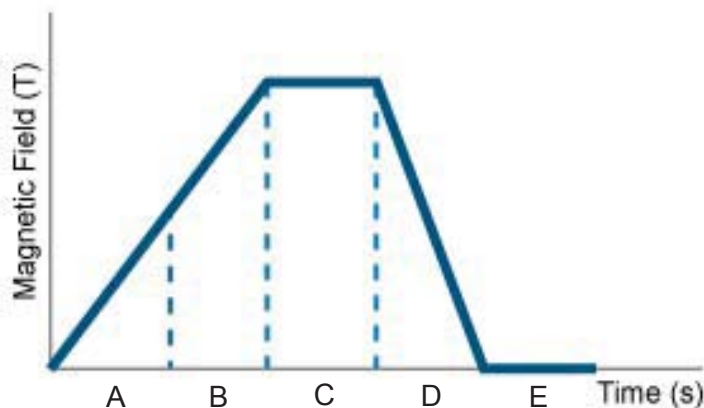
Magnetic Flux

Figure 4: The change in voltage over this simple transformer depends on the number of turns of wire around each side. The total magnetic field flow, called magnetic flux, is the same through each set of coils, but the larger number of turns on the right makes V_2 proportionally larger than V_1. Imagine the wires on the left as coming from the electric company, and those on the right as feeding into long-distance power lines.

Pre-Lab Questions

1. Analyze Graph 1 and rank the change in magnetic flux during Times A, B, C, D, and E from least to greatest. Use an equal sign to designate equal magnetic fluxes.

Graph 1: A magnetic field over time.

2. A MRI technician neglected to remove a metal bracelet from a patient. The bracelet is 7.0 cm in diameter. If the magnetic field is oriented from the patient's foot to head, the area of the bracelet will be perpendicular to the magnetic field. During the scan, the magnetic field increases from 0 T to 1 T in 1.5 seconds. What is the magnitude of the induced emf in the bracelet? Show your work.

3. A wire loop is being pulled out of a uniform magnetic field directed into the page at constant speed, v (Figure 5). Draw the direction of the force on the wire due to the magnetic field if the current in the loop is going in the clockwise direction.
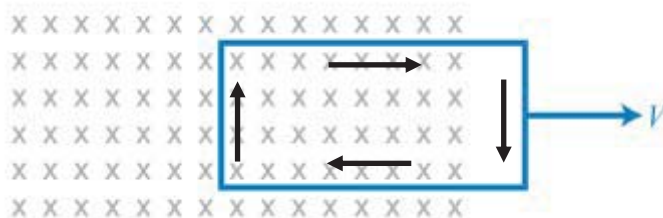

Figure 5: A wire loop (light blue frame) with a clockwise current (black arrows) pulled out of a uniform magnetic field (gray X's). Current is represented by black arrows.

4. Figure 6 shows a conductor moving in a uniform magnetic field. Show that when the conductor moves in the magnetic field, the magnetic force induces an electric field in the conductor by drawing what occurs inside of the conductor. Explain your drawing.

   Hint: Think about the magnetic force on the charges inside the conductor.
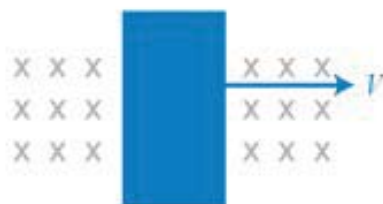

Figure 6: A conductor (light blue rectangle) moving through a magnetic field (gray X's).

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Experiment 1: Faraday's Law

In this experiment, you will predict and test how changing a magnetic field will affect an electric field.

⚗ Materials

2 Alligator Clips	Ruler
4 Ceramic Ring Magnets	Scissors
90 cm Insulated Copper Wire	10 mL Sealable Syringe with Cap
Digital Multimeter	Tape Measure

Procedure

1. Use the tape measure and scissors to measure and cut a length of wire approximately 90 cm long.

2. Wrap the wire around the syringe making a coil of 15 turns around the body of the syringe. Leave a length of excess wire on each end of the coil (Figure 7).

Figure 7: Step 2 reference.

3. Slide the coil off the body of the syringe and secure it by wrapping the excess wire on each end around opposite sides of the ring (Figure 8).

