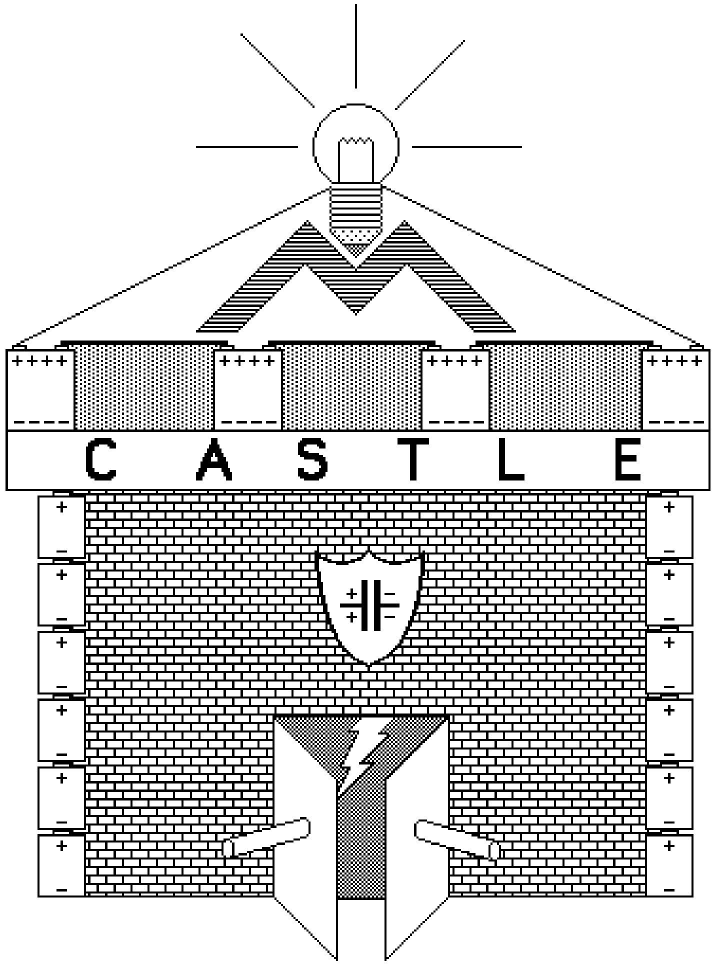
ELECTRICITY VISUALIZED

The **CASTLE** Project



CAPACITOR-AIDED SYSTEM

for

TEACHING AND LEARNING

ELECTRICITY

STUDENT MANUAL

The CASTLE Project

Project Director:

Melvin S. Steinberg, Department of Physics, Smith College

Authors:

Delphia N. Bryant, Frederick Douglass High School, Atlanta, Georgia
Sheila M. Cronin, Avon High School, Avon, Connecticut
Michael L. Cunha, Weaver High School, Hartford, Connecticut
Joseph Drenchko, Cicero-North Syracuse High School, Cicero, New York
Gene L. Ewald, Cuyahoga Falls High School, Cuyahoga Falls, Ohio
Richard B. Feren, Milford High School, Milford, New Hampshire
John D. FitzGibbons, Cazenovia High School, Cazenovia, New York
Mickey Maholtz, Curwensville Area Schools, Curwensville, Pennsylvania
Robert A. Morse, St. Albans School, Washington, D.C.
Marvin L. Nelson, Green River Community College, Auburn, Washington
Fred B. Otto, Maine Maritime Academy, Castine, Maine
Melvin S. Steinberg, Smith College, Northampton, Massachusetts
Louis C. Turner, Western Reserve Academy, Hudson, Ohio
Camille L. Wainwright, Pacific University, Forest Grove, Oregon

Editor:

Camille L. Wainwright, Professor of Science Education, Pacific University

This publication is a product of the CASTLE Project, which has been supported by the National Science Foundation under grant number MDR-9050189 and the US Department of Education National Diffusion Network (grant number RO73A 40037). Any opinions, findings, conclusions, or recommendations expressed in it are those of the authors and do not necessarily reflect the views of the grantees or the Publisher.

Section 1

WHAT IS HAPPENING IN THE WIRES?

INTRODUCTION

Electricity is usually invisible. Except for lightning and sparks, you never see it in daily life. However, light bulbs and a magnetic compass can show you when something electrical is happening. By observing their behavior and making a few assumptions, you can begin forming ideas about electricity. This type of thinking is called “building a model”.

<u>INVESTIGATION ONE: WHAT IS NEEDED TO LIGHT A BULB?</u>

1.1 Activity: Lighting bulbs in a loop

Insert three D-cells into the battery holder (Figure 1.1), and screw two **ROUND** bulbs (<u>not long bulbs</u>) into a pair of sockets. Use three wires to connect the sockets to each other and to the two “terminals” of the battery holder — 1) the spring inside the case near the red spot, and 2) the metal post on the outside of the case near the blue spot. The bulbs should light and be of equal brightness. The battery, bulbs and wires now form a **“closed loop”**.

