Section 12

How Are Electromagnetic Fields Produced? How do They Drive Transformer Operation and Transport Energy?

INTRODUCTION

In this section you will investigate the properties of electromagnetic fields and their applications.

<u>INVESTIGATION ONE: HOW CAN A BATTERY AND A WIRE ACTIVATE A DISTANT RADIO?</u>

12.1 Activity: Using a battery-and-wire circuit as a radio transmitter

Connect a wire to one terminal of a 2-cell battery. Place your radio receiver an arm's length away, as shown in Figure 12.1a, and tune it to a quiet spot at the low frequency end of the AM band.

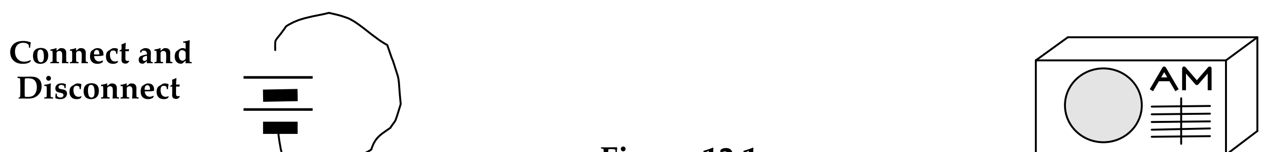


Figure 12.1a

Now connect the free end of the wire to the other terminal of the battery, and maintain the connection for a few seconds (count slowly 1-2-3). Then disconnect the wire for several seconds. Repeat this cycle several times.

1. With a partner, discuss the motion of charge in the battery-and-wire circuit
   (a) before the connection is made,
   (b) when the connection is made,
   (c) during the time the wire connection is maintained,
   (d) when the wire is disconnected, and
   (e) after the wire is kept disconnected.

2. Describe the motion of charge in the circuit when the radio 'pops' and when the radio is silent.

3. What must charge in the circuit be doing to make the radio 'pop'?

4. When you listen to music on a radio, you hear more or less continual sound. Based on what you have just learned, what must charge be doing in the radio station's antenna wire during the time you are hearing music?

5. What is happening during the moments of silence?

6. Refer to Figure 12.1b below. Make and break the circuit. What do you observe? What do you think is happening that causes a sound from the radio?

Observations:

Explanation:

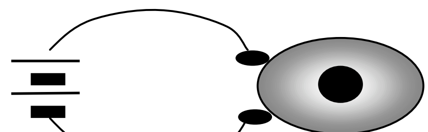


Figure 12.1b

12.2 Activity: Identifying the active agent in radio signals

1. Radio signals that activate a radio can also make a bi-color Light Emitting Diode (LED) glow. To find out what an LED does, connect the LED across a two-cell battery and note which side of the LED base is flat. Record the color of the LED and the direction conventional charge flows through the LED in relation to the flat side. Reverse the LED's connections to the battery. What information does the LED reversal give you?

2. Take one of the D-cells out of the battery and repeat the same activity. What do you now know about what it takes to make the LED glow?

3. To further investigate how this LED operates in a circuit, set up the circuit in Figure 12.2a below so the flat part of the LED faces upward. The resistance of the resistor should be at least 2 ohms, but the most convenient size for single resistors is usually 10 ohms. Close the circuit and record what you observe.

Observations:

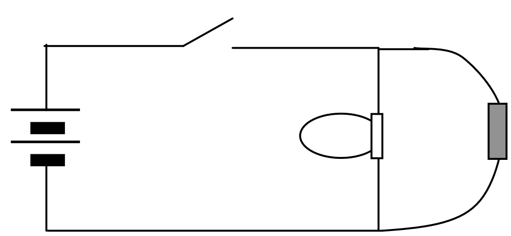


Figure 12.2a

Next, replace the resistor with 5 wires in series – and again make the flat side of the LED face upward. Also add a third D-cell to the battery pack. Connect and then quickly disconnect the battery pack. The resistance of the circuit is very low and the large current (confirmed by a compass under a wire) will damage the D-cells.

4. Record what you observe. Make the room lighting as dim as possible to make it possible to see any faint lighting of the LED.

Observations:

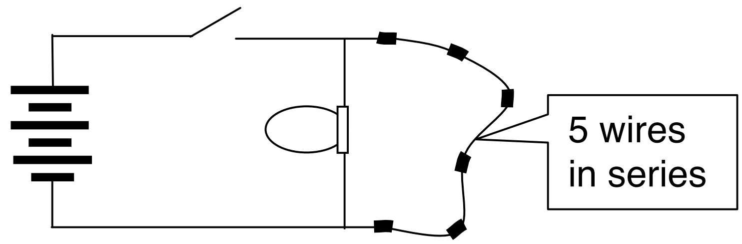


Figure 12.2b

5. Replace the five wires with a cylindrical inner coil and remove one of the D-cells from the battery pack. This inner coil has approximately the same resistance as the five wires in series. Again connect and disconnect the circuit and record your observations. How is the lighting different from the 5-wire circuit?

Observations:

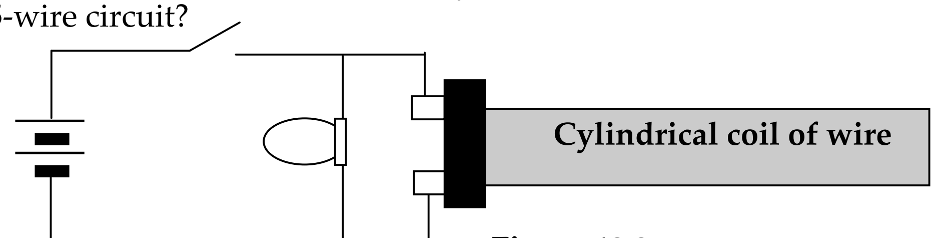


Figure 12.2c

6. Both the inner coil and the 5 wires have approximately the same resistance, but the inner coil has longer wire and lots of turns. We can't change the length of the five-wire loop without changing the resistance, but we could make it into a small coil with many turns. Can the number of turns make a difference in the brightness of the LED glow? To find out, wrap the 5 wires around a cardboard cylinder like the ones inside a paper towel roll and repeat the activity (#4 above). What do you observe and what do you conclude?