4. Use a ruler and scissors to measure and cut the excess wire so that 4 cm tails remain on both sides on the coil.
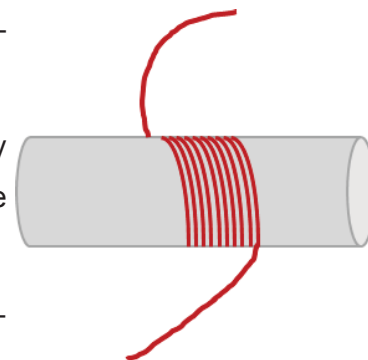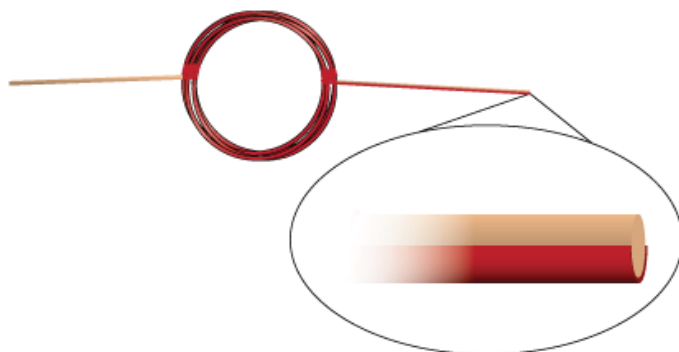

Figure 8: Reference for Steps 3 and 6. The image in the black circle shows a close up of the right tail of the wire coil with the insulation scraped off of <u>one side</u>. The left tail shows all of the insulation scraped off of the tail.

5. Hold the coils vertically and rest one tail on a flat surface.

    Note: The surface may get scratched. Use your kit lid if a scratch resistant surface is not available.

6. Use scissors to scrape **one side** of the insulation off the entire length of one tail, and **all the insulation** off the entire length of the other tail (Figure 8). This is important for connecting to the multimeter in this experiment and for Experiment 2 (if assigned).

    LAB SAFETY: Use caution when scraping the wire with scissors. Always scrape the scissor blade away from the body. Never hold the scissors by the blade.

7. Prepare the digital multimeter by inserting the black cord in the "COM" port and the red cord in the "VΩmA" port.

8. Turn on the digital multimeter and turn the dial to the "200µ" in the "DCA" section.

9. Lay the wire coil flat on a surface.

10. Use one of the alligator clips to connect the red probe of the multimeter to the right tail of the coil (half exposed wire) and a second alligator clip to connect the black probe of the multimeter to the left tail of the coil (fully exposed wire).

11. Connect four ring magnets together to make a cylindrical bar magnet.

12. Rest the bar magnet centered and on top of the coil.

13. Slowly lift the magnet vertically up and away from the coil. Record the maximum current reading on the multimeter in Table 1. If the value is negative, include the negative sign.

14. Repeat Step 13 at a medium speed relative to the slow speed in Step 13.

15. Repeat Step 13 at a fast speed relative to the medium speed in Step 14.

16. Make and record a prediction in Table 2 for what will happen if you repeat Step 13, but instead of moving the magnet away from the coil, start the bar magnet *away* from the coil and move it at different speeds *towards* the coil.

17. Use a ruler to measure and hold the magnet at least 30 cm away from the coil. Then, move it vertically down towards the coil at a slow speed. Record the maximum current reading in Table 2.

18. Repeat Step 17 at medium and fast speeds.

19. Make and record a prediction in Table 3 for what will happen if you used a different number of ring magnets, such as one instead of four.

20. Rest one ring magnet centered and on top of the coil.

21. Lift the magnet vertically up and away from the coil at a medium speed. Record the maximum current reading in Table 3.

22. Repeat Step 20 - 21 for 2, 3, and 4, magnets attracted together. To increase the validity of this part of the experiment, try to lift the magnet combinations at the same speed.