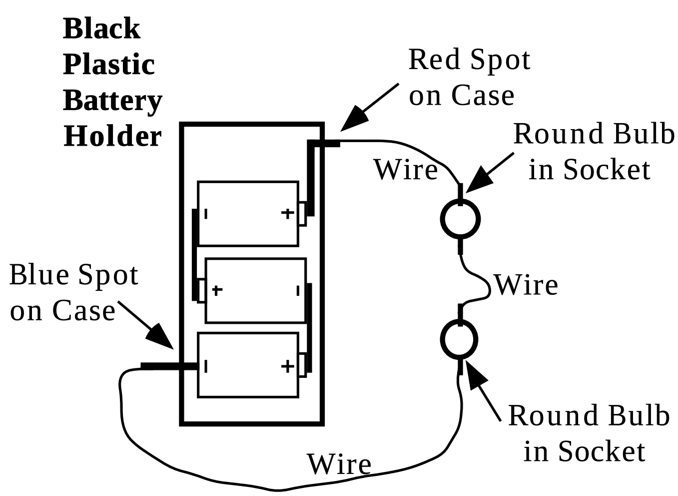


Figure 1.1
BASIC CLOSED LOOP

1. When do the bulbs light? Do you see both bulbs light at exactly the same time? Do you believe that both bulbs actually light at the same time?

2. “Break” the loop by disconnecting a wire from one end of the battery holder. What do you see? Do both bulbs appear to go out at exactly the same time? Do you believe that they both actually go out at the same time?

Reconnect the wire to the battery, and then unhook a different wire somewhere else in the loop. Try doing this in several places. Be sure that you have only one break in the loop at a time.

3. Is there any place where you can break the loop and the bulbs will still stay lit?

Unhook any wire and then bring it back as close as you can to where it was connected — without actually making contact. Do this slowly and carefully, watching the space between the wire and the contact point.

4. Do the bulbs light? Is actual contact needed for the bulbs to light continuously?

<u>INVESTIGATION TWO: IS ANYTHING HAPPENING IN THE WIRES?</u>

1.2 Activity: Using the compass to investigate a closed loop

The magnetic compass in your kit can be used to detect electrical activity in the wires during bulb lighting. Read and follow these instructions very carefully:

1. Place the compass on the table top, as far away as possible from any metal parts. Tape the compass to the table — masking tape works best. Note that the compass is <u>not</u> connected to any wire**.** It is a <u>detector</u> for what is happening in the wires.

2. Stretch the loop out as far as possible; keep the battery as far from the compass as you can. (The steel case of the D-cells may have become magnetized and will interfere with the compass reading.)

3. Disconnect the loop somewhere. Place a wire, which is attached to the battery <u>on top</u> of the compass (Figure 1.2a), and align this wire <u>parallel to the needle</u> of the compass and <u>directly over the needle</u>.

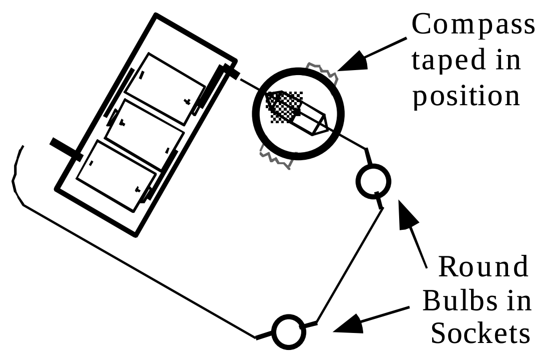


Figure 1.2a
COMPASS TAPED IN PLACE

When you have assembled the loop in Figure 1.2a, connect and disconnect a wire several times while you observe the compass needle. It's a good idea for one person to hold the wire on top of the compass while another connects and disconnects the loop.

1. Does the compass needle deflect clockwise or counter-clockwise when you connect the wire to close the loop? What happens to the compass needle when the battery is disconnected to 'break' the loop?

Close Loop:
Break Loop:

2. Is there any evidence that something is happening in the wire over the compass while the loop is closed? What is the evidence, for or against?

3. Is there any evidence that something is happening in the wire over the compass while the loop is broken? What is the evidence, for or against?

Do not move the compass. Break the loop and rotate the battery, sockets and wires together so that the middle wire is over the compass and parallel to the needle (Figure 1.2b). Be certain the loop is stretched out so the battery is as far as possible from the compass.

Before you connect the wire, predict what compass deflection you will observe.

Prediction:

Connect and disconnect the loop, and observe the compass needle.

