

Section 3

WHERE DOES THE MOVING CHARGE ORIGINATE?

INTRODUCTION

Where does the charge that flows through a light bulb filament come from? Where was it located before it began to move? These questions will be investigated using a charge-storing device called a “capacitor” in the battery-and-bulbs circuits that we used in the previous section.

SCHEMATIC DIAGRAMS WITH BULB LIGHTING AND CHARGE FLOW

3.1 Commentary: Schematic diagrams with battery, wires and bulbs

Many of the circuit diagrams in earlier sections sketched the “visual” appearance of circuits — drawing batteries, bulbs, and wires as they actually appear. From now on we will draw “schematic” diagrams — using symbols to represent the circuit components. The battery symbols used in this manual from now on are shown in Figure 3.1a.

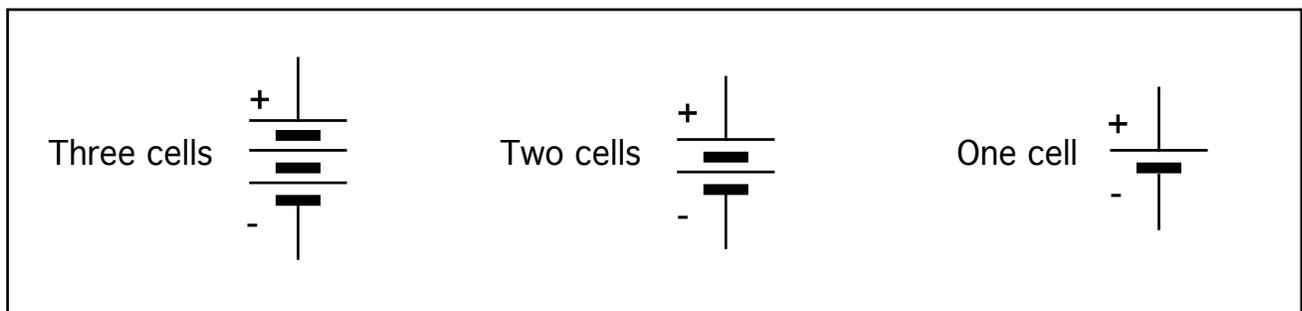


Figure 3.1a
SYMBOLS FOR BATTERIES

The “+” near the long line shows that it represents the positive terminal of the battery. The “-” near the short, thick line shows that it represents the negative terminal of the battery.

Besides the symbol for the battery, other symbols will be used for drawing schematic diagrams. (Figure 3.1b)