Observation:

Conclusions:

12.3 Activity: Using radio signals to produce light

The glowing LED has given us evidence that a transient electric field is produced in the inner coil when charge in the coil wire is accelerating – speeding up or slowing down. In Activity 12.1, we heard the radio sounding off when charge in a distant wire accelerates. Is an electric field produced by this accelerating charge the causal agent that causes sound from the radio? For that to be the case, the field would have to (a) <u>move out</u> of the coil wire where it is produced, and (b) make charge move in wires outside the coil. Putting a larger coil over the inner coil will allow us to test this.

Figure 12.3 shows the outer coil (and the attached LED) displaced to the right, in order to make the inner coil with the accelerating charge visible in the diagram. When actually doing the experiment, the outer coil should slide over the inner coil.

Before connecting and disconnecting, **predict** the color of LED 2 in each case on the assumption that the transient fields actually are radiated and cause charge to move in the outer coil.

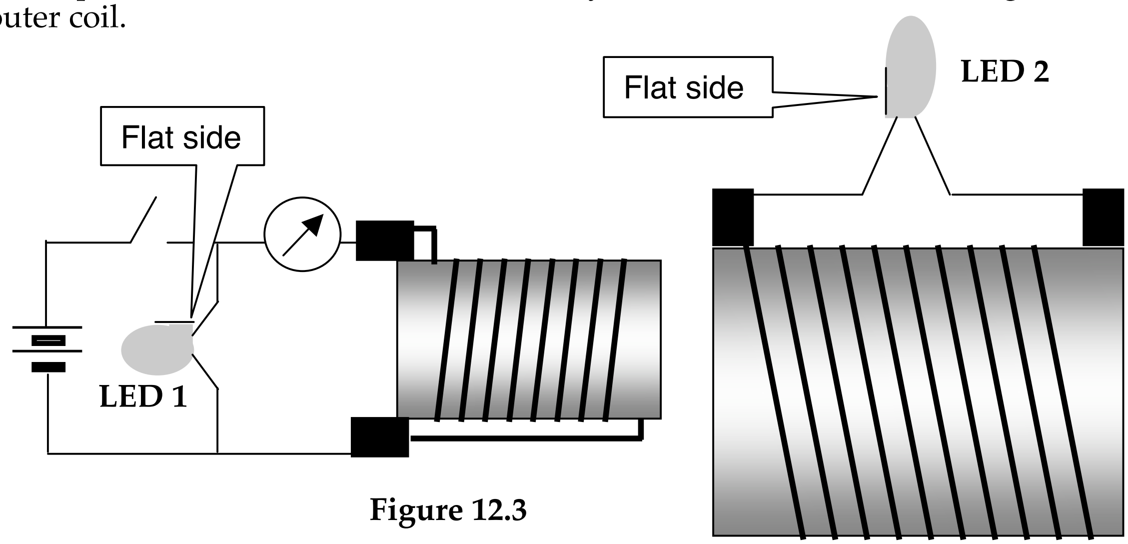


Figure 12.3

1. Draw an arrow on the inner coil showing the direction charge is moving immediately after connection. Then add an arrow showing the direction of the transient electric field when charge in the wire is speeding up.

2. Draw an arrow on the outer coil to show the direction that this electric field will make charge move in the outer coil if the field moves out of the inner coil and passes through the outer coil. What color glow – red or green -- would you expect to see in LED 2?

3. Repeat steps 1 and 2 for disconnecting the inner coil from the battery. Draw an arrow on the inner coil showing the direction of charge motion immediately after disconnection. Then add an arrow that shows the direction of the electric field that's produced when the speed of the charge is decreasing.

4. Draw an arrow on the outer coil to show the direction that this transient electric field will cause charge to move in the outer coil if the electric field moves outward from the inner coil after being produced by accelerating charge in the inner coil. What color would you expect to see LED 2 glow in this circumstance?

5. Now connect and disconnect the circuit. Record what you see. What do you conclude?

Observations:

Conclusions:

12.4 Activity: Depicting electric field radiated from accelerating charge in a coil

The circular cross-section of the coil makes it easy to depict an electric field being produced in the wire where accelerating charge is located and then moving out of the wire into empty space. The following diagram shows the situation on opposite sides of the coil when the circuit is closed. The vectors represent the transient electric field that opposes the acceleration of charge that is caused by the battery.

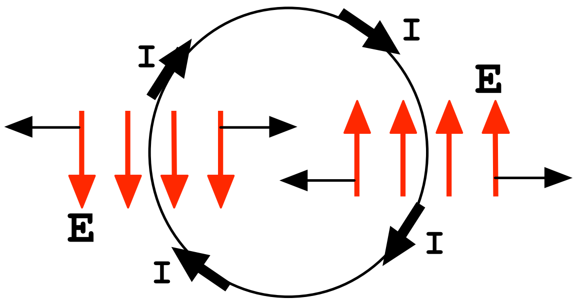


Figure 12.4a

Charge in the wire coil is speeding up. An electric field that opposes speeding up is produced in every part of the wire and moves away from it. Some goes outward away from the coil, and some goes inward toward the center of the coil.

