

## Section 11

# HOW DO MOTORS & GENERATORS WORK? WHAT DO MAGNETIC FIELDS DO?

### INTRODUCTION

You have probably used electric generators before – to operate bicycle lights, for example. And you have almost certainly used electric motors – in fans, hair dryers, and automobile windshield wipers. Now is your opportunity to investigate how these devices work.

### INVESTIGATION ONE: HOW TO CHARACTERIZE A GENECON ELECTRICALLY?

#### 11.1 Activity: Identifying the “motor effect”

Plugging two wires into a Genecon connects these wires to the metal cylinder that you can see inside the Genecon. Connecting a battery to the free ends of the wires applies an electric pressure difference to the cylinder that will make the crank rotate. The cylinder becomes a “motor”. This rotation is called the “motor effect”.

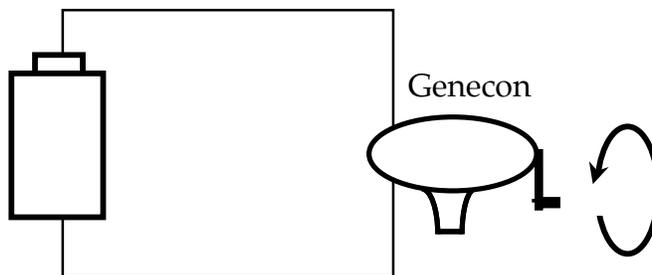


Figure 11.1  
OBSERVING THE MOTOR EFFECT

#### 11.2 Activity: Identifying the “generator effect”

Rotating the crank of a Genecon that is connected to a bulb creates an electric pressure difference in the connecting wires that makes the bulb light. Generating this pressure difference is referred to as the “generator effect”. The Genecon causing this effect is acting as a “generator” in this situation.

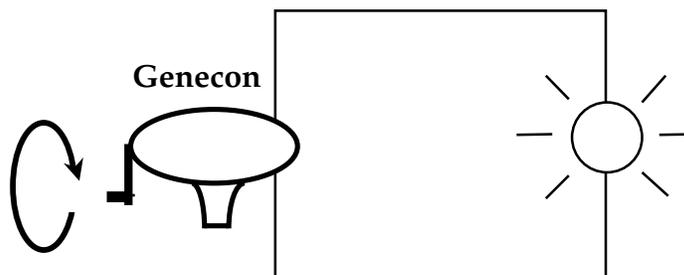


Figure 11.2  
OBSERVING THE GENERATOR EFFECT

### 11.3 Activity: Identifying parts of the motor that make these effects possible

Instead of destroying a Genecon to look inside the metal cylinder, you will open a similar (and cheaper) electric motor provided by the teacher. There you will see coiled wire that:

- provides a conducting path for charge flow through the motor
- is attached to a metal shaft that rotates with the Genecon crank
- is located between 2 magnets with north and south pole faces

These magnets are slightly curved, so they can be glued to the inside of the cylindrical motor housing.

### 11.4 Activity: Investigating the “magnetic field” inside the motor

Use magnets similar to those in the motor, standing on a table on their thin sides. Use a small compass, as in Figure 11.4a, to show how a single magnet affects a compass needle at different points in the space around the magnet. Place paper under the compass, and draw small arrows on it to show directions in which a compass needle is pointing. Think of the arrows as indicating local directions of an invisible MAGNETIC FIELD supported by the magnets.

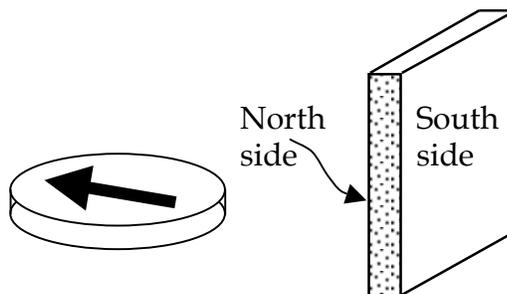


Figure 11.4a

#### COMPASS NEEDLE REVEALS MAGNETIC FIELD DIRECTIONS.

The magnetic field inside the motor is supported by two thin magnets. To visualize this “field”, place two small flat magnets about 8 inches apart and use a small compass as in Figure 11.4b to investigate the magnetic field pattern. To properly orient these magnets, check them with a compass as in Figure 11.4a. It is helpful to mark their North and South faces with small pieces of tape.

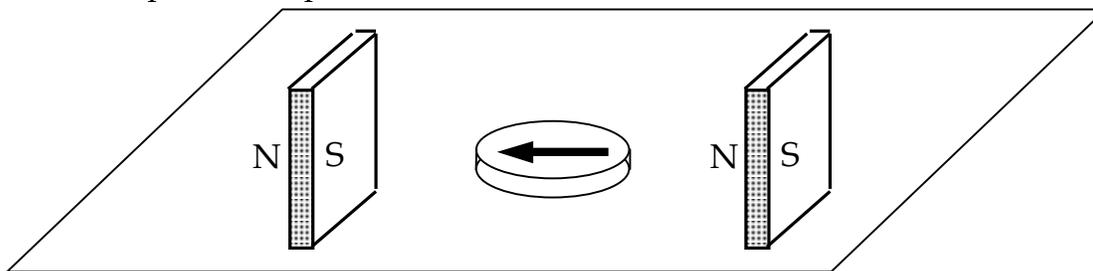


Figure 11.4b

#### TWO MAGNETS ORIENTED AS IN A GENECON

Now remove one magnet. Use observations of compass needle deflection to reveal the difference between the magnetic field of a single magnet and the magnetic field of the two magnets in Figure 11.4b. Why do you think the motor is designed with two magnets, rather than one?

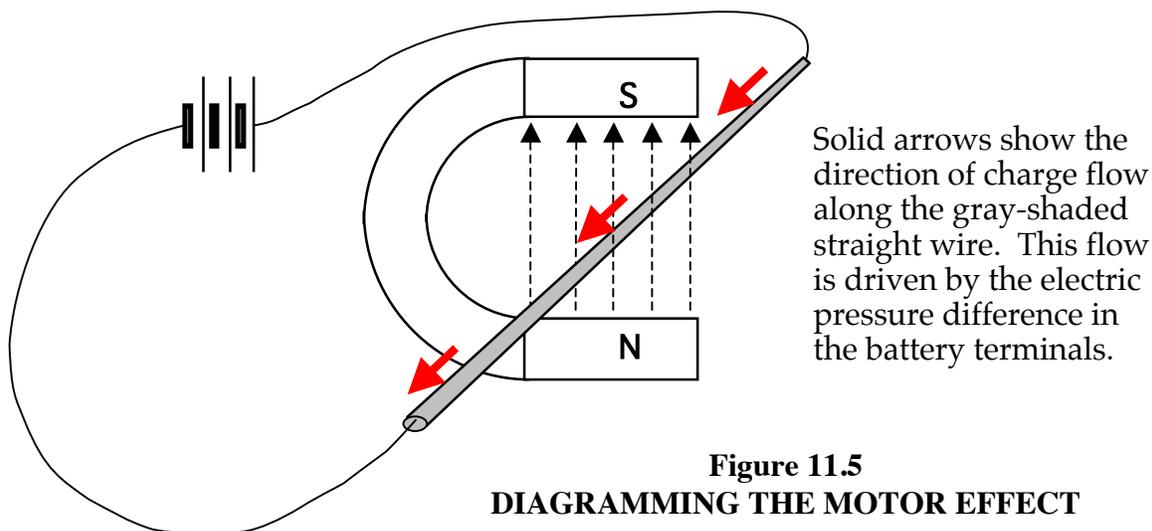
## INVESTIGATION TWO: HOW IS THE MOTOR EFFECT PRODUCED?