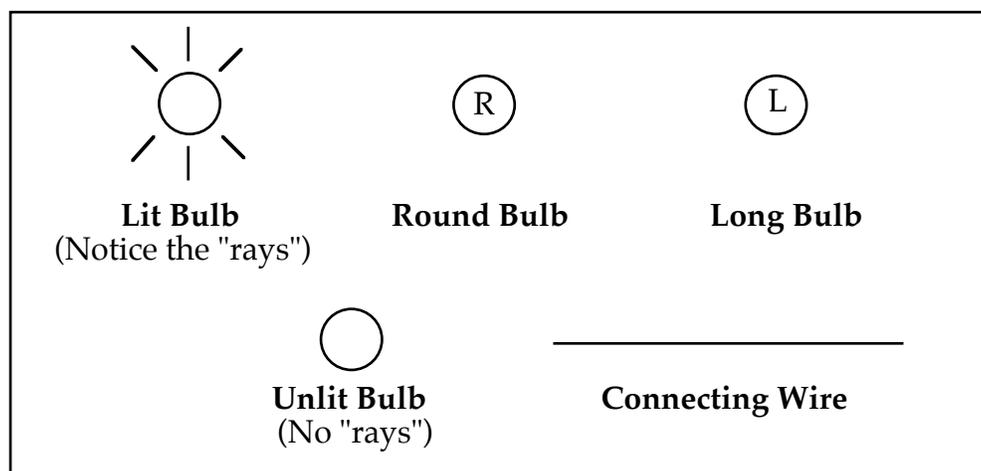


Figure 3.1b
SYMBOLS FOR WIRES AND BULBS

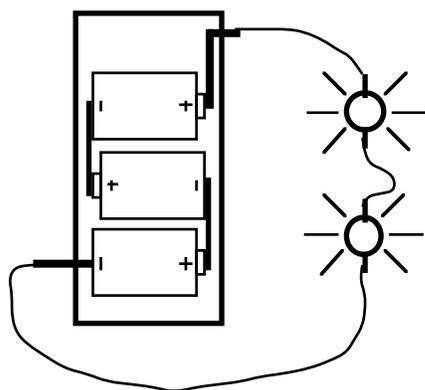


Figure 3.1c
VISUAL APPEARANCE

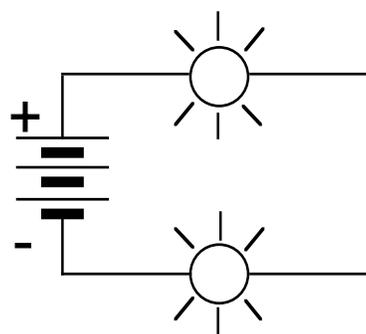


Figure 3.1d
SCHEMATIC DIAGRAM

Figure 3.1c shows the appearance of three cells, two lit bulbs and connecting wires which form a closed conducting loop. Figure 3.1d shows a schematic diagram of the same circuit.

3.2 Commentary: Representing conventional charge flow (Review)

The deflection of a compass needle under a wire will reverse if the direction of charge flow in the wire reverses. But it cannot tell you which of the two possible directions of charge flow is the actual one. The direction of movement in a simple circuit with lit bulbs is either clockwise or counter-clockwise – but a compass cannot tell you which is actually occurring.

To avoid confusion, we need to assume charge travels in one of the two possible directions in a wire. The scientific and engineering professions agreed long ago on a “conventional” flow direction.

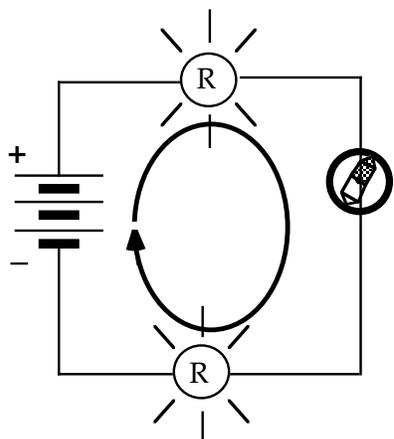


Figure 3.2a
Standard Battery Orientation

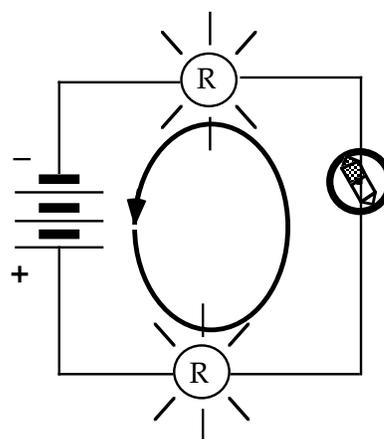
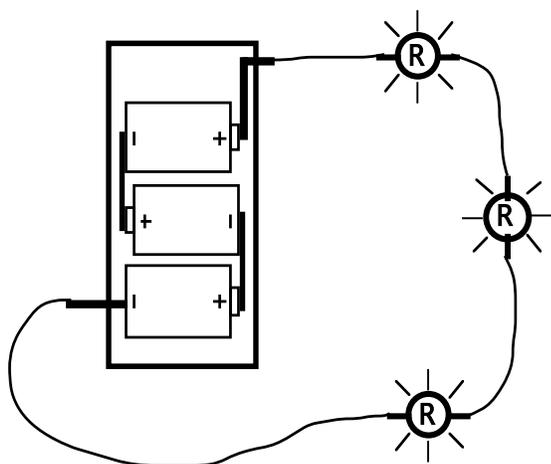


Figure 3.2b
Reversed Battery Orientation

The word “conventional” means by agreement – and the agreement is that mobile charge in a circuit with a single battery is assumed to flow out of the “+” terminal of the battery and into the “-” terminal. Arrows in Figures 3.2a and 3.2b illustrate this conventional flow direction. The arrows in these schematic diagrams are drawn as one continuous (unbroken) arrow – to represent continuous flow through the bulbs and wires.