4. Does the compass deflect in the same direction as it did under the first wire? Does it deflect by the same amount?

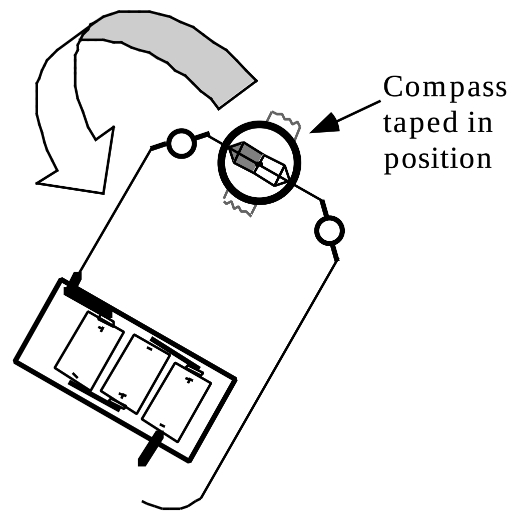


Figure 1.2b
COMPASS TAPED IN PLACE – ROTATED CIRCUIT

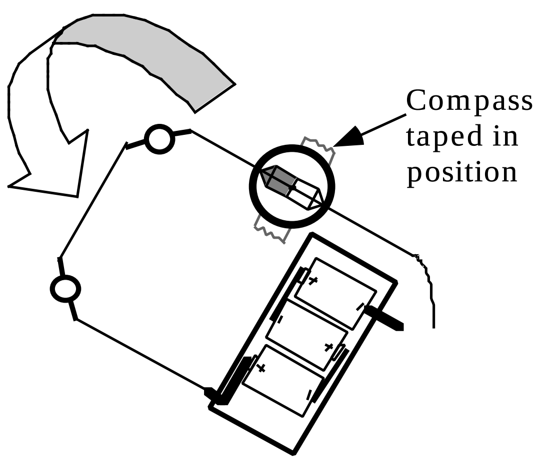


Figure 1.2c
CIRCUIT ROTATED AGAIN

Rotate the entire loop again, so that the third wire is over the compass (Figure 1.2c). Predict what you will observe when you connect and disconnect the loop again, and observe the compass.

Prediction:

Then try it.

5. What happened to the compass needle? How does this compare to its behavior under the other two wires?

6. Do you think the same thing is happening in the wires all the way around the loop? Why?

Next, reverse the orientation of the battery — by disconnecting the wires from the battery and then reconnecting them at opposite ends of the battery. Before doing so, predict what you will observe.

Prediction:

7. What needle deflection do you observe when you close the loop after you reverse the battery orientation? What do you observe when you break the loop?

8. Predict the compass deflection in the other two wires. Rotate the circuit and test your predictions. Describe the compass deflection in the three wires; compare it to the deflection you observed in questions #1, #4 and #5 above.

9. Can a compass be used to identify the direction of charge flow in a circuit? Explain **carefully**.

1.3 Exercise – Model-Building Discussion

1. What do you think might be changing in the wires to make the compass deflection change direction when the battery orientation is reversed? Explain your reasoning.

2. Some people think that there is something moving in the wires. Is there any direct evidence of this? Explain.

3. **If** something is moving in the wires, does the direction of movement and the amount of movement appear to be the same in every wire of this circuit at one time? What is the evidence?

4. What do you think the battery does in this circuit? What is the evidence?

1.4 Commentary: What's moving?

No one can see what moves through the wires, but something about the moving substance causes a compass needle to deflect. The property that enables the substance to do this is called **CHARGE**, from a Latin word that means "vehicle". Particles that carry charge from one place to another are called "charge carriers". The experiments you've done provide evidence that CHARGE is carried through wires, but they provide no evidence yet about the nature of the charge carriers.

1.5 Commentary: Which direction is it moving?

The reversal of compass needle deflection when the battery orientation is reversed indicates a **change** in the direction of charge flow in the loop, but provides no information about which actual direction exists before or after the change. Scientists searched for hundred of years trying to determine which way the charge really moved, but were unable to do so until the late 1800's. In the absence of any evidence, they decided to **assume a direction** for the motion. Such an assumption is "conventional" — that is, simply an "agreement" which isn't necessarily right or wrong but is **useful** because it is necessary for communication. The international convention is that the charges circulating around a circuit **leave the battery at the "positive" end** (red spot), travel around the circuit and **re-enter at the "negative" end** (blue spot), and pass through the battery. In later Sections we will collect evidence to determine whether this "conventional" direction is accurate or not.

1.6 Commentary: What is a "circuit"?

Any unbroken loop of electrical components that forms a continuous conducting path is called a **CIRCUIT,** from a Latin word that means "to go around".

1.7 Exercise: Which is the "conventional" direction in an actual circuit?

1. Figure 1.7 shows the same circuit as in Activity 1.2. Draw arrows next to each of the three wires to show the conventional direction of charge flow in these wires.

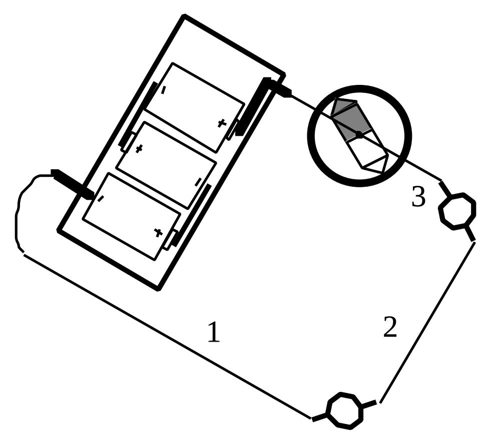


Figure 1.7
CHARGE FLOW DIRECTION

2. If the battery leads were reversed, what would happen to the direction of charge flow in the wires?

INVESTIGATION THREE: TESTING CONDUCTORS AND INSULATORS

1.8 Activity: Identifying conductors and insulators

Use the same loop as before (Figure 1.1), but with an additional wire (Figure 1.8).