1. Describe what happens with the electric fields radiating towards the center of the coil from both sides of the coil.

2. Describe what happens with the electric field radiating away from the coil from both sides of the coil.

3. In Figure 12.4b, make a sketch similar to Figure 12.4a that shows what is happening after the charge in the wire is moving with a constant speed.

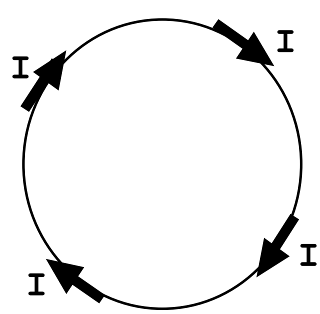


Figure 12.4b

The radiation of electric field shown in this diagram is happening everywhere around the loop. Using the following copy of Figure 12.4b as a starting point, draw a new diagram, and call it Figure 12.4c (below). To draw Figure 12.4c, add more radiating electric field vectors at additional places around the loop. Remember that radiation leaves the coil in all directions. We have depicted radiation going right and left in a horizontal direction, but it can also go up and down in a vertical direction and at angles between the vertical and horizontal directions. When you have added more electric field vectors, use them to guide you in drawing lines that describe the electric field pattern. How do these lines differ from the lines associated with concentrations of stationary charge?

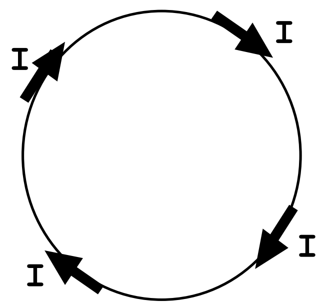


Figure 12.4c

Using the information you have just obtained, draw a corresponding set of diagrams for a situation where charge moving in a coil is slowing down—from maximum amount of charge moving to no charge moving. The starting point is the same as Figure 12.4b because the current is still going in the same direction, just slowing down. Sketch in the radiation that would be occurring just after disconnection, when there is some radiation moving into the center of the coil, and some moving away from the coil. Explain your reasoning.

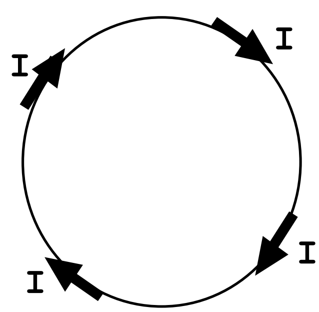


Figure 12.4d

INVESTIGATION TWO: HOW DO MAGNETIC FIELDS FORM NEAR A CURRENT-CARRYING WIRE?

12.5 Activity: Finding directions of the magnetic field near a wire with current

Very early in this curriculum, we used a compass under circuit wires to detect charge flow in the wires. In Section 11 we used a compass again to detect magnetic fields in the space around magnets.

The compass needle deflection that we observed under wires with charge flow shows there is a magnetic field in the space around moving charge. This demonstrates that magnetic field as well as electric field exists in the space around charge when charge is moving.

Orient a long straight wire vertically, so that it passes through a hole in a piece of cardboard as shown in Figure 12.5, and connect it to a battery pack with two D-cells.

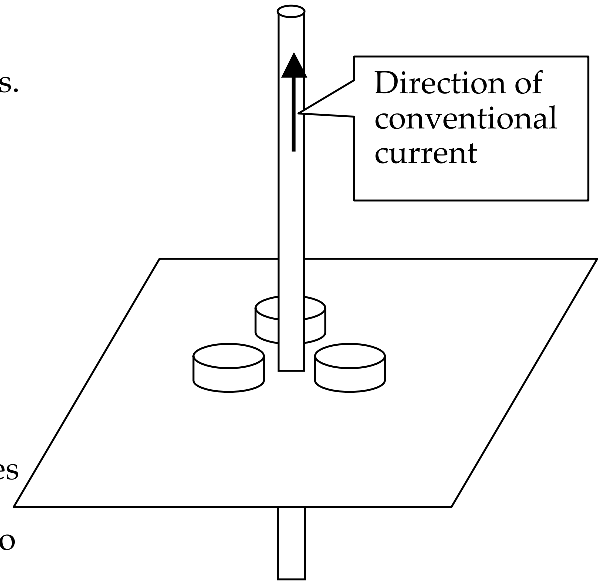


Figure 12.5

1. To explore the pattern of magnetic field directions around the moving charge in this wire, place several compasses on the cardboard near the wire. By observing the compasses, what can you learn about the shape of the magnetic field lines near the wire?

2. Which Right Hand Rule will allow you to easily determine the direction of the magnetic field at any point near the wire?

3. Before the current is established in the wire, there is no magnetic field in the space around the wire. After the current is established, there is a magnetic field around the wire. Do you think any radiation has occurred? What is the evidence?

4. Has a transient electric field been radiated?

12.6 Activity: Mapping the magnetic field in space around a coil of several turns

The magnetic field was not there before the circuit was closed -- but it is there after closure. How did it get there? How was it produced? In seeking an answer to these questions, let's take a look at the structure of the magnetic field that is produced.

The structure of the magnetic field around a coil of wire is more complex. The reason for this is suggested by examining the magnetic field in the space around two long parallel wires carrying current in opposite directions. Charge moving in any wire of a coil moves opposite to that in a wire located on the other side of the coil, so the magnetic field of a coil should have similarities to the magnetic field of two parallel wires with charge moving in opposite directions.