3.3 Exercise: Drawing circuit diagrams

1. In the space to the right of the visual representation in Figure 3.3a, draw a schematic diagram of the circuit.



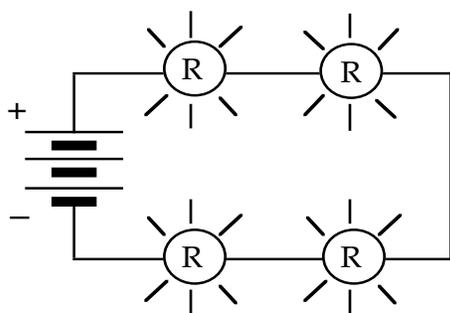
VISUAL APPEARANCE

DRAW SCHEMATIC DIAGRAM

Figure 3.3a

2. On the diagram you made for question 1, draw a continuous arrow to show where and in what direction charge is flowing — according to “conventional flow”.

3. In the space to the right of the schematic diagram in Figure 3.3b below, draw a visual representation of the circuit.



SCHEMATIC DIAGRAM

DRAW VISUAL APPEARANCE

Figure 3.3b

4. Draw a continuous arrow on the schematic diagram in question 3, to show where and in what direction charge is flowing — according to “conventional flow”.

INVESTIGATION ONE: WHAT DOES A CAPACITOR DO IN A CIRCUIT?

3.4 Commentary: What is a capacitor?

Two layers of conducting material separated by a layer of an excellent insulator form what is called a **CAPACITOR**. The name comes from the “capacity” of this three-layer device to store charge. The conducting layers are called capacitor **PLATES**. The insulating layer prevents movement of charge from one plate to the other inside the capacitor. You can make a simple capacitor by placing a sheet of waxed paper between two sheets of aluminum foil.

In most capacitors the plates have very large surface area -- so they can store a large amount of charge. The plates are also made very thin, so that the three layers can be rolled into a cylinder and placed inside a small can. Each plate has a screw or a wire attached to it, called a **TERMINAL**, which extends outside the can and allows the plate to be connected to a circuit.