This circuit (Figure 1.8) will be referred to as the "Testing Circuit". The "SOMETHING" may be anything you like — for example a key, a rubber band, or a comb.

You will record your results on the next page.

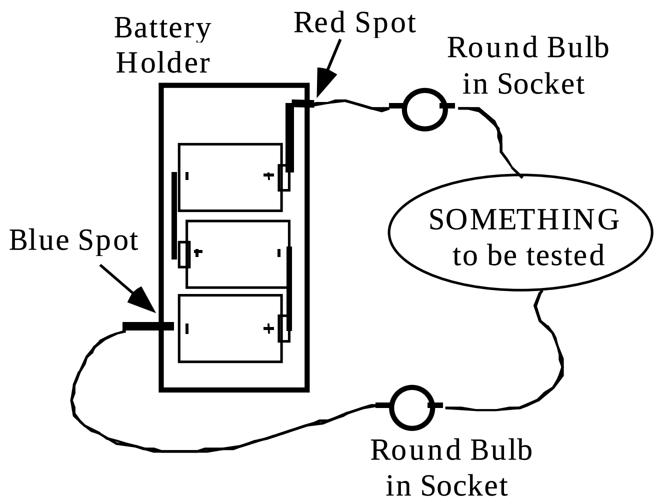


Figure 1.8
TESTING CIRCUIT FOR CONDUCTORS

- A material in the "SOMETHING" test location that permits the bulbs to **light** is called a **CONDUCTOR**.
- A material in the "SOMETHING" test location that prevents the bulbs from lighting is called an **INSULATOR**.

Select several ordinary objects, and **predict** whether each will turn out to be a conductor or an insulator when you test it. Record your predictions in Table 1.8 before you test each object.

Next assemble the loop in Figure 1.8 to check your predictions. Insert each object into the "something" spot by firmly connecting the alligator clips of wires to it; then observe whether or not the bulbs light. Record your observations in Table 1.8, and classify each object as actually a conductor or insulator.

TABLE 1.8

Test Object	Prediction (Insulator or Conductor)	Observations (Lit or Not Lit)	Classification (Insulator or Conductor)
Key			
Waxed Paper			
Aluminum Foil			
Shoe Lace			
Pencil Wood			
Pencil “lead”			
Socket Base			
Socket Clip			
Other:			

1. Do most or all of the conductors have something in common? If so, what? Write a general statement.

2. Do most or all of the insulators have something in common? If so, what?

1.9 Activity: Bulb testing — conducting path

In order to analyze the conducting path in a light bulb, you will use a household light bulb whose glass globe has been removed; the components will be large and easy to observe and test. Obtain a 'dissected' bulb from the teacher. The filament is ***very*** delicate so work carefully.

1. Using the **Testing Circuit** (Figure 1.8), test each of the wire supports (as the 'Something' in the test circuit) to determine whether each one is a conductor or an insulator. Then carefully test the delicate filament. Record your results in Figure 1.9a.

<u>Conductor or Insulator?</u>

Filament -

Supports -

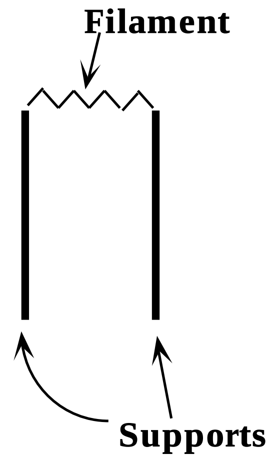


Figure 1.9a
BULB INTERIOR PARTS

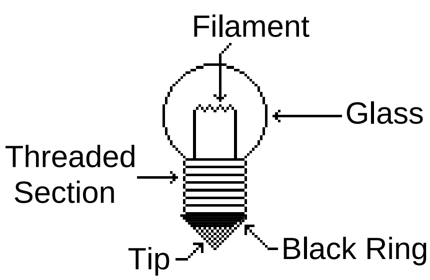


Figure 1.9b
DIAGRAM OF LIGHT BULB

2. Study the bulb diagram in Figure 1.9b, and predict whether each of the accessible parts is a conductor or an insulator. Write your predictions in Table 1.9.

3. Test your predictions by using the Test Circuit (Figure 1.8) and record your results in Table 1.9. (You may need to attach a thin copper wire to each alligator clip to use as a probe for small areas.)

TABLE 1.9

Test Points on Bulb	Prediction (Insulator or Conductor)	Observations (Round Bulbs Lit or Not Lit)	Classification (Insulator or Conductor)
Glass Bulb			
Threaded Section			
Black Ring			
Tip			

4. Find the combination of contact points which will cause the test bulb you are testing to light in order to determine which parts of the bulb form a continuous conducting path. In the space below, make a sketch of your test bulb showing the conducting path through the bulb.

1.10 Activity: Socket testing — conducting parts

Look at an empty socket and the socket diagram below; identify its five parts – a plastic base, two metal clips, and two metal plates (Figure 1.10).

1. Using your **Testing Circuit** (Figure 1.8), test each pair of socket parts to determine whether they act as a single continuous conductor. For example: if you connect one wire to each of the two metal clips, will the bulbs light? If they do, then the two clips act as though they were a single conductor. Test every possible combination of clip, plate and base, in order to determine which parts form a continuous conductor.