### 11.5 Commentary: Apparatus for investigating the motor effect

Next we will investigate the cause of the motor effect. We will make the task easier by using:

- magnets that support a stronger magnetic field than we found inside the motor
- a straight wire connected to the battery, rather than coiled wire as in the motor

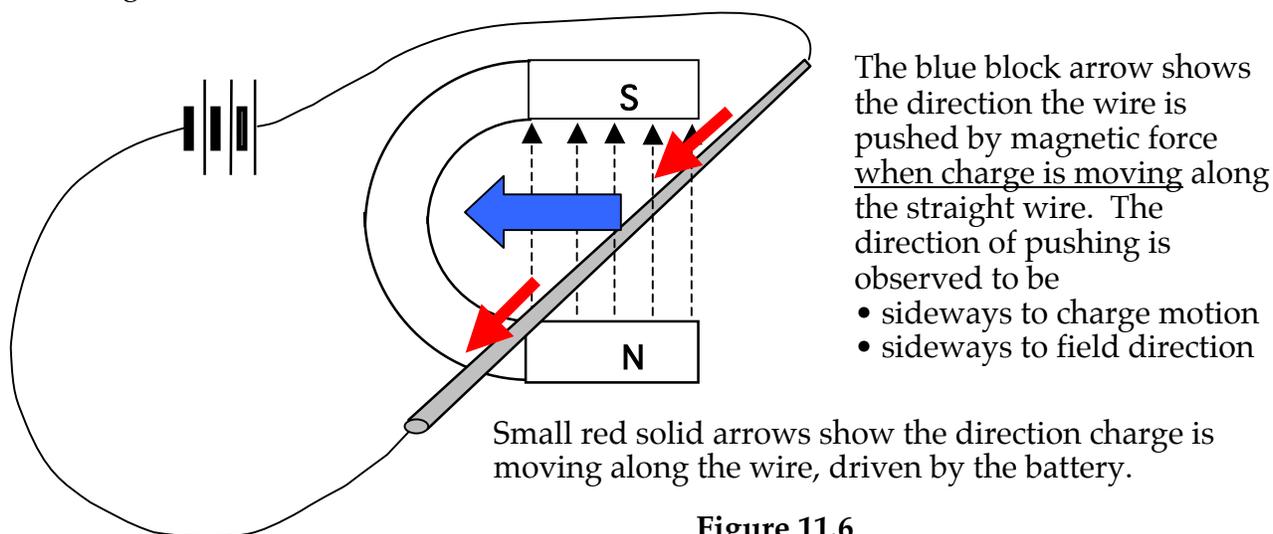
Figure 11.5 illustrates the magnetic field pattern in the space between these magnets, which is similar to the magnetic field pattern inside the Genecon motor. Dotted arrows show the nearly uniform directions of this magnetic field everywhere in the space between the two magnets.



**Figure 11.5**  
**DIAGRAMMING THE MOTOR EFFECT**

### 11.6 Activity: Observing the motor effect using the apparatus in Figure 11.5

Set up the apparatus with the circuit disconnected and no charge flow in the straight wire. Then close the circuit -- and observe what happens to the straight wire when the charge in it is moving.



**Figure 11.6**  
**SIDWAYS PUSHING ON MOVING CHARGE**

### 11.7 Exercise: What makes the wire move?

1. We have seen the wire moving sideways after it is connected to the battery.
  - What in the wire is getting pushed?
  - What is doing the pushing?

2. On a new clean sheet of paper: Draw a blue, a black and a red arrow perpendicular to each other and with their tail ends all touching at a common point. Label the black arrow "Magnetic Field", the blue arrow "Charge Flow in Wire", and the red arrow "Pushing on Wire".

To find out if the same directional relationship holds in all situations:

- Reverse the battery polarity in your drawing (charge flows in opposite direction); observe the direction of pushing, and draw the 3 arrows again.
- Reverse the polarity of the magnets, and repeat.

### 11.8 Commentary: Relating the three directions involved in magnetic pushing

Our experiments suggest there is a unique perpendicular directional relationship in all circumstances between:

- direction of charge movement in the magnetic field
- direction of the magnetic field
- direction of pushing on the moving charge

Figure 11.8a illustrates this directional relationship in a diagram based on the right hand. Scientists and engineers use this "Right Hand Rule" as a handy way to visualize the relationship.

**Figure 11.8a**  
**THE RIGHT HAND RULE**

Note: The symbol  stands for a vector pointing out of the page.

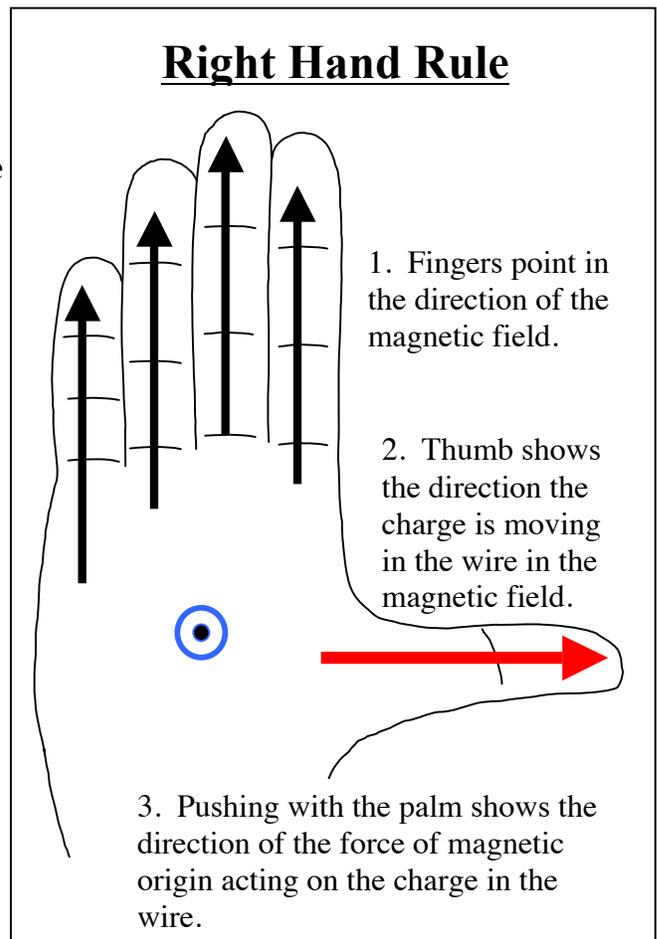
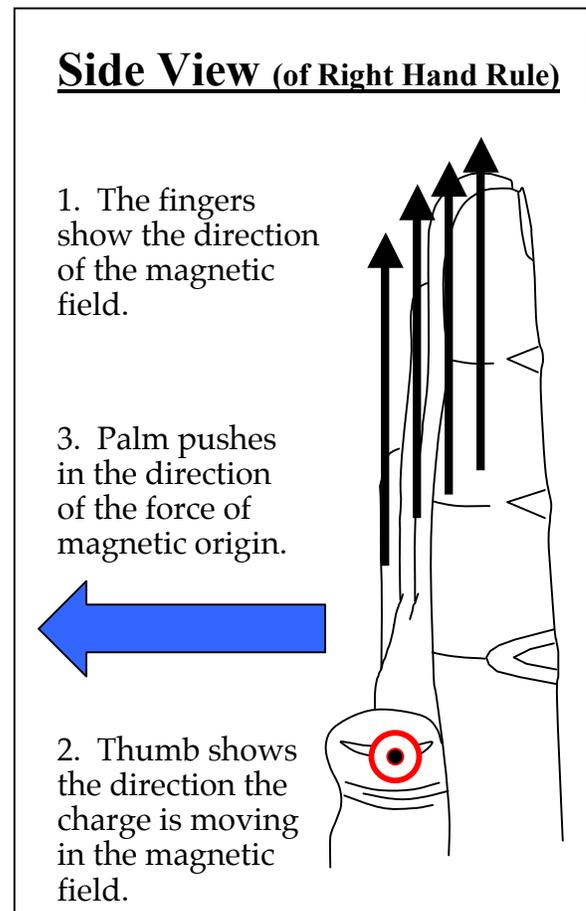


Figure 8b demonstrates the same Right Hand Rule as viewed from the side.