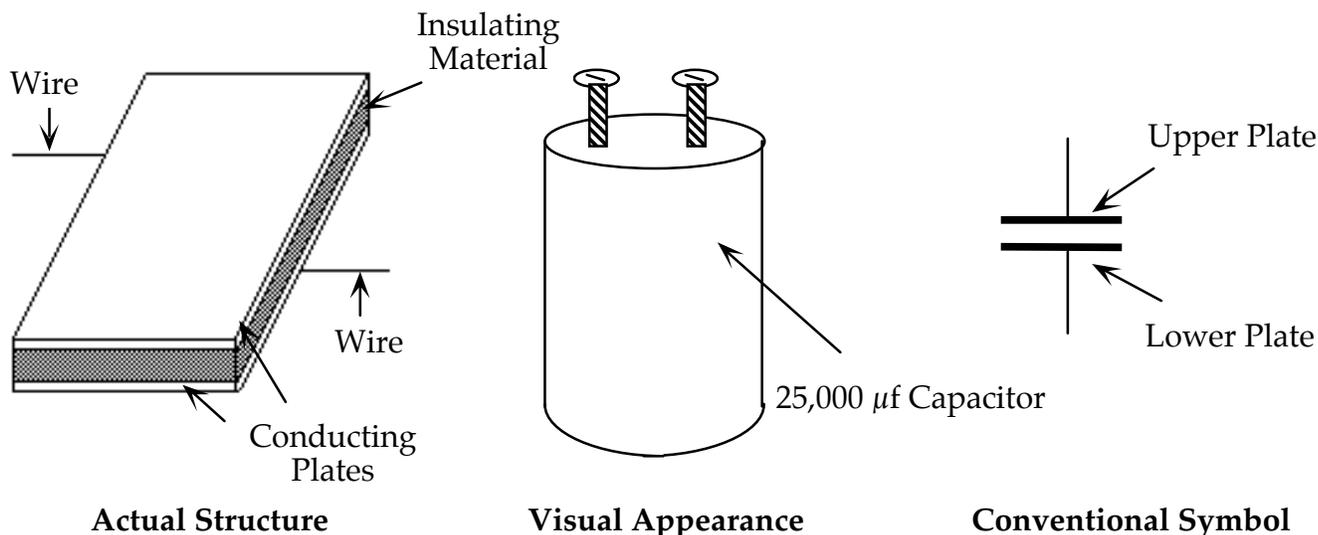


Figure 3.4 – CAPACITOR DIAGRAMS

The “charge-holding” ability of a capacitor is called its **CAPACITANCE**. Capacitance is measured in a unit called the **FARAD**, named after the British scientist Michael Faraday (1791-1867). The capacitor in your CASTLE kit has a capacitance of 0.025 farad, or 25,000 microfarads (μF or MFD).

Some older kits may also have a small capacitor with a capacitance of .005 farad, which will not be used at this time. Your teacher will have some large capacitors, which are to be shared by the class in a number of activities. These have a capacitance of 0.1 farad, or $100,000\mu\text{f}$ — four times as much as the 0.025 farad capacitor.

NOTE: Sometimes capacitor plates may pick up stray charge that needs to be removed. A good way to avoid this problem is to keep a wire connected to the terminals of your capacitor when you are not using it. Also, after using a capacitor you will want to “**neutralize**” it so you can start all over again. To do this, touch a wire simultaneously to both of the capacitor terminals.

3.5 Activity: What happens to charge that flows into a capacitor plate?

Look at Figure 3.5a, but don’t assemble the circuit yet. This is the same circuit you have been using, but with a capacitor added between the two bulbs. (Remember that an “R” inside a circle represents a round bulb.) Note that the compass is under the wire that could carry charge coming out of the battery into the upper capacitor plate.

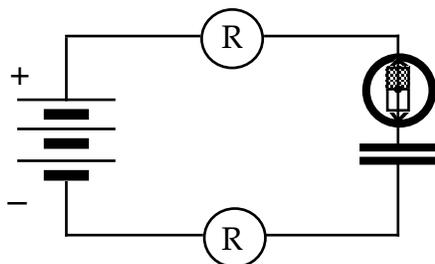


Figure 3.5a
CAPACITOR CHARGING

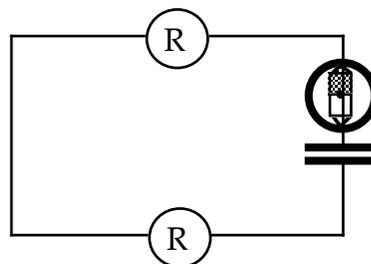


Figure 3.5b
CAPACITOR DISCHARGING

Assemble the circuit illustrated in Figure 3.5a using the 0.025 farad capacitor from your kit, but leave a break somewhere in the circuit. Position the compass under the wire connected to the top capacitor plate, and **be sure to orient the wire so that it is parallel to the needle.**

1. The process that occurs in the circuit after you close the loop is called **CHARGING A CAPACITOR**. What did you observe as you watched the bulbs and the compass?

You can repeat the capacitor charging process by first discharging it. The procedure is:

- break the circuit somewhere by disconnecting a wire.
- touch the ends of an extra wire simultaneously to both capacitor terminals.
- reconnect the loop to start over again.

2. Compare the direction of compass deflection to the direction when there is **no capacitor** in the circuit – just the battery and bulbs. An easy way to do this is:
 - a) remove the capacitor from the circuit – but be sure to keep the wire over the compass in place.
 - b) close the loop to form a circuit with only the battery and two bulbs.

Observations?

3. Draw an arrow (or arrows) on Figure 3.5a to show where and in what direction you think charge moves during the capacitor charging process.



Charge the capacitor again as you did in step #1 above. Then remove the battery from the circuit and close the loop. Do this while holding the wire down on top of the compass which is taped in place.