Figure 12.6a

CURRENT IN TWO WIRES PERPENDICULAR TO PLANE OF PAPER

1. In the space below (Figure 12.6b), draw circles (centered on the wires) representing the magnetic fields around each of the two wires. Draw one small circle around each, and one large circle around each. Then draw arrows representing the strength and direction of the magnetic field at the vertical part of each circle.

(a) What can we say about the magnetic field direction between these wires?

(b) What can we say about the magnetic field direction on either side of the wires?

Figure 12.6b

We may also infer that if the two wires are curved and joined to form a loop or coil, then the magnetic field will be stronger in the interior of the coil than in the exterior space. You can get a sense of this if you imagine looking down at the two wires. Sketching a magnetic field near the wires, it would look something like Figure 12.6c. Bend the wires to form a closed path and get Figure 12.6d. Round the corners to form a circle and get Figure 12.6e. The field inside the coil is more concentrated and stronger than the field outside the coil.

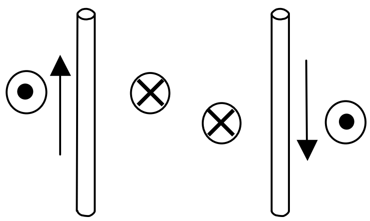


Figure 12.6c

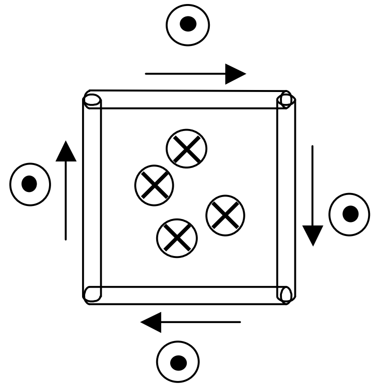


Figure 12.6d

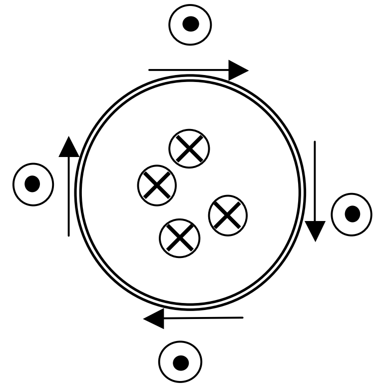


Figure 12.6e

12.7 Activity: Depicting formation of a magnetic field by the radiation process

We learned in Activity 12.6 that current flowing in a wire results in production of a magnetic field around the wire. Note that initiating current flow requires making charge <u>accelerate</u> from speed zero to some final speed.

We found evidence that a <u>moving electric</u> field is produced when charge is accelerating. Now it appears that accelerating charge also provokes the production of a <u>stationary magnetic</u> field. How can we describe this additional field production process?
Let's try to depict:

- a curly electric field moving outward from the accelerating charge
- a curly magnetic field <u>also</u> moving outward from the wire
- leading edges of <u>both</u> fields moving forward at the same speed
- interpenetration forming pure magnetic field near steady current

We have earlier depicted moving electric field in three stages: (1) Charge in a wire is accelerating (speeding up) when current begins to flow; (2) Charge in the wire is moving at constant speed after a steady current flow is reached; (3) Charge in the wire is accelerating (slowing down) when the circuit is disconnected and current ceases to flow.

An electric field is produced during charge acceleration (in stages 1 and 3) that always acts to oppose the change in speed of charge movement. When charge is increasing speed (in stage 1), the produced electric field acts in the direction opposite to the motion of charge. When charge is decreasing speed (in stage 3), the produced electric field acts in the same direction as the motion of charge. (This is determined experimentally in Activities 12.2 and 12.3, and revisited at the end of 12.4.) During stage 2, there is no production of an oppositional electric field, but the field produced during stage 1 continues to move through space away from the wire of its origin.

Now let's look at the magnetic field that is simultaneously produced and radiated with the electric field.

1. A sketch of the loop from Figure 12.6e is below (Figure 12.7a), showing the direction of charge flow. Just outside the left side of the loop, draw and label symbols for each of the following:

(a) The direction of charge acceleration at the moment the circuit is closed.

(b) The direction of the oppositional electric field produced during charge acceleration.

(c) The direction of the magnetic field produced at the same time as the oppositional electric field.

(d) The direction of radiation of the co-produced electric and magnetic fields.

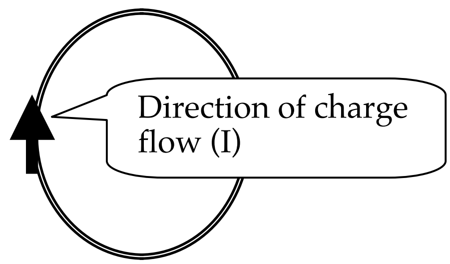


Figure 12.7a

Remember that
- a magnetic field has a direction everywhere, just like an electric field does
- these two fields move together -- away from where they are produced
- same-kind moving fields can reinforce or cancel during interpenetration

2. In the following diagram, draw symbols to show the pattern of magnetic fields inside and outside the coil, and their direction of radiation.