Describe your results.

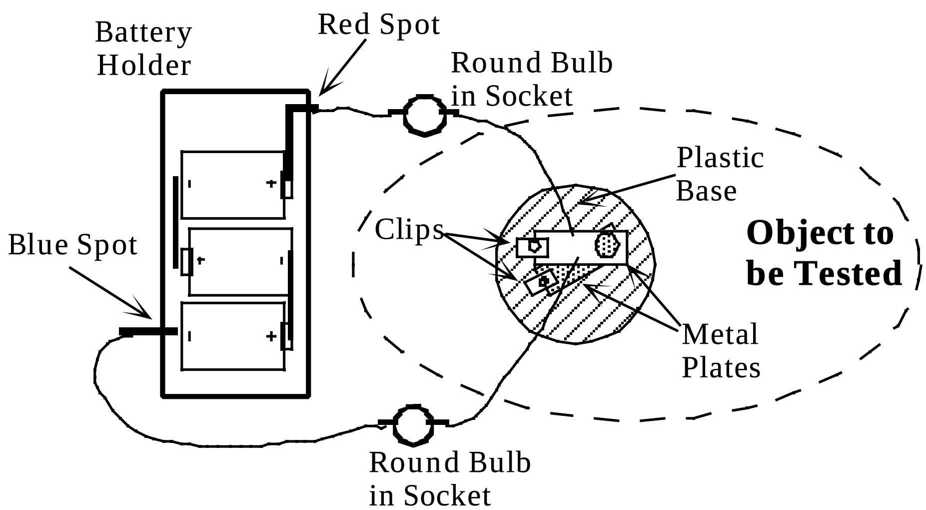


Figure 1.10
TESTING THE BULB SOCKET

2. Considering the conducting parts of the socket, and the conducting parts of a light bulb, explain why the socket is designed the way it is.

1.11 Activity: Lighting a bulb with a single cell

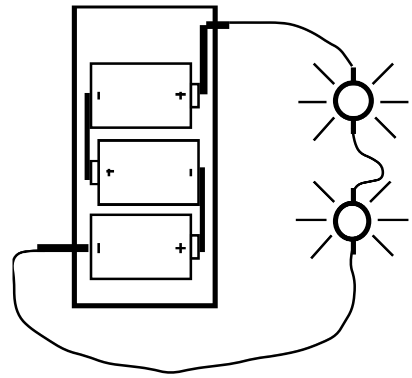
Investigate all the ways you can use one wire and a single D-cell — and nothing else — to make a round bulb light. (Don't use a bulb socket or a battery holder).

1. Once the bulb lights, draw a sketch of the arrangement in the space provided. Then – **find as many different combinations of the bulb, wire and cell as you can which will cause the bulb to light**. Draw a sketch of each one in the space provided.

2. Based on your observations, what is needed to make a bulb light? In other words, what do all successful circuits above have in common?

SUMMARY EXERCISE

Refer to the diagram at right to answer questions 1 through 3.



1. Are there any breaks or insulators in this circuit? If so, mark them on the sketch.

2. Is this circuit a continuous conducting path? What is the evidence?

3. On the diagram, draw a heavy line to show the path along which you think the moving charge travels. Draw arrows to indicate the direction the charge travels, based on the establish convention.

4. What evidence suggests that something happens in the wires when the bulbs are lit?

5. What is your current working hypothesis about what is happening in the wires when the bulbs are lit?

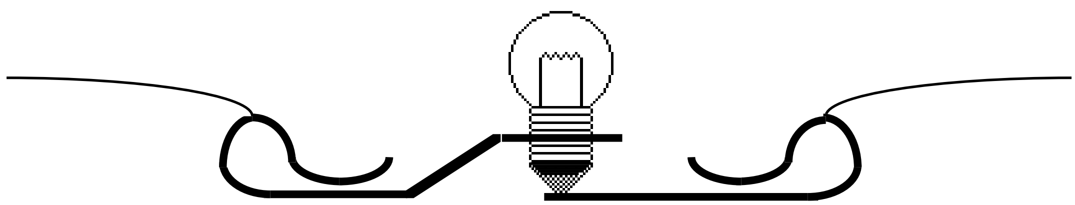
6. What happens in the wires when the battery connections are reversed? What is your evidence?

7. What is the <u>battery</u> doing when the bulbs are lit?

8. Assuming that something flows through wires when bulbs are lit in a circuit, is the direction of the flow the same in all the wires, or does it vary in different parts of the circuit? What is the evidence for your answer?

9. What materials and conditions must be present for a bulb to light? Explain carefully.

10.   On this cross-section diagram of a bulb in its socket, draw a heavy line to show a continuous conducting path that starts at a wire attached to one clip, goes through the bulb and exits through a wire at the other clip.



11. Based on your observations up to this point, how would you define the term 'electricity'?

Section 2

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? In this section you will investigate these questions by using a circuit in which there is a charge-storing device called a “capacitor”.