4. The process that occurs in the circuit after you close the loop without the battery in it (Figure 3.5b) is called **DISCHARGING A CAPACITOR**. What did you observe as you watched the bulbs and the compass?
5. Draw an arrow (or arrows) on Figure 3.5b to show where and in what direction you think charge moves during the capacitor discharging process.

Repeat the capacitor charging and discharging processes a few times, to be sure of your observations.

Ask your teacher for a large 0.10 farad capacitor. Remove the 0.025 farad capacitor from the circuit, and replace it with the 0.10 farad capacitor. With the battery in the circuit, charge and discharge the large 0.10 farad capacitor several times in the same way, observing the bulbs and compass needle.

6. Are the bulbs lit longer using the 0.025 farad capacitor or the 0.10 farad capacitor? Speculate: Why do you think this happens?

3.6 Exercise Where does the moving charge come from?

1. Does the charge that flows into the capacitor during charging get used up in the capacitor? Or does it get stored somewhere in the capacitor? How do you know?
2. Is the same thing happening in every wire during charging? Is the same thing happening in every wire during discharging? What's the evidence?

3. Where does it appear the charge originates from that lights the top bulb during capacitor charging?

4. Where does it appear the charge originates from that lights the bottom bulb during capacitor charging?

5. Where does it appear the charge originates from that lights the bottom bulb during capacitor discharging?

6. Consider this statement regarding these circuits: If charge is moving in one part of the circuit, then charge is moving everywhere in the circuit.

True or False? _____ What's the evidence?

Do you think the wires are ever empty of charge? _____

INVESTIGATION TWO: HOW IS CHARGE DIFFERENT FROM ENERGY?

3.7 Activity: Non-battery origin of charge — using a Genecon

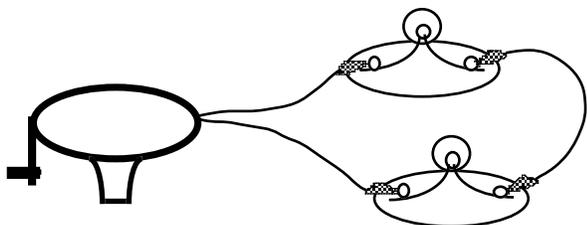


Figure 3.7a
GENECON IN A CIRCUIT

Remove the battery from the circuit you have been using, and replace it with a Genecon. Remove the capacitor, and connect the free ends of the wires to each other. That will give you the circuit illustrated in Figure 3.7a.

Turn the crank on the Genecon at a steady rate of one or two revolutions each second, and feel the effort needed for lighting the bulbs. **Caution:** if you turn the crank too rapidly you will burn out the bulbs!

1. Unscrew one of the bulbs enough to break the circuit. Then turn the crank on the Genecon for about ten seconds. Is it easy or difficult to turn the crank when the circuit is broken?

Turn the bulb back in to complete the circuit, and turn the crank at about the same speed as before.

2. Is there any difference in the “effort” required to keep the Genecon turning at the same speed?



3. Since the bulbs light, what can you conclude about what a Genecon does?

Set up the circuit in Figure 3.7b, with only ONE D-cell in the battery holder. Carefully observe the brightness of the bulbs.

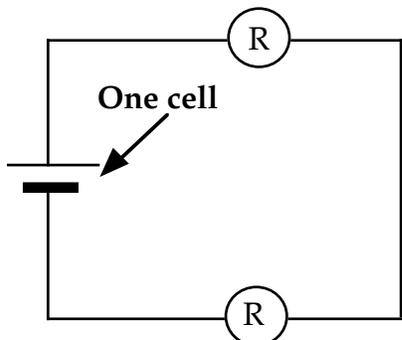


Figure 3.7b
CIRCUIT WITH ONE D-CELL IN BATTERY HOLDER

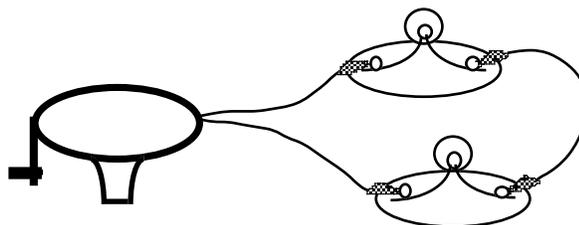


Figure 3.7c
CRANK GENECON TO PRODUCE SAME BRIGHTNESS

4. Observing the brightness of the bulbs in Figure 3.7b, crank the Genecon until the bulbs have the same brightness as with one D-cell. During ten seconds, approximately how many turns of the crank do you have to make in order to maintain this brightness?

