Lab 12

Motors and Generators

Continuing Objectives

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

10. Be able to work with physical vector quantities.

Introduction

Electricity and magnetism are responsible for nearly every interaction that occurs at the macroscopic scale. All the forces normally collected together as “contact” forces (tension, normal, friction, etc.) are actually a result of electric interactions. We’ll see during the course of the semester how deeply electricity and magnetism are related, how electricity can be used to create magnetism and vice versa. In today’s lab, we’ll explore some extremely practical and important consequences of the connection between electricity and magnetism.

During the first part of this lab, you will see how the interaction of a current-carrying conducting element with a magnetic field results in a force acting on that element. You will gain further experience using the right hand rule to determine the direction of the force on a current in a magnetic field. You will build a working electric motor, which is a device that uses the magnetic force acting on a current element to convert electrical energy into mechanical energy.

Next, you will create different forms of an electric generator. You will move a conductor in a magnetic field and generate an electrical potential difference. You will also observe that electricity can be generated when the magnetic field inside a conductor changes. You will use a generator to convert mechanical energy into electrical energy, causing a light emitting diode (LED) to light up. You will study all of the various phenomena you see in this lab during this semester.

Part I: Motors

Theory

Consider current moving through a conductor. If this current-carrying conductor is in a magnetic field, the field exerts a force on the conductor. The equation for the magnetic force $\vec{F}$ on a length $\vec{L}$ of a conductor carrying current I in a magnetic field $\vec{B}$ is

$$\vec{F} = I\vec{L} \times \vec{B}. \tag{12.1}$$

The direction of the vector $\vec{L}$ is given by the direction of the current moving through the conductor. The magnitude of this force is

$$F = |\vec{F}| = I|\vec{L}|\,|\vec{B}|\sin\theta = I\,L\,B\sin\theta, \tag{12.2}$$

where θ is the angle between $\vec{L}$ and $\vec{B}$. To determine the direction of the force $\vec{F}$, which is a cross product, use the following two steps.
Step 1: To narrow down the direction of $\vec{F}$ to two possible directions, find the place in which the two vectors of the cross product, $\vec{L}$ and $\vec{B}$ lie. The direction of the cross product, $\vec{F}$, is perpendicular to this plane.
Step 2: To break the tie between the two possible directions, use the **right hand rule**: point your right arm in the direction of the current and curl your fingers in the direction of the magnetic field; whichever direction your thumb points in is the direction of the force.

The magnetic field from bar magnets

In this experiment, the magnetic field will be provided by the cylindrical bar magnets at your station. Note that near the North pole of a bar magnet, the magnetic field points away from the magnet, and that near the South pole of a bar magnet, the magnetic field points toward the magnet. **Note that the batteries, compasses, safety pins, and alligator clip leads used in this lab will all respond strongly to these magnets.**

1. It turns out to be fairly straightforward to determine the polarity of the cylindrical bar magnets. Simply use the fact that like poles of a magnet repel, and opposite poles attract. Try it with your two bar magnets: you should find that when you bring the two taped ends together, they will (strongly!) repel. If you bring the taped side near the side without the tape, you will observe a strong attraction. At this point, we still do not know if the end with the tape or the end without tape is the North pole end or the South pole end.

2. Take out your compass, and put it on your table (make sure there are no other magnets nearby). **Whichever end of the needle is pointing towards the back corner of the room should be the North pole end of the little bar magnet in the compass (for some compasses it's the red end, for other compasses it's the white end)**. If that's the North pole end of your compass, isn't it attracted to the South pole end of the Earth? It is! The magnetic South pole of the Earth is actually near the *geographic* North pole!
3. Now bring one of your bar magnets near the compass, and watch the needle deflect. Confirm that the end with tape is the North pole.

Deflection of current-carrying conductor in a magnetic field

1. To observe the force acting on a current-carrying conductor in a magnetic field, we'll need to suspend a wire so that it can move freely. To do this, you need to make a stand to hold the wire. We'll use this stand for various parts of this lab. Follow the *Instructions for Making a Stand* located at your bench.
2. From the front of the room, obtain a bare metal wire approximately 6 inches long. Verify that this bare metal wire by itself is not magnetic. Use the template at your station and the board with pins to bend the bare metal wire into the shape shown in Figure 12.1. Next, place the wire into one of your stands as shown in Figure 12.1. The wire should swing back and forth freely; if it doesn't, gently bend it so that it does.