2.1 Commentary: Schematic diagrams with battery, wires and bulbs

Many of the circuit diagrams in Section 1 sketched the “visual” appearance of circuits — drawing batteries, bulbs, and wires as they actually appear. From now on you will draw “schematic” diagrams — using symbols to represent the circuit components. The battery symbols used in this manual are shown in Figure 2.1a.

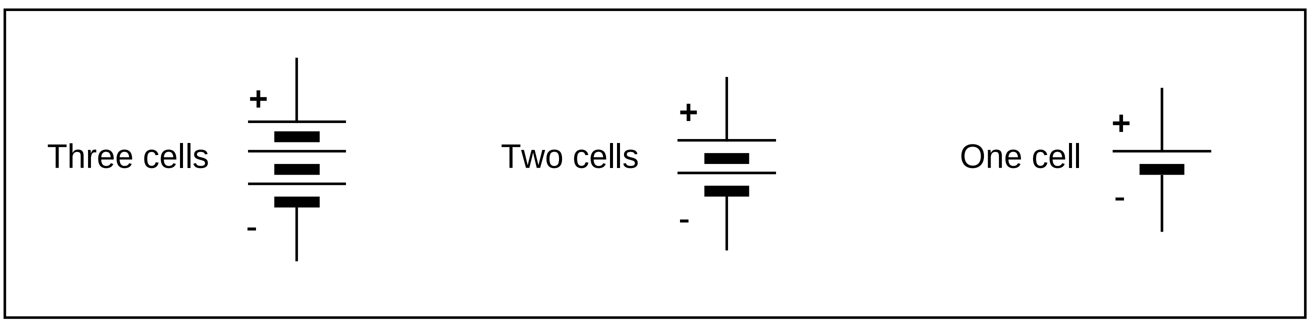


Figure 2.1a
SYMBOLS FOR BATTERIES

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 2.1b)

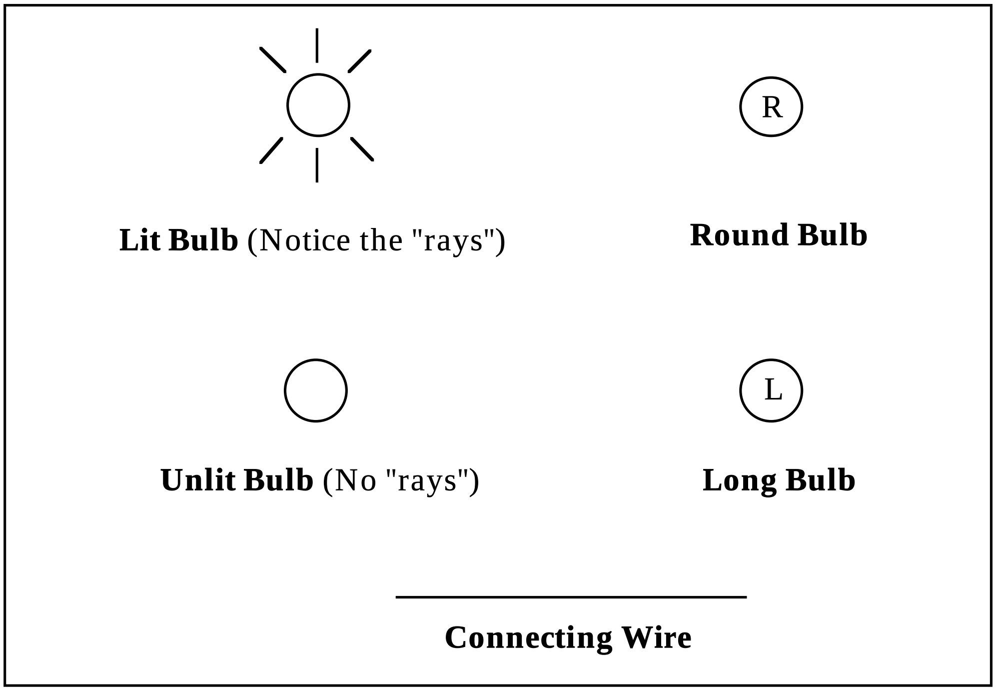


Figure 2.1b
SYMBOLS FOR WIRES AND BULBS

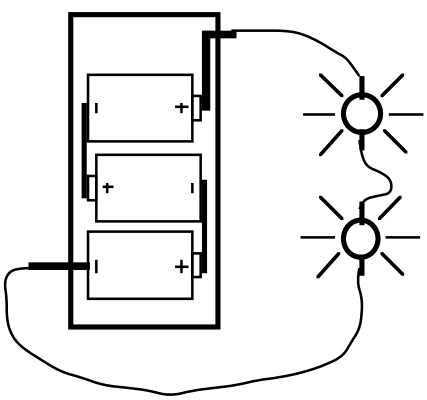


Figure 2.1c
VISUAL APPEARANCE

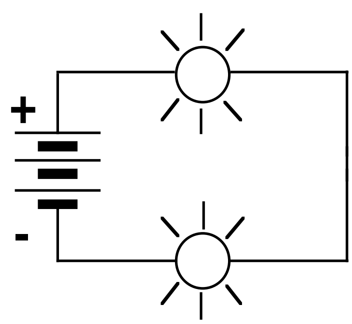


Figure 2.1d
SCHEMATIC DIAGRAM

Figure 2.1c shows the visual appearance of three cells, two lit bulbs and the connecting wires which form a closed conducting loop. A schematic diagram of the same circuit is shown in Figure 2.1d.