5. Put TWO D-cells in the battery holder. During ten seconds, how many turns of the crank do you have to make to match the brightness of the bulbs with the 2-cell battery?

6. Estimate the number of turns needed in ten seconds to match the bulb brightness that would be produced by three D-cells.

Try it — was your prediction correct?



3.8 Exercise: The Genecon

1. When using a Genecon, where does the charge originate that moves through the bulbs?

2. A hair dryer is a pump for air. A vacuum cleaner is also an air pump. Do a battery and a Genecon act like a pump for charge? Explain.

3. How is increasing the number of D-cells in a battery holder similar to cranking a Genecon faster?

3.9 Activity: Charging an air capacitor

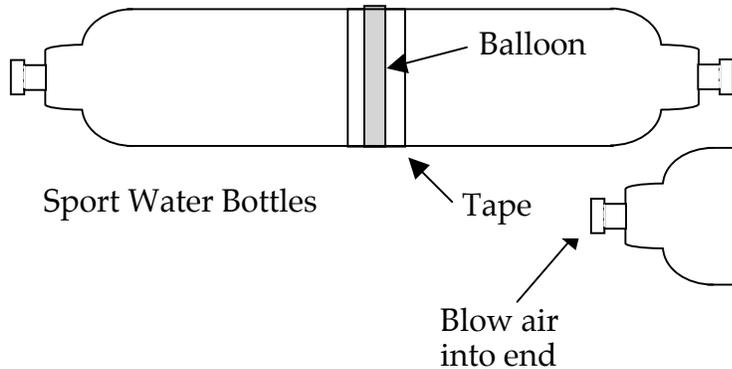


Figure 3.9a
NORMAL AIR CAPACITOR

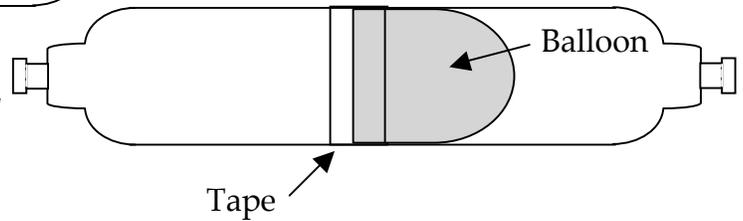


Figure 3.9b
CHARGED AIR CAPACITOR

1. Blow through the tube at one end. What happens to the balloon in the middle?
2. Repeat, except this time hold your hand near the open tube as you blow in the other end. Does any air go in or come out? If air comes out, where did the air coming out originate?
3. If air must flow through both tubes to “charge” the air capacitor, must air flow through both tubes to discharge it? “Charge” the air capacitor again and place your finger over the open tube before releasing the tube from your mouth. What happens?
4. Inhale air through the tube nearest you while keeping the other tube open. Describe what happens to the balloon. Describe all the air movements that occur.



3.10 Exercise: The air capacitor

1. When you blow air in through the one tube, air comes out through the other tube. Is the air that comes out the same air as the air that goes in? Explain.
2. How is the air capacitor similar to an electric capacitor? Explain.



3. Use your observations from the air capacitor to predict what would happen in the following circuit: A capacitor is charged, and the wire connected to the plate from which charge was pumped out is disconnected. Would you expect the charge that was pumped into the other plate to remain there? Explain your thinking. Then build the circuit to check your answer.



4. A friend argues that the air capacitor is not really like the electric capacitor because movement of the balloon is what drives air out during charging. The friend points out that there is nothing moving in the electric capacitor which could drive charge out during charging. How could you counter this argument?

5. Speculate: Using the analogy of the air capacitor, what do you think might be **making charge move** during capacitor discharging?