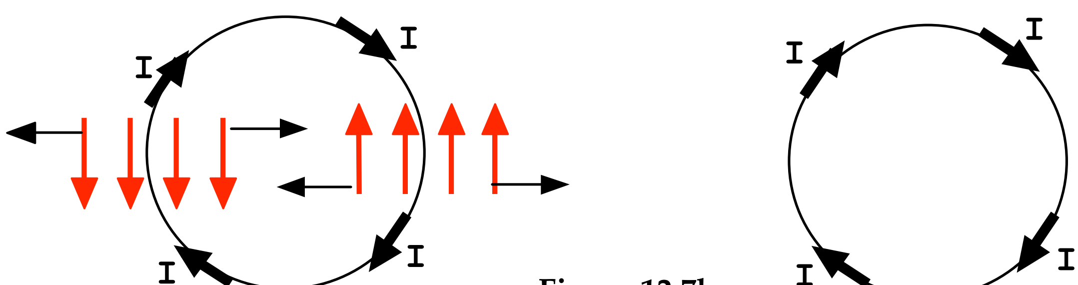


Figure 12.7b

Flow-opposing electric field moving out of wire coil while charge in wire is accelerating

Pattern of magnetic field inside and outside of coil while charge is accelerating

3. Using the information contained in both parts of Figure 12.7b, superimpose them to draw a single diagram combining the radiated electric and magnetic fields (Figure 12.7c), showing them leaving and traveling together on both sides of the coil.

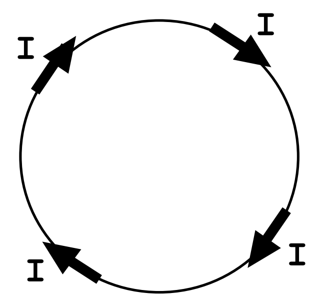


Figure 12.7c

12.8 Activity: Identifying energy transfers that enable the radio to sound off

You have heard a radio sound off when a battery and wire loop circuit is closed and opened (Activity 12.1), and you have seen an LED light up with this circuit as in Activity 12.3. In both cases, the sound and lighting occurred just after connection and just after disconnection. Just after connection, the energy comes from the battery, but where does the needed energy come from after disconnection when the battery is no longer a part of the circuit?

INVESTIGATION THREE: TRANSFORMERS

12.9 Activity: Testing a commercial transformer for use as an "AC battery"

Standard electrical outlets provide 120 volts alternating voltage, which drives alternating current in electrical devices that are plugged into wall sockets. We will use a commercial transformer as an "AC battery" that provides a choice of 3.2 or 6.4 volts alternating voltage – equivalent in energy-transfer and bulb-lighting capability to either 2 or 4 of our D-cells.

The teacher will provide a small step-down transformer, which can be plugged into any standard electrical outlet to obtain reduced alternating voltage that will not burn out our bulbs and LEDs. We will test this transformer, to verify that it does indeed function as an "AC battery".

Plug the transformer into a wall outlet, and connect two of its output leads (the middle lead and one of the outer leads) to a bicolor LED as shown in the figure below.

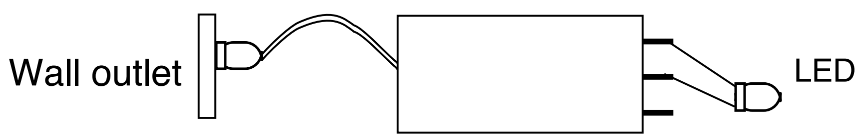


Figure 12.9

1. Describe what you see. What is the evidence that the LED is lit by alternating current rather than by direct current?

Observations:

12.10 Optional Activity: Detecting transient radiation produced by AC

When direct current begins to flow in a circuit, an AM radio can detect a pulse of electromagnetic radiation moving outward from accelerating charge. Does this transient radiation also occur when alternating current flows? Consider the activity below, and predict what results you will observe.

Prediction:

Replace the LED in Figure 12.9 with your small-diameter inner coil. Then place your radio near the coil as in Figure 12.10, and tune it to a quiet spot near the low frequency end of the AM dial.

Figure 12.10

Repeatedly connect and disconnect the coil from the transformer. Describe and explain what you hear.

12.11 Commentary: What is a transformer?

A transformer is a device that “transforms” an input voltage to a different output voltage – usually to fit some practical need. For example, the AC battery we are using is a “step-down” transformer, which transforms the 120 V input voltage from household outlets to 6.4V output voltage. The lower voltage is more desirable (and safer) for use with our light bulbs than the full 120 V.

There are also step-up transformers for circumstances in which it is desirable to have higher than 120V output, such as transporting energy over long distance power lines. For power lines, energy is lost as heat due to the resistance in each mile of the wires – and lots of miles between Niagara Falls and New York City can mean huge energy loss. This loss is greatly reduced by transmitting energy using very low current but very high voltage, resulting in the same rate of energy transport. The step-up transformers can reach output voltages of 100,000 V. Because of these high voltages, a step-down transformer at your house, with output voltage of 120 volts AC, is necessary to make the energy usable with your household appliances.
The coil in which charge flow is driven by the external alternating voltage source is called the “primary coil”. The coil that provides alternating output voltage of a different magnitude is called the “secondary coil”. The ratio of output voltage to input voltage depends on the ratio of the number of secondary coil turns to the number of primary coil turns. You will soon do an experiment that illustrates this principle.

We will use nested straight coils to investigate transformer operation, because they can be taken apart to investigate how the transformer works. Input voltage is applied to the inner (primary) coil. Output voltage is provided by the outer (secondary) coil.

12.12 Activity: Output voltage of nested coils with alternating input voltage

Connect an LED across the outer coil of the nested coils as shown in Figure 12.12a, and connect the inner coil to the 3.2 VAC terminals of the transformer. Then plug the transformer into a wall outlet.

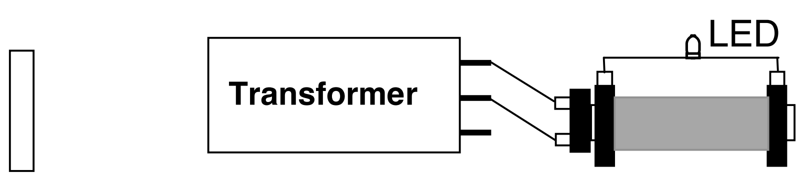


Figure 12.12a

1. Describe your observations of the LED. Explain the process that produces what you see.

Observations:

Explanation:

Using a variation of the diagrams from Activity 12.3, let's take a look at the curly electric field surrounding the inner (primary) coil of the coaxial transformer.