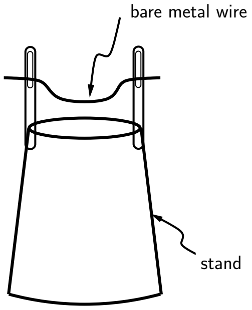


Figure 12.1: Bare metal wire should swing back and forth freely in stand.

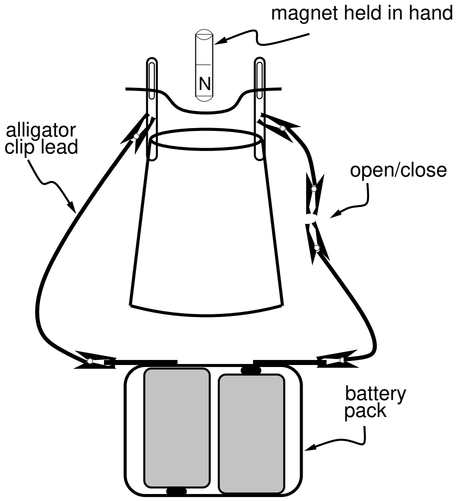


Figure 12.2: Testing deflection of a current-carrying wire.

3. Construct the set-up shown in Figure 12.2 but *do not close the circuit yet.* If

you were to complete the circuit shown in Figure 12.2, would current flow to the right or to the left in the bare metal wire? Note that current flows in the wire from the positive side of the battery towards the negative side. Now, consider *your* set-up. If you were to complete the circuit (*it shoudl still not be closed yet)*, what direction would current flow through the wire?

WARNING: In this and later parts of this lab, you will essentially be connecting one end of your battery directly to the other end. This will both quickly drain your battery and cause various elements to heat up! Make sure that you don't leave these circuits connected for too long a time.

4. First, make a prediction: If you hold your cylindrical bar magnet close to the bare metal wire, with the North pole side down (as shown in Figure 12.2), what direction will the magnetic field point in the region of the bare metal wire? Use the direction of the current, the direction of the magnetic field, and the right hand rule to **predict** the direction of the magnetic force acting on the wire. Explain your reasoning and write down your prediction.

STOP

Discuss your predictions and show your experimental set-up to your instructor or TA.

5. Test your prediction. Hold a cylindrical bar magnet, North pole end down, as shown in Figure 12.2. Bring the magnet as close to the bare metal wire as you can while still allowing the metal wire to swing freely. Make sure the hanging bare metal wire is essentially at rest, and then briefly complete the circuit (it may help if one partner holds the magnet while the other completes the circuit). Does the direction of the wire's initial deflection match your prediction from before? (If the wire doesn't move, it is possible that the wire isn't making good electrical contact with the safety pins. Adjust the position of the wire a little bit, while still allowing it to swing freely.)

A Simple Motor

Current-carrying wires feel a magnetic force in a magnetic field. If the wire is bent into a loop, then the loop will also feel a net torque due to the magnetic field which might cause the loop to rotate. You will convince yourself in the next section "Analysis of a Simple Motor," that the loop will rotate continuously only if you apply an additional trick. We will use the trick of turning off the current at the right moment. Now let's build a simple motor, where electrical energy is transformed into the mechanical energy of a rotating loop.

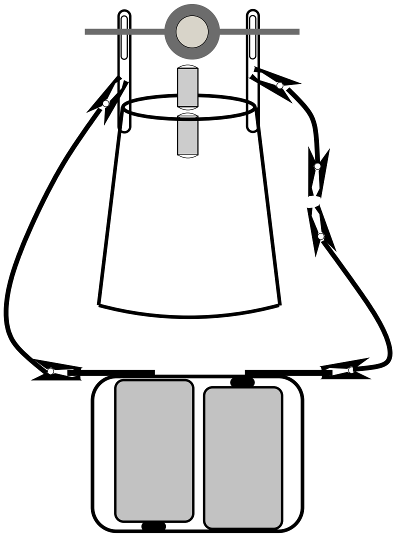


Figure 12.3: Simple motor.

1. How do we get a loop where the current turns off for part of the cycle? Please follow the *Instructions for Obtaining a Coil* located at your bench.

2. Construct the setup shown in Figure 12.3. One magnet should be on top of your stand, and the other magnet should be inside the stand so that they attract each other through the cup surface; center the magnets in the middle of the stand. Mount your coil in the stand. Make sure the coil spins freely, and that it doesn't bump the magnet. You can adjust the axles for smoother spinning.