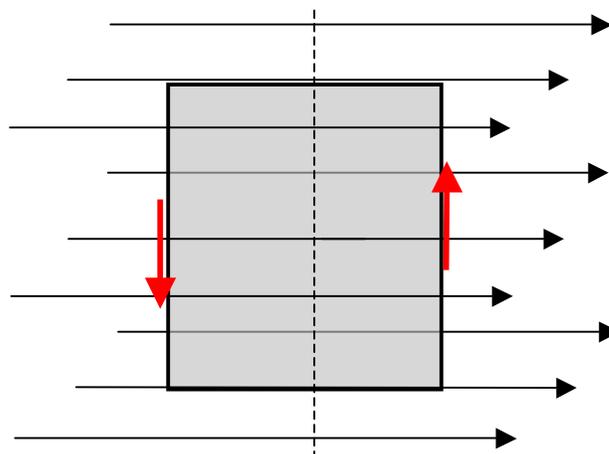


**Figure 11.8b**

**11.9 Exercise: What makes the motor effect happen?**

1. The plane of a wire loop shown in Figure 11.9a is initially parallel to the uniform magnetic field directions shown by the black arrows. Your task is to determine how (or whether) this loop will move when there is charge flow in it as shown in the diagram.

A wire loop with counter-clockwise flow is free to rotate about a dotted-line vertical axis. The plane of the loop is parallel to field directions at all points of the loop.



**Figure 11.9a**

2. In Figure 11.9b, your task is the same -- but the loop's initial position is now rotated  $90^\circ$  from its initial position in 11.9a, so the loop is perpendicular to the magnetic field directional arrows.

Charge is still moving in the counter-clockwise direction. But the loop has been rotated  $90^\circ$ , so that its plane is now perpendicular to the magnetic field directional arrows.

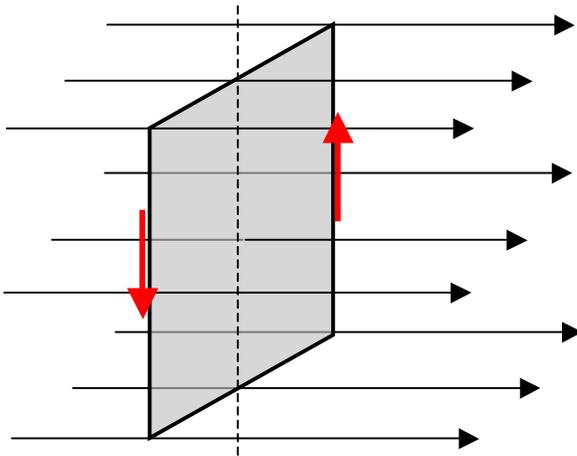


Figure 11.9b

3. Why does the motor have three coils? And why does each have more than one loop of wire?

### INVESTIGATION THREE: HOW IS THE GENERATOR EFFECT PRODUCED?

#### **11.10 Activity: Where does charge moving between a generator and a lit bulb originate?**

Our generator-effect experiment involved charge moving between the Genecon and a lit bulb. It is easy – but wrong -- to think of the moving charge as originating only inside the Genecon. If the charge that's driven through a lit bulb by a cranked Genecon originates in wire that's inside the Genecon motor, then it must also originate in circuit wires that are outside the motor. The crucial idea here is that charge is always present in wires – and it moves with wires when they move.

### 11.11 Activity: What happens when you make a wire move in a magnetic field?

Turning the Genecon crank makes coils of wire rotate between two magnets inside the motor. This makes the charge contained in the coil wire move in a magnetic field -- in a direction sideways to the wires. How does this make charge move through a bulb connected to the motor? We will investigate the simpler situation in Figure 11.11a, with your hands making a straight wire move in a stronger magnetic field with a nearly uniform pattern like that of the field in the Genecon motor.

Figure 11.11a shows a digital multimeter with its selector set to read current, making it an ammeter. To determine which direction of charge flow the meter readout indicates, connect a D-cell and two long bulbs in series with the meter. The D-cell's orientation in the circuit tells you which direction conventional charge moves -- and the meter reading will display either a negative sign or no sign corresponding to that direction of charge flow.

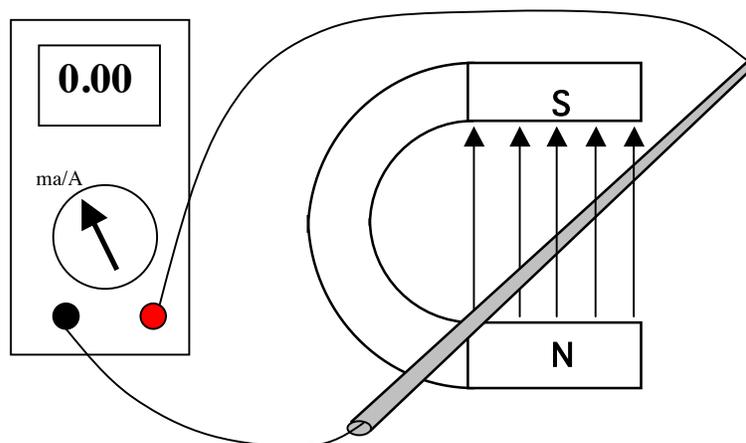


Figure 11.11a

After you connect the circuit in Figure 11.11a, use your hands to make the wire move. Watch the galvanometer needle, which will respond to charge movement along the wire.

1. To simulate what happens in a generator, you will make the straight wire in Figure 11.11a move to the left in the magnetic field. This movement will be sideways to the wire and sideways to the direction of the magnetic field arrows. Draw a red arrow on Figure 11.11a to indicate the direction the charge in the wire moves during this sideways wire movement. **Before pushing the wire, use the Right Hand Rule to predict the direction that charge will move along the length of the wire.** If the galvanometer detects charge flow in the circuit with the straight wire, you should draw blue arrows on that wire to show the direction the magnetic field pushes moving charge in the wire to make the observed flow occur. Then move the wire in the opposite direction, and again note the direction of magnetic pushing on the charge that's present in the straight wire.

What do you observe?