Figure 12.12b below shows a side view of the primary coil, with an AC input. Figure 12.12c shows the view from the right end into the coil. During the particular part of the cycle shown, the upper terminal is positive, and the lower terminal is negative. Also, the upper terminal is becoming more positive and the lower terminal is becoming more negative. This means that the strength of the electric field acting on the charge in the wires of the coil is increasing and the speed of the charge is increasing.

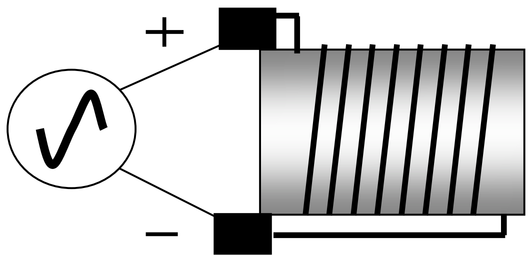


Figure 12.12b

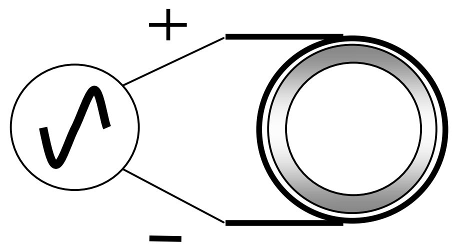


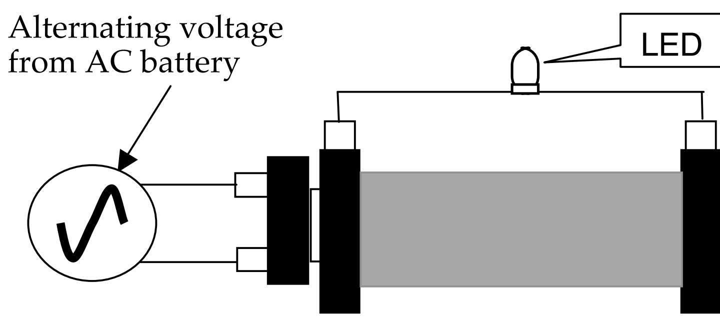
Figure 12.12c

2. For this set of conditions, sketch arrows to show the direction of charge flow, the direction of acceleration, and the direction of the produced electric field that is radiated. Label charge flow arrows with the letter "I", acceleration arrows with the letter "a", and radiated electric field arrows with the letter "E". On the diagram to the right that shows the end view, sketch the pattern of "E" arrows.

12.13 Activity: Using the number of secondary coil turns to control output voltage

Insert the primary coil inside the secondary coil, but do not insert the iron core. Connect an LED across the terminals of the outer coil, and connect the AC battery to the inner coaxial coil, as shown in Figure 12.13a.

Figure 12.13a



1. Hold the inner coil motionless, and slide the outer coil slowly to the right. Then slide the outer coil slowly back and forth. What do you observe, and how do you explain it?

Observation:

Explanation:

2. How could you modify the outer coil to make the output voltage higher?

How could you modify the outer coil to make the output voltage lower?

INVESTIGATION FOUR: IRON CORES, MAGNETS, AND REFERENCE FRAMES

12.14: Activity: Finding out how an iron core influences output voltage

1. Put three LEDs in series across the outer coil. Insert the inner coil completely inside the outer coil. Connect the inner coil to an "AC battery". Obtain an iron rod and hold it as shown below. Slowly slide the iron core all the way in and then all the way out. Describe what you observe. Try to explain it.

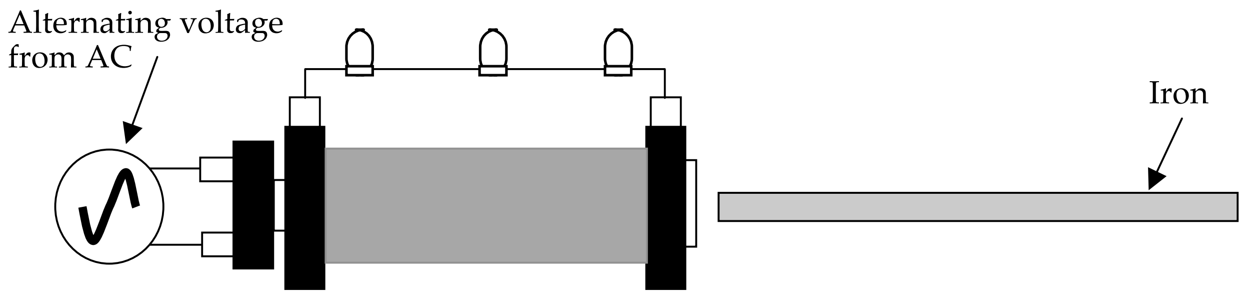


Figure 12.14

2. To help develop an explanation, try the following. Remove the inner coil and set it on the table in an east-west direction. Place a compass to the right, a few cm away, directly off the end of the coil. Remove the iron core and connect a 2-cell battery to the inner coil for about two seconds, and note the compass deflection. Insert the iron core into the inner coil, reconnect the battery to the inner coil for about two seconds and again note the compass deflection. What do you observe?

12.15 Activity: Using the iron rod to light LED's

With the iron rod in place, the three LEDs are lit, as shown in Figure 12.15. Follow the given directions and describe the lighting you see—including when changes in lighting occur. Explain why the changes happen.

1. Slide the outer coil to the right until the inner coil is completely exposed, and there is about 2 or 3 cm space between the ends of the inner and outer coils.