3. You're ready to go! Connect the circuit allowing current to flow. You may need to give the coil a gentle push to get it started. What do you notice? If you don't see much happening, check your electrical connections (your coil might need resanding, your alligator clips might have come loose, etc.).

   Your coil might be unbalanced and attempt to rotate off the holders. You can prevent this by bending the axle at a gentle angle on the other side of the loop from the coil.

4. Stop the coil from spinning, and try to get it to spin in the opposite direction by giving it a push in that direction. What do you notice? What do you need to do in order to get the coil to spin in the opposite direction?

STOP

Show your motor to your instructor or TA, and discuss what you needed to do to get your motor to spin in the opposite direction.

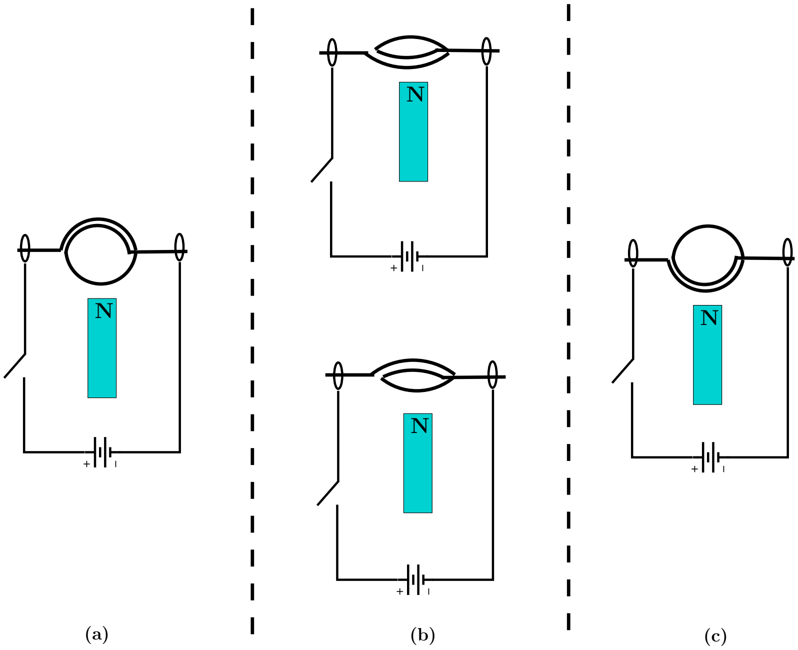


Figure 12.4: Motor analysis. The diagrams in (a) and (c) show the coil with the center facing in and out of the page, and the diagrams in (b) show the coil with the center facing up and down (aligned with the magnet).

Analysis of a Simple Motor

The motor you just made can be analyzed in terms of the torque acting on the loop. Recall that torque $\vec{\tau}$ is given by

$$\vec{\tau} = \vec{r} \times \vec{F}, \tag{12.3}$$

where $\vec{r}$ is the vector from some arbitrary reference point to the point where the force is applied. For the coil, you could sum up all the torques acting on all parts of the coil. An alternative approach is to model the coil itself as a little bar magnet (any current carrying loop can be modeled as a bar magnet) with magnetic moment $\vec{\mu}$, where the direction of $\vec{\mu}$ is determined by a right hand rule: curl your fingers in the direction of the current, and your thumb points in the direction of $\vec{\mu}$. The torque on a magnetic moment $\vec{\mu}$ in a magnetic field $\vec{B}$ is given by

$$\vec{\tau} = \vec{\mu} \times \vec{B}. \tag{12.4}$$

1. Consider the simplified schematic drawings of a battery, switch, and coil, along with a bar magnet, as shown in Figure 12.4. Please take a copy of Figure 12.4 and paste it into your notebook. With the magnet positioned as indicated in the figure, what is the general direction of the magnetic field due to the bar magnet at the location of the coil?