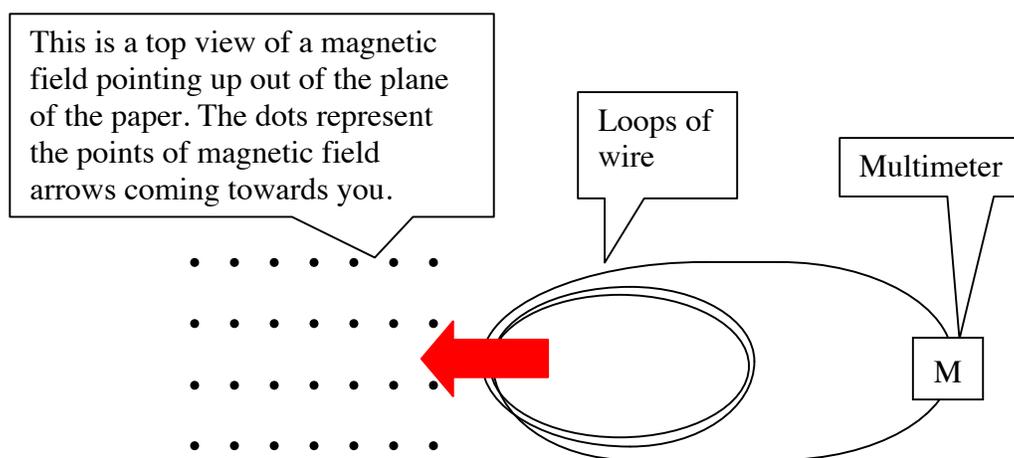
2. The Genecon motor has many turns of wire, so you should explore using coils with many turns of wire to see if that causes a greater effect. The teacher will provide various coils with different numbers of turns. Figure 11.11b shows a top view of Figure 11.11a with a coil replacing a straight wire. This has been done to make the physical situation easier to visualize and analyze.

Make a prediction: Indicate what you expect to observe on the galvanometer when you:

- Position each coil as in Figure 11.11b and hold the plane of a coil horizontal.
- Push the coil's **leading edge** into the uniform middle of the magnetic field.

Did your observation agree with your prediction? If not recheck everything until your prediction and observation agree.

Again using the Right Hand Rule, predict what direction charge will move when you move the coil in the opposite direction out of the field. Repeat until prediction and observation agree.



**Figure 11.11b**

3. Quickly move the leading edge of the coil most of the way into the magnetic field. Record your observations of the amount of needle deflection, the direction of needle deflection, and the number of turns of the coil.

4. Repeat with coils having different numbers of turns. Try to move each coil at the same rate. Record your observations.

5. Next start with the leading edge of a coil well into the magnetic field. Then move the coil to the right and out of the field. Then repeat, but moving the coil faster. What, if anything, is different from what you observed in #3 above?

6. Place the leading edge of the coil at about the middle of the magnetic field, and move the coil vertically. As in earlier cases, use the Right Hand Rule to predict what will happen before you move the coil. Does your observation agree with your prediction?

7. Summarize your findings in words.

8. Draw a simple colored diagram for Figure 11.11b that includes and relates
- the direction of a magnetic field (dotted black line)
  - the direction in which charge inside the wire is caused to move in this field (red block arrow)
  - the force exerted on the charge in the wire by the magnetic field as a result of this motion (small blue solid arrow).

### 11.12 Commentary: Applying the Right Hand Rule to bulb lighting

Let's apply the Right Hand Rule to the apparatus in Figure 11.11a, diagramed below with arrows. Refer to the diagram of the Right Hand Rule in Figure 11.8 while doing each of the following:

- 1) Hold your right hand so that the fingers point upward, in the direction of the magnetic field.
- 2) Orient your right hand so that the thumb points to the left, in the direction the straight wire and the charge in it are moving (blue arrow).
- 3) Thrust the palm of your right hand in the direction that the charge carried leftward by the wire is also being pushed along the wire by action of the magnetic field on the moving charge. This direction is into the page, away from you.

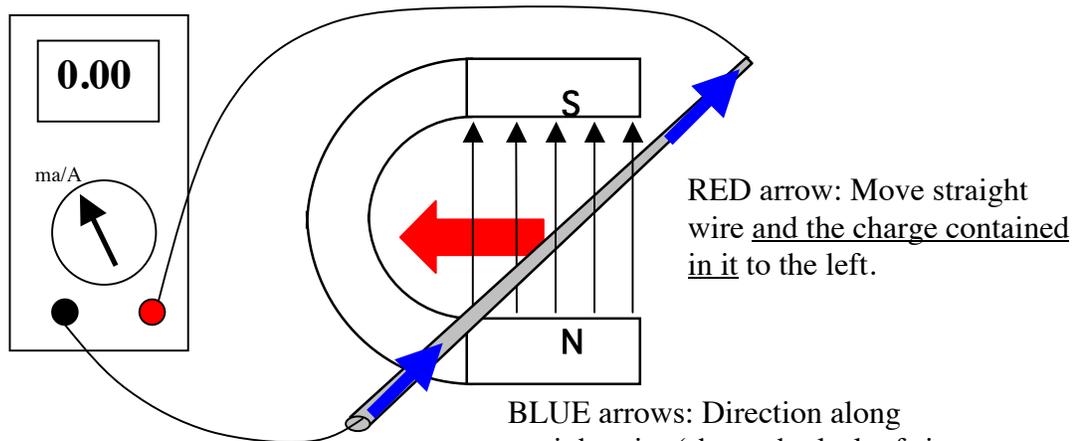


Figure 11.12

(Figure 11.11a WITH DIRECTIONAL ARROWS AND EXPLANATION)

### 11.13 Discussion: Is the moving wire behaving like a battery?

Imagine that the multimeter in Figure 11.11a is replaced by a light bulb. The wire moving in a magnetic field will cause charge flow through the bulb -- exactly like it caused flow through the multimeter. This is the generator effect. Is there an electric pressure difference in the generator terminals driving charge flow through the bulb -- just like in battery terminals? Why or why not?

### 11.14 Commentary: Electromotance created by magnetic pushing on moving charge

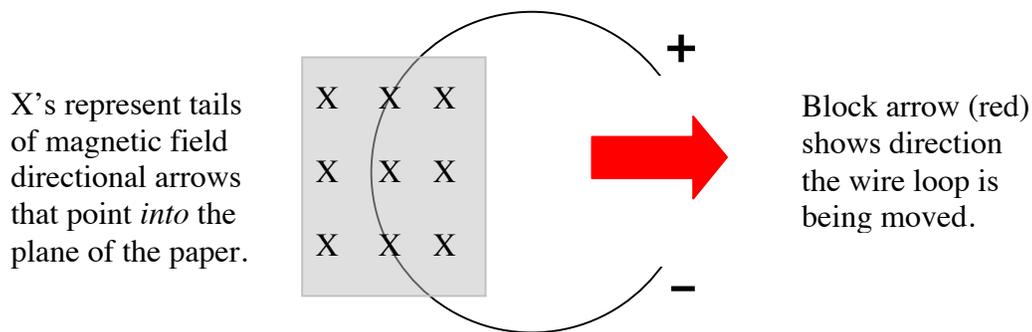
In Section 6 it was pointed out that the pressure difference  $\Delta V$  in a battery's terminals is due to the chemical activity strength  $\mathcal{E}$  in the battery. A quantitative value was assigned to  $\mathcal{E}$  that is large or small according to whether the voltage  $\Delta V$  in the battery terminals is large or small:

$\mathcal{E}$  = magnitude of  $\Delta V$  measured before the battery is connected in a circuit

The voltage-creating strength of a generator is called the "electromotance" of the coil, and can be assigned a quantitative value  $\mathcal{E}$  in the same manner:

$\mathcal{E}$  = magnitude of  $\Delta V$  measured before the generator is connected in a circuit

To identify the variables that this magnitude depends on, consider a loop of wire moving to the right in a magnetic field as in Figure 11.14a. It is important to be aware that mobile charge is always present in this wire. Mobile charge in the part of the wire that's moving in the gray-shaded magnetic field will experience a force exerted by the magnetic field that makes it move in a clockwise direction. This movement will bring more than the normal amount of charge (+) into the upper end of the wire and leave the amount in the lower end below normal (-).