2. Then slide the iron rod to the right until it is entirely in the outer coil. (It may be helpful to push the iron rod with a wooden rod or pencil.)

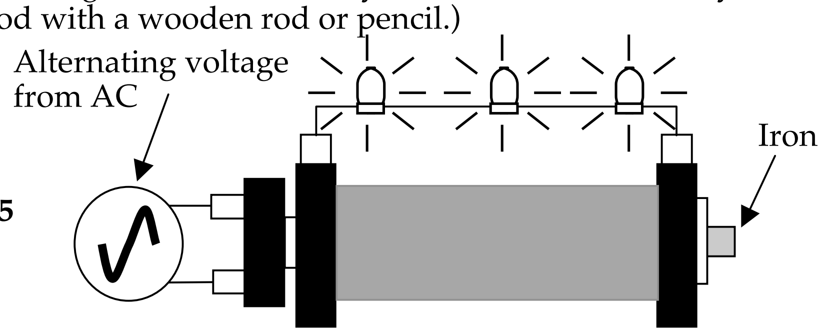


Figure 12.15

Observation:

Explanation:

12.16 Activity: Using a permanent magnet to change the magnetic field inside a coil

The previous activity suggested that a changing magnetic field produces an electric field that radiates outward and can make charge move in the outer coil. There are other ways to change the magnetic field in a coil. Figure 12.16a shows a permanent magnet being pushed towards a coil that has a device to detect motion of charge. In Section 11, you found that magnetic field lines come out of the north pole of a permanent magnet and enter the south pole. Therefore, in Figure 12.16a, the magnetic field is increasing in the coil, and the field lines point to the left.

1. Move the magnet towards the coil. Does the meter detect charge movement in the coil? If so, add an arrow to the coil to show what direction charge moves.

Next move the magnet away from the coil. Does charge move again? In what direction?

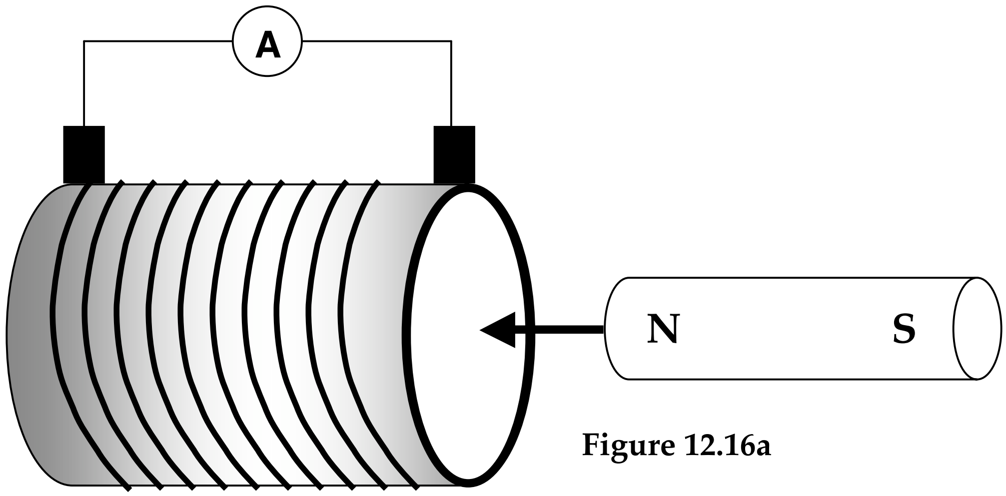


Figure 12.16a

The diagrams at right (Figure 12.16b) show the magnetic field of the magnet as it approaches the circular opening of the coil, demonstrating how the magnetic field in the coil changes as the magnet approaches it. The diagrams show the magnetic field strength at the end of the coil increasing from two lines to four lines to six lines.

2. Move the magnet faster into the coil. How does the ammeter respond? What can you conclude from your observation?

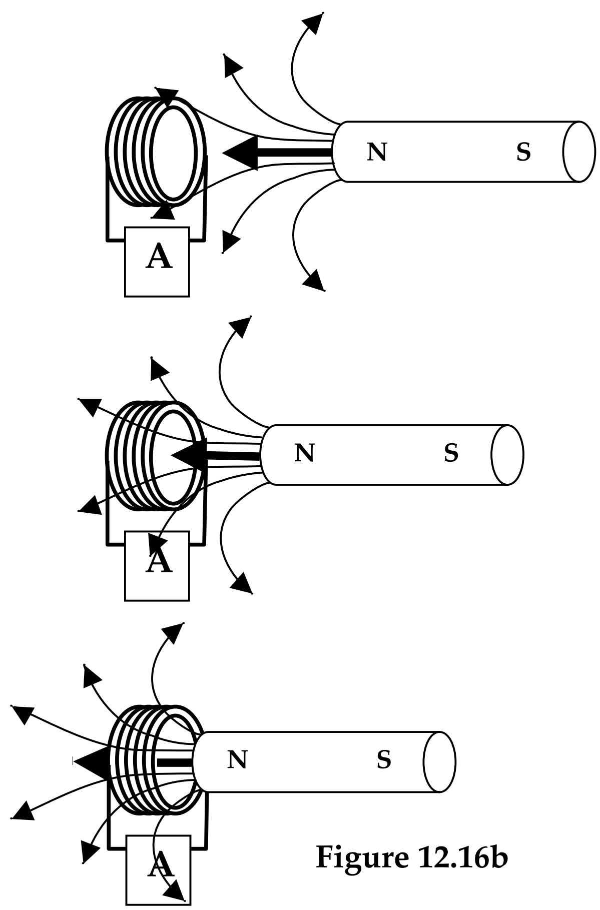


Figure 12.16b

12.17 Activity: Changing the frame of reference

In Activity 12.16, the coil was stationary. This means the motion was seen by an observer who was not moving relative to the coil. This observer sees the permanent magnet moving to the left. But what if the observer is in the frame of reference of the magnet. That is, this observer sees the magnet at rest with the coil moving to the right as shown in Figure 12.17 below.