2. Consider the situation shown in Figure 12.4a. When you connect the switch:
   - Will the current in the coil flow clockwise, counterclockwise, or will no current flow in the circuit? Indicate the direction of I on Figure 12.4a.
   - For the orientation shown in Figure 12.4a, when the switch is connected: What is the direction of the magnetic moment μ? What is the direction of the torque $\vec{\tau}$ acting on the coil? Indicate in Figure 12.4a $\vec{B}$, $\vec{\mu}$, and the torque $\vec{\tau}$ on the coil. If there is no net torque, indicate that.
   - If the coil is initially at rest when the switch is connected, indicate in Figure 12.4a the force on the top and bottom parts of the coil and describe the motion of the coil.
3. Consider the situations shown in Figure 12.4b, where the coil is oriented in the horizontal plane. Answer the same questions as in 2 above for each of the situations.
4. Consider the situation shown in Figure 12.4c. Answer the same questions as in 2 above.
5. Sanding the motor coil as you did ensures that current only flows in the system for part of a cycle. Explain using your results above why you want to interrupt the flow for part of the cycle.

STOP

Discuss your analysis of a simple motor with your instructor or TA.

Part II: Generators

Theory

You have seen how a magnetic field exerts a force on a current that causes a conductor to move. This converted electrical potential energy into mechanical energy. This process can be reversed: moving a conductor in a magnetic field will create a potential difference and possibly drive a current through the conductor. Additionally, it turns out that changing a magnetic field in the region of a conductor will also generate electric fields and a potential difference in the conductor. Here you will observe both of these effects.

Moving the conductor

Use the big coil made of red wire at your lab bench. Using the banana plug leads, connect the coil to the galvanometer at your station. The galvanometer has an indicator needle whose deflection is proportional to the potential difference so that it acts as an analog voltmeter. Remove the motor coil from your stand, but leave the magnets. See Figure 12.5.

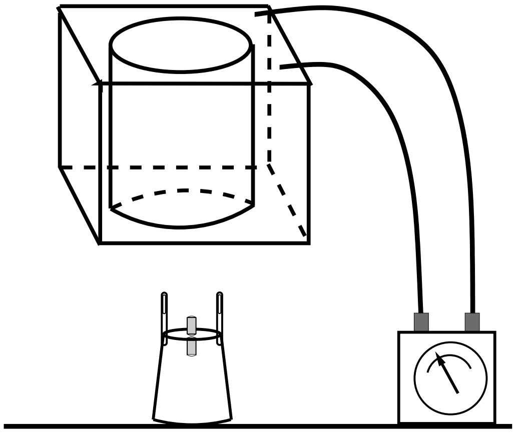


Figure 12.5: Moving the coil in a magnetic field.

1. Next, hold the big coil above the magnets (Figure 12.5), and steadily move the coil directly towards the magnets (keep the axis of the coil aligned with the axis of the magnets). While the coil is moving, observe the galvanometer. Does the needle move? In what direction does it deflect? Repeat, but this time steadily move the coil directly away from the magnets. In what direction does the needle deflect this time? Write down your observations about moving a conductor in a magnetic field.

Changing the magnetic field

Explore the effects of a changing magnetic field in a conductor. You will change the magnetic field by moving the magnet.

1. Place the big coil on the table; keep it connected to the galvanometer. Move your magnet steadily towards the stationary coil, again keeping the axis of the magnet aligned with the axis of the coil. Record your observations about the galvanometer needle. Repeat, but this time move your magnet steadily **away** from the stationary coil. What do you observe on the galvanometer? What happens if you move the magnet faster?

A simple generator

You saw in the previous part that moving a magnet near a conductor induced a potential difference in that conductor. A potential difference in a conductor can drive a current if the conductor is part of a complete circuit. We can increase the induced potential if we increase the speed with which we move the magnet. We'll do that by spinning the magnet around very quickly.

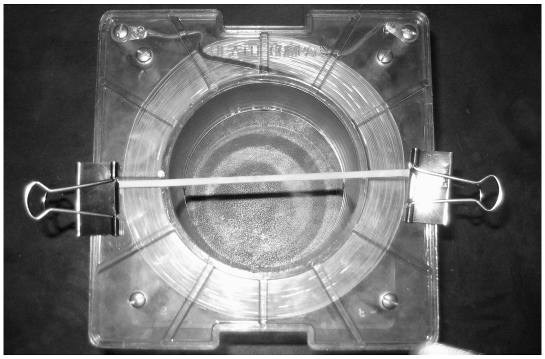


Figure 12.6: Rubber band attached to big coil.