2.2 Commentary: Arrows representing conventional charge flow (Review)

Charge could be moving either clockwise or counter-clockwise in a simple circuit with lit bulbs, and the compass does not tell you which is actually occurring. The direction of needle deflection will reverse if the direction of flow reverses; while the compass needle can indicate the reversal, it cannot indicate the actual or absolute direction.

In Section 1, we discussed the best way to avoid confusion about the flow direction -- to assume that charge travels in one of the two possible directions. The scientific and engineering professions have agreed on a choice, which they call the direction of "conventional flow ". The word "conventional" means by agreement. The agreement is that the direction of conventional flow in a circuit with a single battery is out of the "+" terminal of the battery, into the "-" terminal, and through the battery. This direction is illustrated by arrows in Figures 2.2a and 2.2b. The arrows in the schematic diagrams below are drawn as one continuous (unbroken) arrow to represent continuous flow through the bulbs and wires.

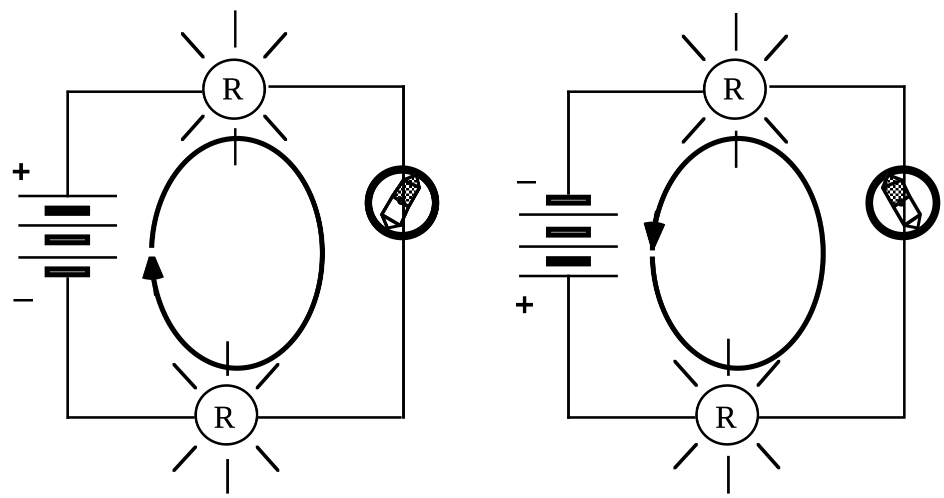


Figure 2.2a
Standard Battery Orientation

Figure 2.2b
Reversed Battery Orientation

ILLUSTRATIONS OF CONVENTIONAL FLOW DIRECTION

2.3 Exercise: Circuit diagrams

1. In the space to the right of the visual representation in Figure 2.3a, draw a schematic diagram of the circuit.

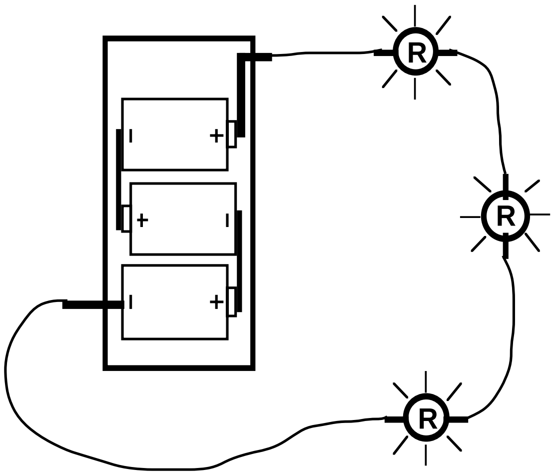


Figure 2.3a

VISUAL REPRESENTATION **SCHEMATIC DIAGRAM**

2. In the space to the right of the schematic diagram in Figure 2.3 below, draw a visual representation of the circuit.

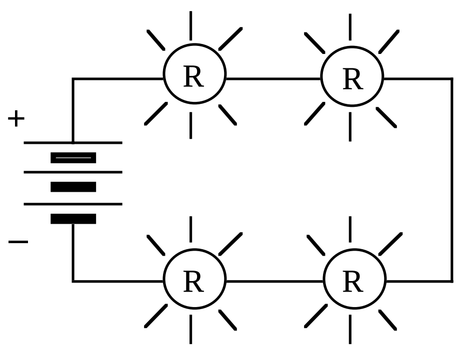


Figure 2.3b

SCHEMATIC DIAGRAM **VISUAL APPEARANCE**

3. 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".