**Figure 11.14a**  
**MAGNETIC PUSHING ON MOVING CHARGE**

A battery causes a similar build-up of (+) and (-) charge in the free ends of the wires connected to its terminals, as shown in Figure 11.14b. Chemical charge-pushing in a battery can maintain an excess (+) and deficiency (-) of mobile charge in the free ends of the wires for a long time. In the case of magnetic charge-pushing, however, the (+) and (-) charge accumulations will disappear very rapidly after the wire stops moving.

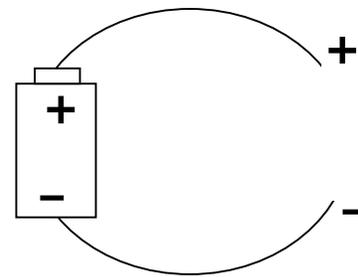


Figure 11.14b

Two turns of coil wire will create double the pressure difference in the ends of the coil. Think of a two-turn coil as acting like two batteries in series, which will drive twice as much (+) and (-) charge onto the plates of a capacitor that they are connected to, and make the pressure difference across the capacitor twice as great. Figure 11.14c shows the basis for similar behavior by a generator coil.

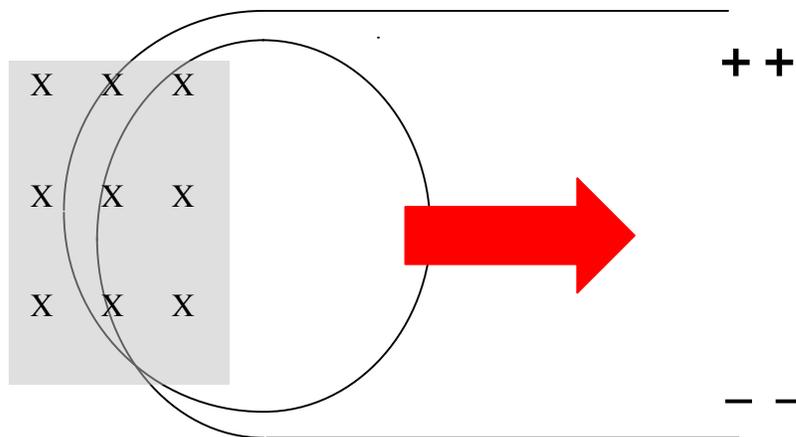


Figure 11.14c

This example – supplemented by examples for a three-turn coil, a four-turn coil, etc. -- shows that the electric pressure difference created by wire moving in a magnetic field is proportional to the length of the moving wire. Thus, the electromotance ( $\epsilon$ ) that causes this pressure difference is proportional to the length ( $l$ ) of wire moving in a magnetic field.

Knowing that we can make bulbs glow brighter by cranking a Genecon faster suggests that the pressure difference created across a moving coil also varies directly with the speed of hand cranking and coil wire movement. So it seems reasonable to assume that the electromotance is also proportional to the velocity ( $v$ ) of the wire moving in a magnetic field.

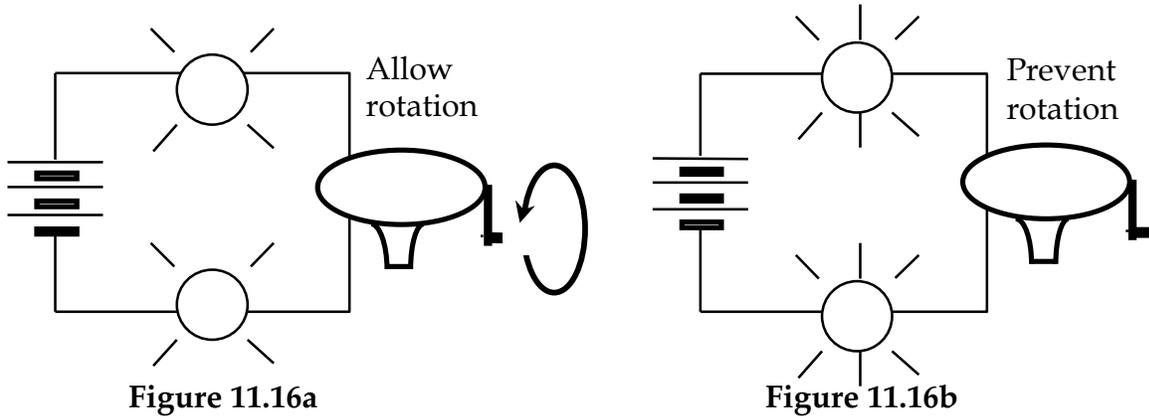
Since we know that moving a wire in a stronger magnetic field produces a greater electric pressure difference in the ends of the wire, it seems reasonable to assume that the electromotance is also proportional to the strength ( $B$ ) of the magnetic field. This kind of reasoning suggests (though of course it does not prove) that the product of magnetic field strength ( $B$ ), wire length ( $l$ ), and wire velocity ( $v$ ) determines the strength of the electromotance created by the generator effect. All this can be expressed by a simple equation:

$$\epsilon = B l v.$$

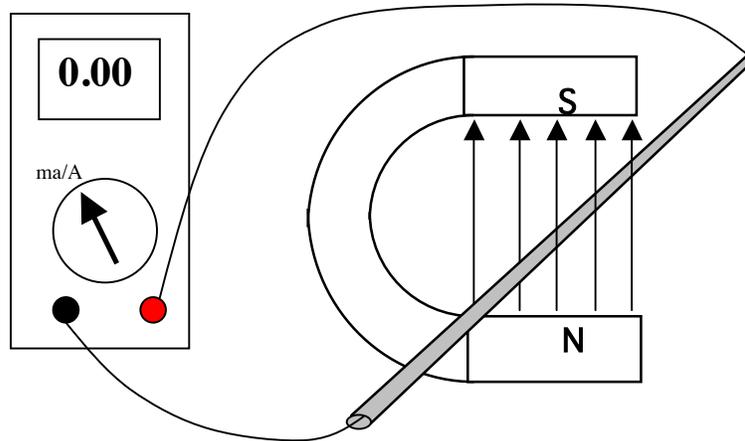
**INVESTIGATION FOUR: CAN THE MOTOR & GENERATOR EFFECTS OCCUR SIMULTANEOUSLY?**

**11.16 Activity: An additional effect in using the Genecon as a motor**

Connect a battery to your Genecon and observe the motor effect (Figure 11.16a). Then hold the crank motionless – don't let it rotate (Figure 11.16b)

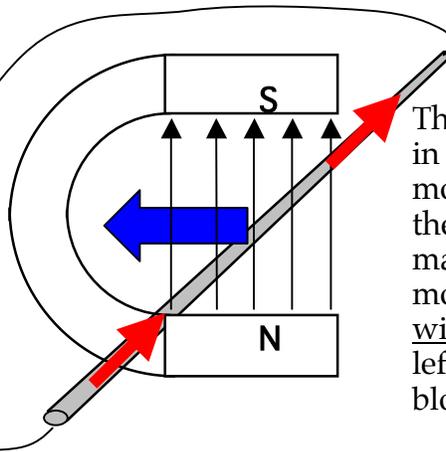
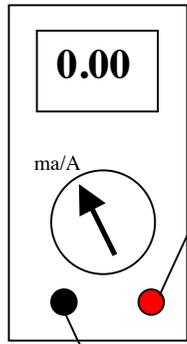


1. Compare your observations of bulb lighting in these cases. Compare also with the case where
  - a) your hand just gently obstructs crank movement, allowing rotation at a slower rate
  - b) your hand makes the crank turn in the “wrong” direction -- opposite to free rotation
2. Can you suggest a mechanism that would explain the observed variations in bulb lighting? Draw arrows on Figure 11.16c to illustrate your reasoning.