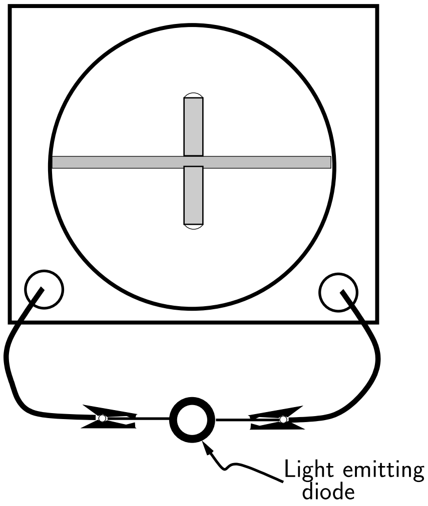


Figure 12.7: Simple generator. Magnets squeeze rubber band between them; coil is hooked up to a light emitting diode (LED).

1. Take a length of rubber band and two binder clips from your lab bench. Stretch the rubber band along a diameter of your big coil, and use the binder clips to secure it in place (see Figure 12.6).
2. Set things up as shown in Figure 12.7. Two magnets should be placed together so that they pinch the rubber band between them. Take a light emitting diode (LED) from your bench and hook it to your coil as shown. Make sure the alligator clips are not touching each other. Twist the magnets about the band multiple times, which should wind up the rubber band as well. **Be careful about winding too much — if the magnets spin too fast they'll come flying apart!** Now, release the magnets and watch the LED. What do you see?

You've just made a simple generator! You've turned mechanical energy into electrical potential energy. In many ways, this is how most of the electricity that you use every day is made (some differences may be that the coil is rotated instead of the magnet, that electromagnets are used instead of bar magnets, and that there *probably* aren't any rubber bands involved).

Part III: More Magnet Marvels!

Another generator?

1. One person in your group should hold the plastic tube vertically in one hand. The other person should hold the copper tube vertically. Use a bar magnet to verify that neither the plastic tube nor the copper tube is magnetic. To avoid breaking the magnet, **do not drop the magnet on the floor**. Each of you should drop your magnet down the tube you are holding. Catch the magnet with your hand at the bottom end of the tube. To make it more interesting, release them at the same time. Have a race! See which magnet reaches the bottom of the tube faster. What do you observe? Does it make a difference which pole of the magnet is facing down? Record your observations.

2. What is going on here? Explain your observations in terms of physics principles you have learned in class or observed today.

STOP

Discuss your observations and explanation with your instructor or TA.

The world's simplest motor?

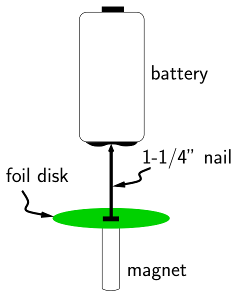


Figure 12.8: Battery, nail, foil, and magnet combination.

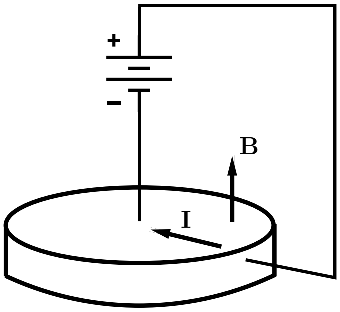


Figure 12.9: Schematic representation of “simplest” motor.

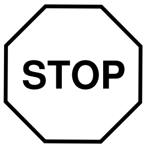
1. Cut out a disk of aluminum foil at the front table. Put the items shown in Figure 12.8 together, holding the arrangement up in the air. The cylindrical magnet turns the nail into a magnet temporarily and the nail can then hang suspended from the bottom of the battery. The aluminum foil disk is just there for visual enhancement.

2. Next, use the non-magnetic insulated wire (ends stripped) to connect the top

(positive) end of the battery to the *side* of the magnet. What do you observe when you complete the circuit?

This can be explained by applying Eq. (12.1) which relates the magnetic force on a current-carrying conductor to the direction of the current and the magnetic field. Consider a schematic representation of the motor you just created (Figure 12.9). This magnet is also a conductor, so current goes from the outside edge in towards the center. Here, the magnetic field points axially along the magnet.

3. With the given directions of current and magnetic field, what is the direction of the magnetic force acting on the cylinder? What would happen if the South pole were up instead of the North pole? Try it and see.



Share your analysis of the generator and motor discussed in this section with your instructor or TA.

4. **Write a conclusion** for this lab.

Please return the borrowed sample coil to the front table where you obtained it. The stand, bare bent metal wire, and simple motor coil that you made are yours to take.