6. Using the air capacitor analogy, how could you relate charge, pressure, and energy?

3.11 Commentary: Benjamin Franklin's "+" and "-" notation

Movable charge is normally present in all conducting matter. Adding some charge to a normal capacitor plate will result in there being more than the normal amount of charge in the plate, while removing some charge will result in there being less than the normal amount of charge in the plate.

Benjamin Franklin (1706-1790) came to the same conclusions when he did his pioneering work in electricity a few years before the American Revolution. Franklin is the person who first used (+) and (-) symbols in electricity. However, he did not mean them in the sense of the modern explanation. He definitely was not referring to positive charge and negative charge; he simple was talking about the quantity of *one* kind of charge. He used them to represent these two conditions:

(+) represents a MORE-THAN-NORMAL amount of charge ("extra" charge)

(-) represents a LESS-THAN-NORMAL amount of charge ("missing" charge)

In the next section we shall begin using these symbols with the same meanings Franklin gave them.

3.12 Commentary: Energy in electric circuits

The term “energy” is probably one you often use. However, if you attempt to define it, you may find it difficult to do so. “Energy” is best defined as **an invisible substance that can be stored in matter and transferred to other matter** -- and is what gives matter the **ability to make something happen**. We have identified a number of things that happen in circuits – charges move, bulb filaments become hot and give off light. What is the source of the energy that makes it possible for these things happen? What are some ways to think about this energy?

In most of the circuits we have observed, the source of the stored energy has been the battery. In some circuits, however, there was no battery present. When a capacitor discharges, it can make the same things happen -- so it must also have been a source of energy when it was charged. In circuits where a Genecon was used, the source of energy was not the Genecon itself; the source of energy was the person doing the cranking. The cranking action transferred the energy stored in your muscles to moving charges and lit bulbs. The Genecon can be thought of as a pump, like a pump putting air into a tire. Energy is being transferred into the tire and can be felt as a harder tire (more pressure).



You know that batteries eventually wear down, and may become “dead”. This means that they no longer have sufficient energy stored in them to make something happen in a circuit. Some batteries are called “rechargeable” and can be re-used. This is an incorrect term, however, since the battery’s task was never to supply charge to the circuit – it was already there! These batteries would more properly be called “re-energizeable”.

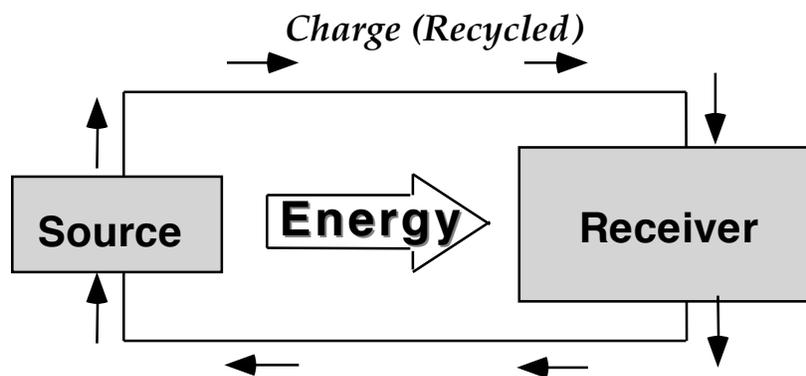


Figure 3.12

DIAGRAM REPRESENTING RECYCLING CHARGE AND ONE-WAY TRANSFER OF ENERGY FROM SOURCE TO RECEIVER

In a circuit, charge originates in every conductor, and constantly re-cycles around the circuit. However, energy leaves the energy source where it is stored and travels one-way to a receiver. Energy can leave a circuit as heat or light energy from the bulbs (the receivers of the energy). The energy source might be the stored energy in a battery, or the stored energy in muscles used to crank a Genecon, or other energy sources.

In addition to a transfer of energy (as shown in Figure 3.12), there is a transformation of energy from one type to another. For example, when charge in a circuit carries energy from source to receiver, some of the electrical energy is transformed to thermal energy and the

wires become warmer. When energy is transferred to a capacitor, the energy shows up as a difference in electrical pressure between the two plates. When charge carries energy to a bulb, some of the electrical energy is transformed to light energy. Through either heat or light, the energy is leaving the circuit.