23. If you are completing Experiment 2, keep the coiled wire.

Table 1: Speed of Magnet vs. Current when Motion is Away from Coil	
Speed of Motion of Magnet (qualitative)	Maximum Current Reading (µA)
Slow	
Medium	
Fast	

Table 2: Speed of Magnet vs. Current when Motion is Toward Coil	
Prediction:	
Speed of Motion of Magnet (qualitative)	Maximum Current Reading (µA)
Slow	
Medium	
Fast	

Table 3: Number of Magnets vs. Current when Motion is Away Coil	
Prediction:	
Number of Magnets	Maximum Current Reading (µA)
1	
2	
3	
4	

Post-Lab Questions

1. Explain the rationale you used to construct your predictions in Tables 2 and 3. Did your predictions match your results?

2. Do your results support Faraday's Law? Use your results to explain your answer.

3. What do you predict will happen to the maximum current if you used the same magnet, moving at the same speed, but increased the radius of the loop?

4. What do you predict will happen if you used the same magnet, moving at the same speed, but through a coil with less loops?

5. Estimate the change in flux for one of your results in Table 1.
    <u>Note</u>: Resistance of a wire is equal to $\rho L / A$ and the resistivity of copper is 1.68×10^{-8} Ωm.

Experiment 2: Building a Simple Electric Motor

In this experiment, you will create a simple electric DC motor to demonstrate the relationship between current and magnetic fields. This motor will use magnetic force to propel through one half rotation and use only inertia to rotate the other half. When constructed carefully, this simple motor will reach high speeds using only a small alkaline battery.

⚗ Materials

2 Alligator Clips	*Scissors
9V Battery	*10 mL Sealable Syringe with Cap
*Insulated Copper Wire	*Cardboard (Kit Lid or Divider Inserts in Kit)
2 Large Paper Clips	
Masking Tape	*You Must Provide
3 Ceramic Ring Magnets	*Needed to make wire coil. If Experiment 1 was completed, then these materials are not necessary.
Ruler	

Procedure

Creating the Wire Coil

1. If you made a wire coil in Experiment 1 proceed to the next section. If not, follow the procedure below to create the wire coil before moving on to the next section.

2. Use the tape measure and scissors to measure and cut a length of wire approximately 90 cm long.

3. Wrap the wire around the syringe making a coil of roughly 15 turns around the body of the syringe. Leave a length of excess wire on each end of the coil (Figure 9).

Figure 9: Step 3 reference.

4. Secure the coil by wrapping the excess wire on each end around opposite sides of the coil (Figure 10).

5. Use a ruler and scissors to measure and cut the excess wire so that 4 cm tails remain both sides on the ring.

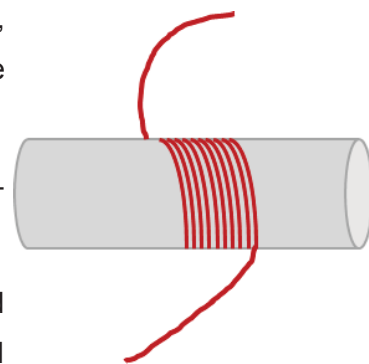6. Hold the coils vertically and rest one tail on a flat surface.

Note: The surface may get scratched. Use your kit lid as a surface if a scratch resistant surface is not available.

7. Use scissors to scrape **one side** of the insulation off the entire length of one tail, and **all the insulation** off the entire length of the other tail (Figure 10).

   LAB SAFETY: Use caution when scraping the wire with scissors. Always scrape the scissor blade away from the body. Never hold the scissors by the blade.
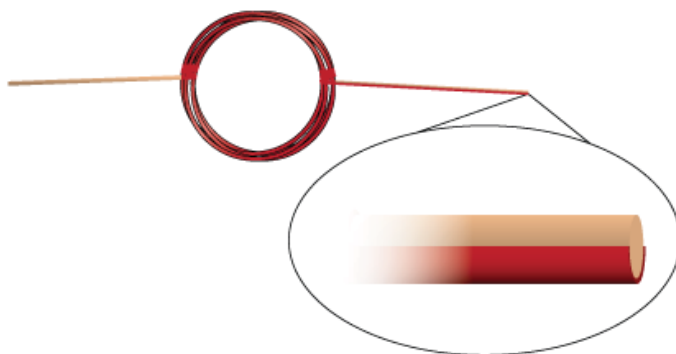

Figure 10: Reference for Steps 4 and 7. The image in the black circle shows a close up of the right tail of the wire coil with the insulation scraped off of <u>one side</u>. The left tail shows all of the insulation scraped off of the tail.