**Figure 11.16c**

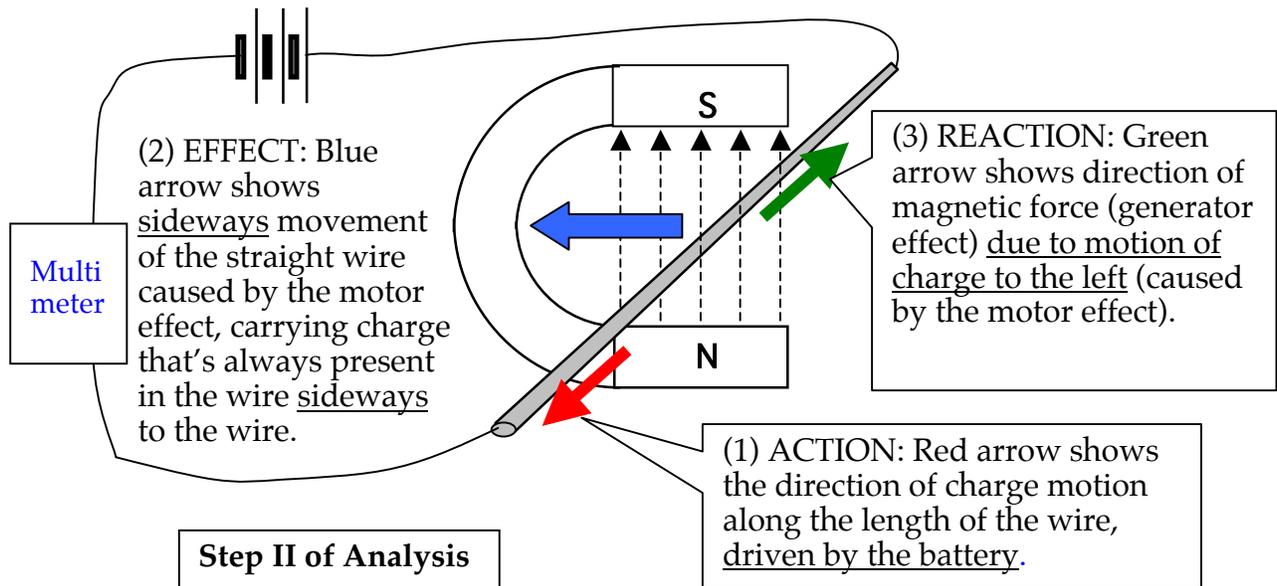
Why does the free-rotation generator effect oppose the battery that causes it? Two stages of arrow-drawing on Figure 11.16c can show that this is how the Right Hand Rule works.



The battery causes charge in the gray-shaded wire to move in the direction of the solid (red) arrows. A magnetic field pushes this moving charge and the wire that contains it to the left, in the direction of the block (blue) arrow.

**Step I of Analysis**

Charge pushed along the straight wire (red arrows) by the battery is also pushed sideways to the wire (blue arrow) by the magnetic field acting on moving charge. The sideways movement is the motor effect.



Multi meter

(2) EFFECT: Blue arrow shows sideways movement of the straight wire caused by the motor effect, carrying charge that's always present in the wire sideways to the wire.

(3) REACTION: Green arrow shows direction of magnetic force (generator effect) due to motion of charge to the left (caused by the motor effect).

(1) ACTION: Red arrow shows the direction of charge motion along the length of the wire, driven by the battery.

**Step II of Analysis**

Now use the Right Hand Rule to determine the direction of the magnetic force on charge moving to the left. This force opposes the motion of charge along the wire. This force decreases the speed of charge along the wire resulting in a smaller speed of charge. The effect is equivalent to adding a cell in a circuit, oriented to oppose the battery. This is the generator effect.

### 11.17 Activity: An additional effect in using the Genecon as a generator

1. Use a Genecon to light a long bulb as shown in Figure 11.17a. Try to keep the bulb brightness constant. (To provide a comparison brightness for you to match, light a long bulb in a circuit with two D-cells.)

2. Repeat with two long bulbs in parallel -- and then with three. Try to keep the brightness of these bulbs the same as for the single bulb. As you crank, pay attention to rate of cranking and to the force you exert on the handle in each of the three cases. You may get a better feel for the forces if you have your partner add the extra bulbs while you continue cranking.

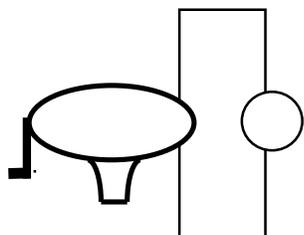


Figure 11.17a

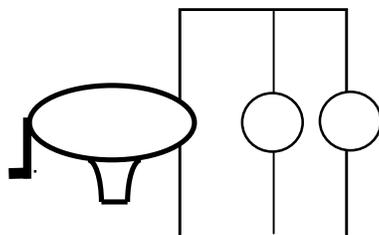


Figure 11.17b

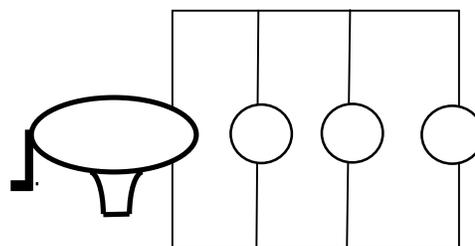


Figure 11.17c

3. Next you should replace the bulb in 11.17a with a single wire as in Figure 11.17d and attempt to keep cranking the handle at the same rate of rotation. First, however, predict you the force you must exert will be different.

Prediction:

Observation:

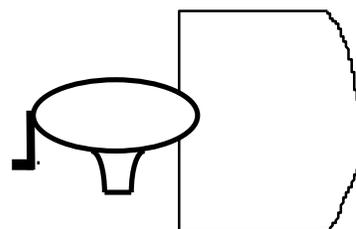


Figure 11.17d

4. What do you think is the mechanism by which a Genecon makes it necessary for you to crank harder (use a greater force) to make more charge flow in a circuit? Draw arrows on Figure 11.17e to illustrate your reasoning.