INVESTIGATION THREE: HOW CAN A CAPACITOR DETECT AMOUNT OF RESISTANCE?

3.13 Activity: Does a connecting wire have resistance?

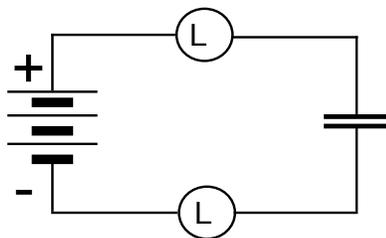


Figure 3.13a
ORDINARY CHARGING
CIRCUIT

Be sure to predict what you will observe before you do this activity!

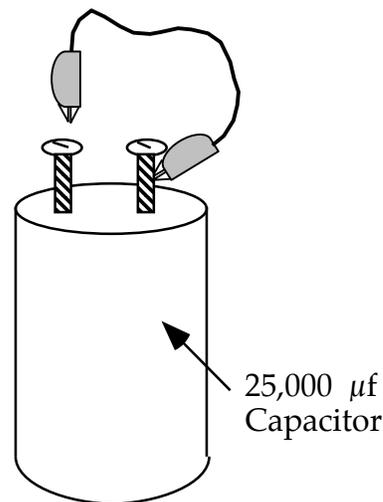


Figure 3.13b
VERY BRIEF CONTACT!

1. What do you predict you will observe when you follow the procedure below?

Prediction:

Procedure:

- Charge a 0.025 farad capacitor through two **long** bulbs as in Figure 3.13a.
 - Carefully remove the charged capacitor from the circuit.
 - Attach a clip from a connecting wire to one terminal.
 - Then **tap** the other clip on the second terminal for as short an instant as you possibly can, as in Figure 3.13b.
 - Remove the connecting wire.
 - Remove the battery from the circuit and return the capacitor to the circuit.
 - Discharge the capacitor through the bulbs.
2. Describe your observations when you actually complete the procedure.
3. Explain what this investigation indicates regarding the resistance of the connecting wire.

3.14 Activity: Does a battery have internal resistance?

For this activity you may need to darken the room for careful observations. Also – ask the teacher for old ‘run-down’ D-cells.

1. Charge a 0.025 farad capacitor through two **round** bulbs while carefully observing the brightness of the bulbs and the length of time they stay lit. Disconnect the battery and discharge the capacitor. What is the difference you observe in bulb brightness and lighting time?



2. Based on bulb brightness, when does the circuit have more resistance – during charging or discharging? Speculate: how can you account for the difference in resistance of the circuit?

3. If you notice that the beam from a flashlight has become dimmer than when it was new, what has happened to the flow rate of charge through its filament? Based on your observations above, is it more likely that over time resistance has increased in the bulb filament or in the battery?

SUMMARY EXERCISE

1. What is the **direction** of charge flow when charging a capacitor? When discharging a capacitor? What is the evidence?
2. Consider a circuit with a capacitor, a battery, wires and two bulbs. What is the **source** of charge during:
 - a. capacitor charging?
 - b. capacitor discharging?
3. What is the cause of charge motion during capacitor charging?
4. Ordinarily you think of charge flowing in a circuit when wires are connected to a battery. Explain how it is possible for bulbs to light in a circuit in which a capacitor is discharging even though there is **NO BATTERY** in the circuit.
5. Consider a circuit with a Genecon, wires and bulbs. What is the source of charge while the bulbs are lit?
6. Where is the source of energy while the bulbs are lit?

7. How are a Genecon and a battery similar when they are connected to a circuit? How are they different? Use the terms “charge” and “energy” in your comparison.

8. How would Benjamin Franklin have described the condition of the plates in a charged capacitor compared with the plates in an uncharged capacitor?

9. In the previous section, you identified two examples of evidence that a wire has essentially zero resistance. In this section you identified an additional example. Describe all three.

10. Describe an investigation which suggests that battery cells have internal resistance.

11. From the experiments you have done and the assumptions we have made, you now have an idea or **model** of the behavior of electricity. List the findings and assumptions that make up this model and describe the supporting evidence that leads you to the assumptions.