1. Will a current still be produced in the loop? Find out. If a current is produced, how does the direction of the current compare to that obtained in Activity 12.16?

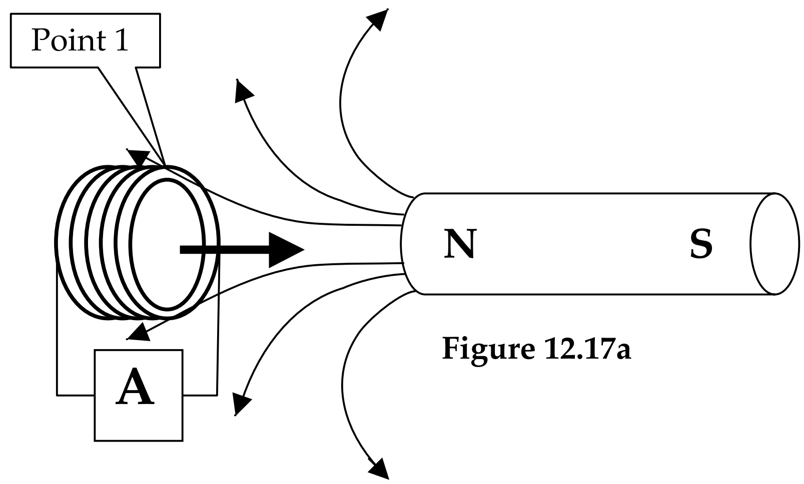


Figure 12.17a

2. Next, referring to Figure 12.17a, focus on what is happening at point 1. Use the right hand rule for the force exerted on a charge moving in a magnetic field, and predict the direction of current produced in the coil. Does this direction agree with or contradict the direction found by the meter?

3. Use a right-hand rule to determine the direction charge will move in this short segment of the wire. Does this direction agree with or contradict the Direction found by the meter? Repeat this analysis at a point diametrically opposite Point 1. How does this direction compare with the direction at point 1?

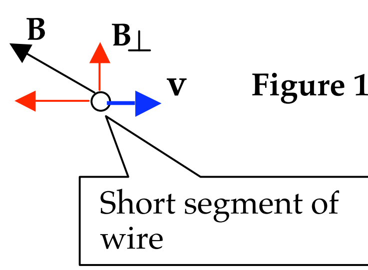


Figure 12.17b

12.18 Commentary

(1) We learned at the beginning of Section 12 that when charge changes speed in a wire, electromagnet radiation is produced that can be detected by a radio located a short distance away. (2) Later in Section 12, we learned that this electromagnetic radiation was eventually shown to have two components—an electric field and a magnetic field.

At first, we focused only on the radiated field being produced when charge accelerates in a wire. In Activity 12.15, however, we learned that a changing magnetic field produces a radiating electric field. A changing electric current in the primary coil produced this changing magnetic field in the secondary coil. We then used a moving permanent magnet to change the magnetic field in a coil, and we discovered the same result, leading to the conclusion that any changing magnetic field produces a radiating electric field.

Lastly, we kept the permanent magnet motionless and moved a coil towards it. A stationary magnetic field does not produce a radiating electric field, but a current was established in the coil in the same direction as when the magnet was moved. The current was caused by the generator effect studied in Section 11. That is, if a wire moves in a magnetic field, a current is produced in the wire whenever there is a component of the magnetic field perpendicular to the motion of the wire.

The conclusion here is that current can be produced in a coil whenever there is relative motion between a coil and a permanent magnet. However, the correct explanation depends on the frame of reference of the observer. When the magnet was moved towards the coil, the coil and the observer were in the same frame of reference. (The observer and the coil did not move relative to each other.) When the coil was moved towards the magnet, the magnet and the observer were in the same frame of reference. (The observer and the magnet did not move relative to each other.)

If you take an AP or college physics course, almost all of the approach to electromagnetic radiation will be mathematical. The mathematical approach makes it harder to understand the underlying physical behavior. On the other hand, Section 12 explains the underlying physical behavior and will be a good reference to help you better understand the mathematical approach.

SUMMARY EXERCISE

1. a) Explain the differences between a curly electric field and a divergent electric field.

   b) Explain how a curly electric field is produced.

2. Give evidence that a curly electric field carries energy.

3. When does a magnetic field: a) appear? b) disappear? c) stay stable?

   a)

   b)

   c)

4. How could you show that a magnetic field stores energy?

5. Explain the difference(s) between Alternating Current and Direct Current, and explain how you could demonstrate any differences.

6. a) Describe the structure and operation of a transformer.

   b) Explain why AC is needed for transformer operation.

   c) Explain the difference between a step-up and a step-down transformer.

7. Explain why inserting an iron core into a coil strengthens the magnetic field of the coil.

8. Why does inserting an iron core into the primary (inner) coil of a transformer increase the voltage of the output?

9. Moving a magnet towards a coil produces the same result (i.e. current in the coil) as moving the coil towards the magnet. The relative motion is the same, but the physics is different. Explain.

10. a) Describe some differences between forces exerted by positive and/or negative charges, and the forces exerted by the north and south poles of a bar magnet.

b) Under what conditions can a copper wire and a magnet attract each other?