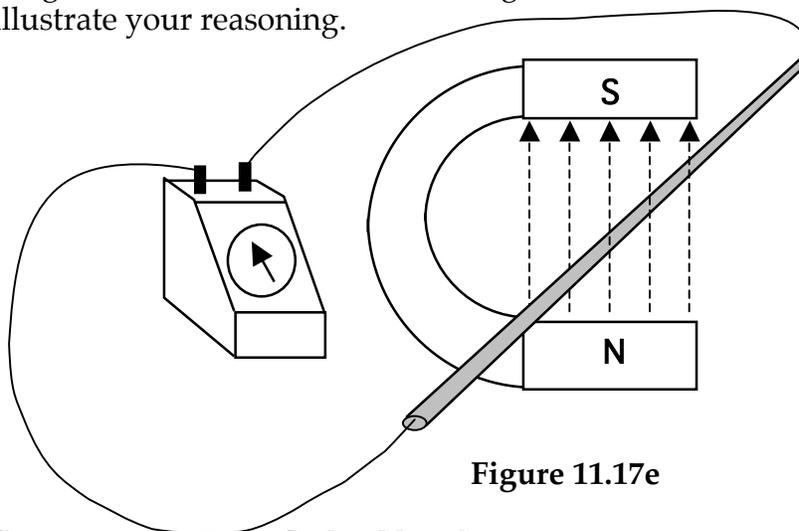
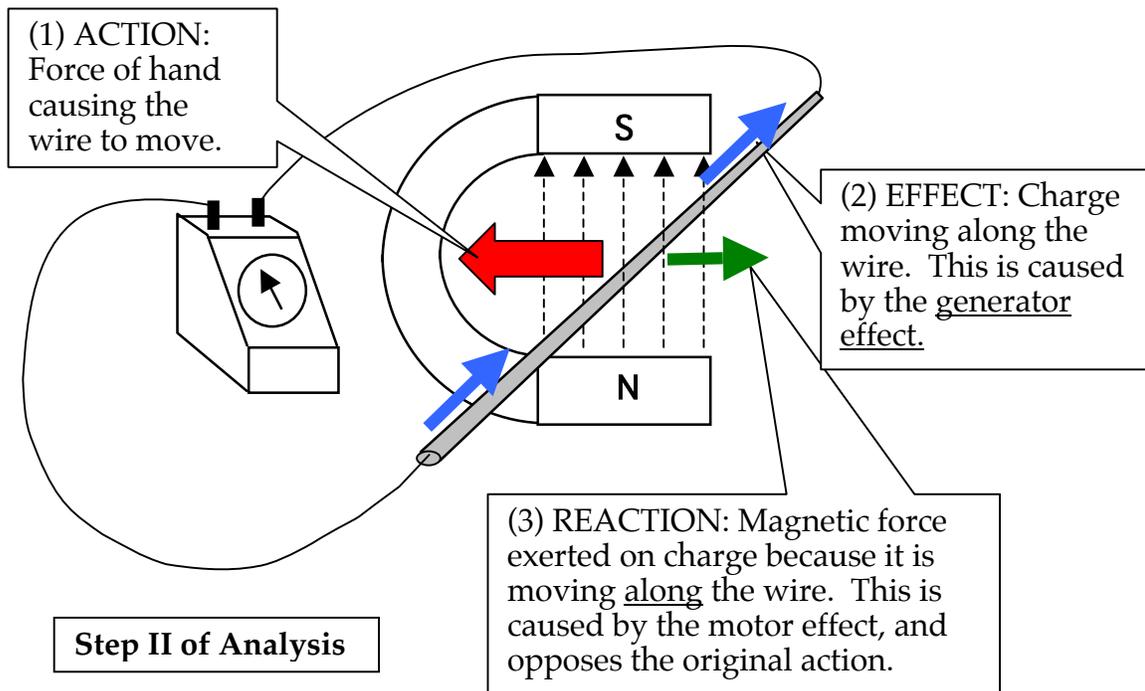
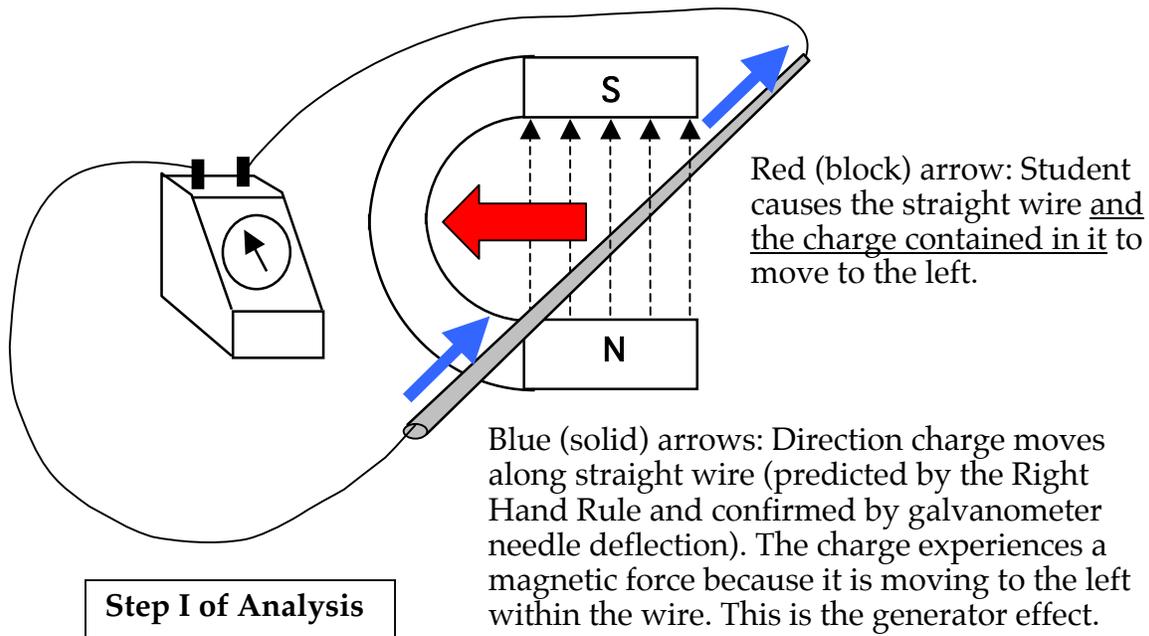


Figure 11.17e

Why does it take more force to crank the handle of the Genecon when more bulbs are added in parallel? As before, a two-step analysis can show why this happens.



Conclusion: A Genecon is never solely acting as just a generator or just a motor. You cannot have one without causing the other.

## INVESTIGATION FIVE: OPTIONAL INQUIRIES

### 11.18 Optional Activity: Revisiting the right hand rule with a cathode ray oscilloscope

In Activity 11.5, the charge in coil wire was made to move parallel to the magnetic field lines -- and there was very little deflection of the galvanometer. This suggests that zero force is exerted by a magnetic field on charge moving parallel to the magnetic field lines, or in the opposite direction -- and that the force exerted is maximum when the charge is moving perpendicular to the field lines.

This can be demonstrated visually with a cathode ray oscilloscope. First, stop the sweep of the electron beam, so there is a single spot in the middle of the screen. Then bring the end of a bar magnet directly toward the screen. There will be no deflection when either end of the magnet is brought straight in toward the screen. Recall from our earlier mapping of the magnetic field lines around the poles of a magnet that the field lines tend to point directly toward or directly away from magnetic poles. Therefore, charge that's directly approaching the pole of a magnet moves essentially parallel to the field lines, and there will be little or no deflection. But when the bar magnet is placed parallel to the screen, a large force will be exerted on the electrons moving in the beam -- and there will be a noticeable amount of deflection.

### 11.19 Optional Discussion: Shaping the magnetic field inside the motor

To maximize the magnetic force that drives the motor and generator effects, it is a good idea to make the field lines inside the Genecon motor as nearly as possible perpendicular to the path of the rotating coil wire. The class should discuss the best shape the magnets in the motor could have in order to support a magnetic field shaped so that the outer part of the rotating coil always moves nearly perpendicular to the magnetic field lines. Think about the structure of the Genecon motor inside the cylindrical shell housing:

- Is there a reason to want the magnets curved -- aside from fitting the curved cylinder?
- Speculate about why many electric motors have a cylinder of iron inside the wire coils.

The two large half-circles represent curved thin magnets glued to the inside of the cylinder.

The gray circle in the center represents the iron core, which helps focus the magnetic field lines.

Curved lines from top magnet to bottom magnet through the iron core are magnetic field lines.

The large circular arrow shows path of the outer part of the coil as it rotates inside the magnets.