Creating the DC Motor

8. Remold a paper clip into an "M" shaped support so that it has a round slot to support a tail of the coil. Refer to Figure 11 for an infographic.

   Note: The legs of the support don't have to be an exact measurement, but try to have both legs end at the same position as indicated by the blue, dashed line in Figure 11. You will need a minimum clearance of 3 cm under the tail rest as indicated by the red, dashed line in Figure 11.

9. Repeat Step 8 with a second paper clip with the goal of making the supports as similar in size as possible.

10. Use masking tape to tape the paperclips to a piece of card board so that they stand 5 cm apart, vertically to the cardboard surface, and parallel to each other (Figure 12).
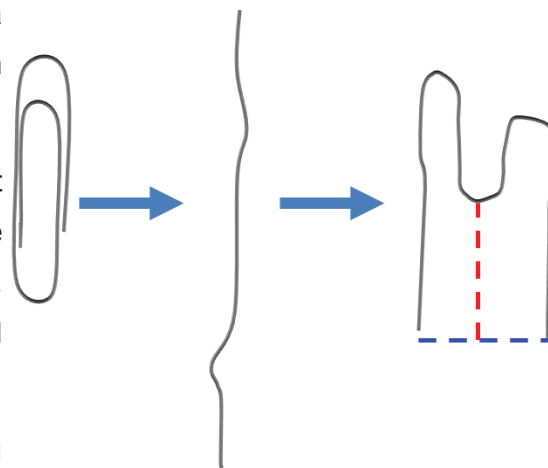

Figure 11: Uncoil a paper clip into a linear piece. Then, bend the paper clip into an "M" shape.

11. Suspend the wire coil between the paper clip support by placing the tails of the coil in the paper clip supports (Figure 12).

12. Place three ring magnets under the coil. Making sure the coil does not touch the magnets when positioned vertically (Figure 12).
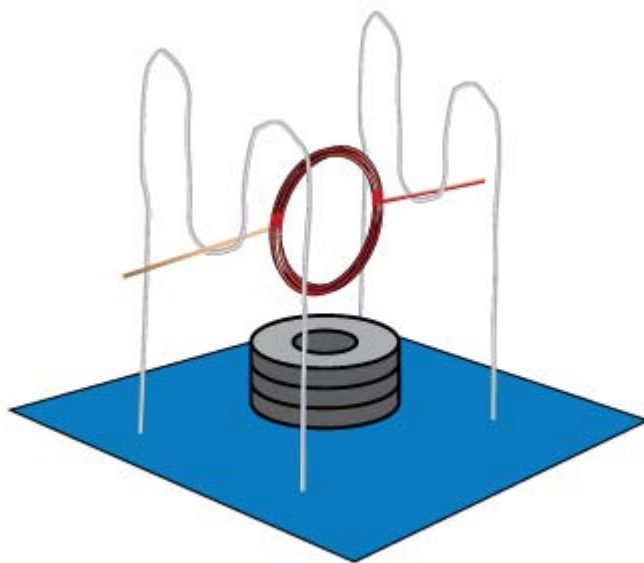

Figure 12: Motor design. Reference for Steps 10 - 12.

13. Use one alligator clip to connect the positive side of the 9V battery to one of the paperclips and the other alligator clip to connect the negative side of the 9V battery to the other paper clip.

14. Give the coil a nudge in one direction and it should start a constant spin. You have created a simple motor.

> Troubleshooting: If the motor does not spin right away, check all of your connections and try making slight adjustments to the position of the magnet. Ensure enough of the insulation has been scraped off of the tails. When the coil rests in a vertical position on one side, the exposed wire on the tails should touch the paper clips.

Post-Lab Questions

1. What orientation of the coil (vertical or horizontal) allows current to flow through the assembly? What happens as you rotate the coil 180º from this position? Explain your answer.

2. Explain what would happen if both tails of the wire coil had all of the insulation scraped off.

3. Analyze the motor design and list three variables in the experiment that if changed will increase or decrease the speed at which the coil rotates. Explain your reasoning.

4. Given the strength of the battery and the size of the coil, there are an ideal number of coil turns that make a motor spin at high speeds without being unstable. Critique a motor design constructed with a coil of 50 coils of wire instead of 15 coils. Use your results to support your critique.