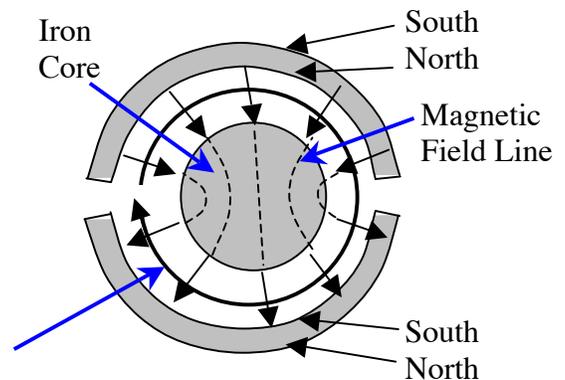


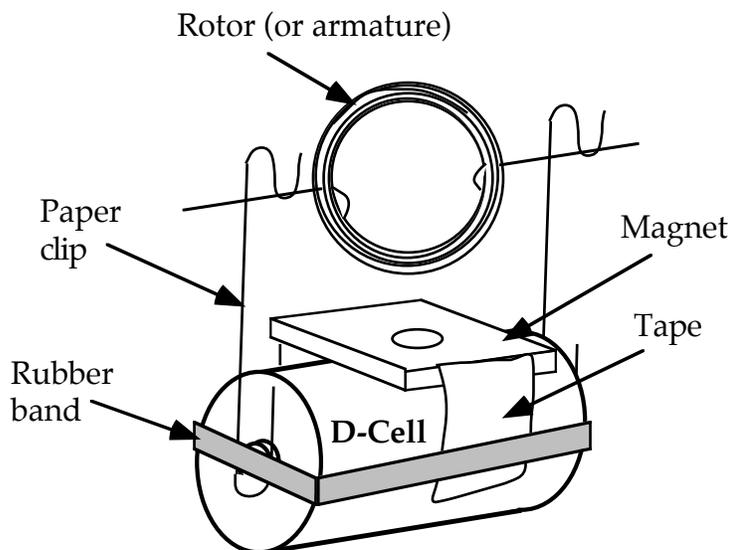
Figure 11.19  
MOTOR INTERIOR

## 11.20 Optional Activity: Making a small single-coil motor

Making a motor takes many steps. In making your motor, you will learn how current can get to the coil and what you have to do to make the coil turn continuously in one direction.

The following list describes the parts that are common to any DC motor.

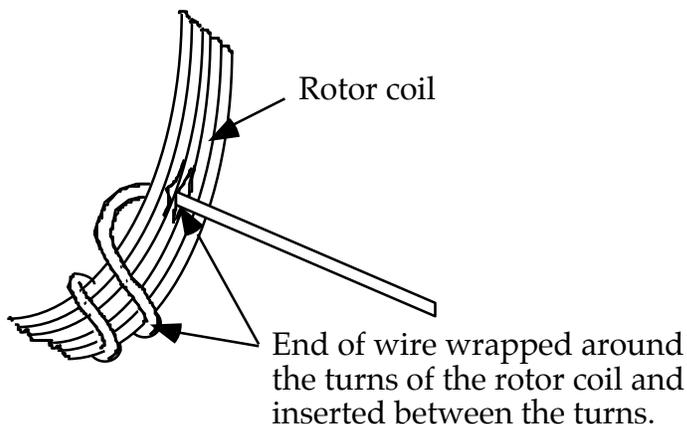
- Field magnet – a magnet that supports the magnetic field in which a coil rotates.
- Armature (or rotor) – a coil of wire that rotates on an axis.
- Commutator – a switching device attached to the armature. It changes the direction of charge flow through the armature in order to keep it rotating.



**Figure 11.20a**  
**FINAL MOTOR CONSTRUCTION**

The completed motor will look like the diagram in Figure 11.20a. Detailed instructions follow.

1. To form the rotor coil, wind approximately 1.5 meters of magnet wire tightly around a test tube or D-Cell, film canister, or some other cylindrical object; the diameter of the coil should be between 2.5 and 5 cm. Leave about 7 cm of wire free at each end.

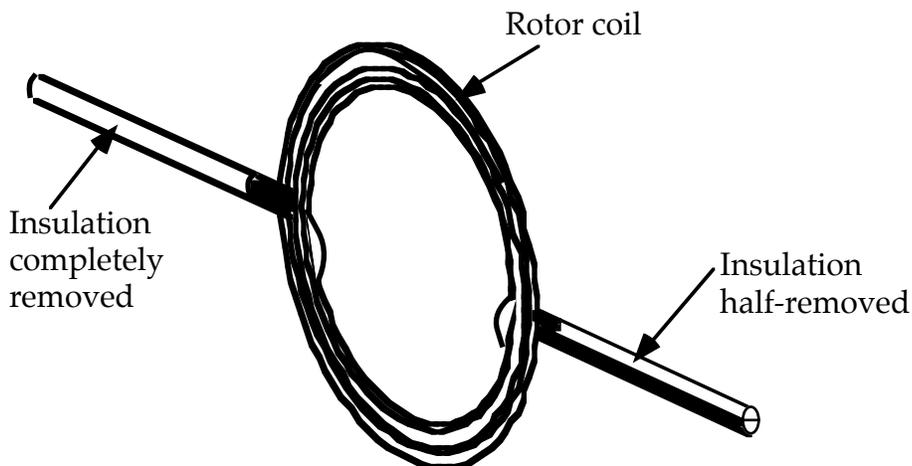


**Figure 11.20b**  
**THE ROTOR COIL**

2. Loop the ends of the wire around and through the rotor coil to hold it firmly together so it doesn't unwind. It is critical that the two end wires are centered and bent parallel to each other across the coil.

3. Completely remove the insulation from one end of the coil wire. To do this, lay the coil flat on the desk and rub the end with sandpaper, turning the wire to scrape off **all** insulation.

4. At the other end of the coil wire, remove **half** the insulation.



**Figure 11.20c**  
**ENLARGED VIEW OF COIL**

5. Tape a flat magnet to a D-cell as shown in 11.20a. (To stabilize the D-cell, you may want to tape it to the desk or to an upside-down foam cup.)

6. Bend the paper clips as in the diagram. Attach them to the D-cell with a rubber band or with tape.

7. Place the coil in the paper clip supports. Spin the coil, and it should continue to spin by itself – a working motor! If it does not, proceed to the Troubleshooting Instructions.

**Troubleshooting Instructions:**

1. If nothing happens, there may not be any current through the coil:
  - a) Spin the coil while squeezing the clips against the battery for better contact.
  - b) Try using someone else's battery and clips. If it spins, check your battery.
  - c) Check to see that the insulation is completely removed from the free end of one wire and half-removed from the free end of the second wire.
2. If the coil rocks back and forth but won't spin, check its balance and adjust the free ends to distribute the weight more evenly.

## SUMMARY EXERCISE

1. Define “motor” and “generator” in terms of the energy transfer that occurs when they are used.
2. What does the term “magnetic field” describe? How can you tell if a magnetic field exists at a given location in space?
3. The Right Hand Rule uses three vectors to represent the directions of three factors at any given space point that are involved in magnetic effects that occur in motors and generators. What are the three directions that these vectors represent?
4. We know it is difficult to crank a generator that is connected to nothing but a wire. Explain why this is so.
5. A bulb and a Genecon are in series with a battery. If you stop the Genecon handle from rotating, the bulb gets brighter. Explain why this happens?
6. A bulb and a Genecon are in series with a battery. When you use your hand to change the rotation rate of the handle, which direction do you push to make the bulb immediately get brighter.
7. In a Genecon charge in the coils always moves in two directions—along the length of the wires and in the direction the coils are moving. If the charge moving along the length of coil wires causes the coil to rotate, is the Genecon being used as a motor or a generator? Explain how you know.