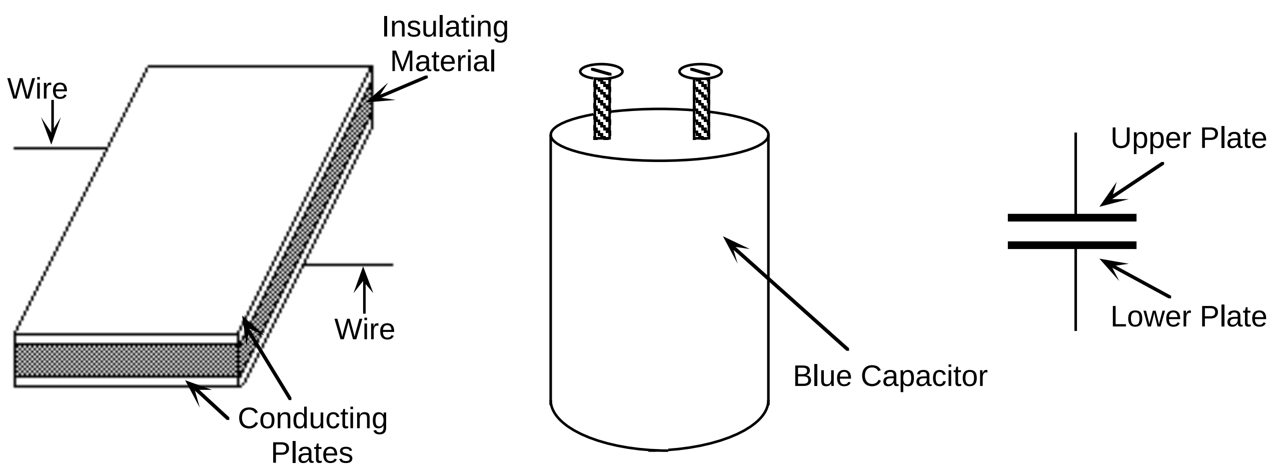
4. Draw a continuous arrow on the schematic diagram in question 2, to show where and in what direction charge is flowing — according to "conventional flow".

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

2.4 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 that 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.



Actual Structure **Visual Appearance** **Conventional Symbol**

Figure 2.4
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 Sir Michael Faraday (1791-1867). The blue capacitor in your CASTLE kit has a capacitance of 0.025 farad, or 250,000 micro-farads, µf. (Some kits may also have a small silver capacitor, which will not be used at this time.)

Your teacher will have some large silver capacitors, which are to be shared by the class in a number of activities. These have a capacitance of 0.1 farad, or 100,000µf — four times as much as the blue 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.

2.5 Activity: Where does charge move in a circuit with a capacitor?

Look at Figure 2.5a, but don't assemble the circuit yet. It's the same circuit you've 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, and is not connected to the circuit.

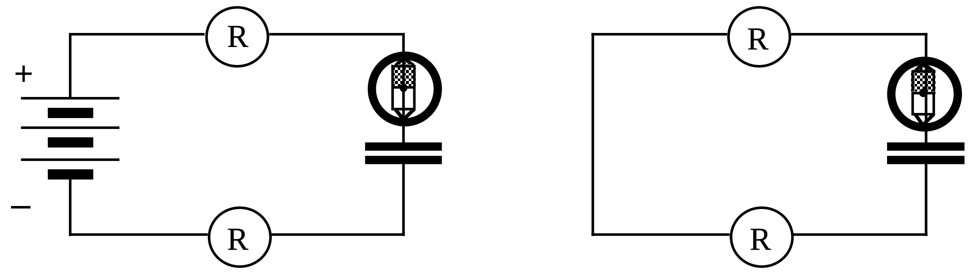


Figure 2.5a
CAPACITOR CHARGING

Figure 2.5b
CAPACITOR DISCHARGING

Assemble the circuit illustrated in Figure 2.5a using the blue capacitor from your kit, but leave a break somewhere in the circuit. Position the compass under the wire and **be sure to orient the wire so that it is parallel to the needle.**

1. Predict what you will observe when you complete the circuit.

Prediction:

This process is called **CHARGING A CAPACITOR.** What did you observe as you watched the bulbs and the compass?

2. Compare the direction of compass deflection to the direction you observed in Section 1 (Activity 1.2a, b, c).

3. Draw an arrow(s) on Figure 2.5a to show where and in what direction charge moves during the charging process.

Next, remove the battery from the circuit and close the loop with the compass in the same position. Predict what you will observe as you watch the compass and bulbs.

Prediction:

4. Observe the compass and bulbs as you connect the free ends of the wires to each other (Figure 2.5b). This process is called **DISCHARGING A CAPACITOR.** What do you observe?

5. Draw an arrow (or arrows) on Figure 2.5b to show where and in what direction charge moves during discharging.

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

Ask your teacher for a large silver capacitor. Remove the blue capacitor from the circuit, and replace it with the big silver capacitor. Charge and discharge the large silver capacitor several times in the same way, observing the bulbs and compass needle.

6. Are the bulbs lit longer using the blue capacitor or the big silver capacitor? Speculate: Why do you think this happens?

7. During the charging and discharging of the big silver capacitor, does the compass deflection stop when the bulbs go out? Speculate: Why do you think this happens?

8. Which capacitor permitted more charge to flow? What is the evidence?

9. Does the charge that flows into the capacitor during charging go all the way through the capacitor and back to the battery, or does it get stored somewhere in the capacitor? How do you know?

10. Does the process of discharging provide evidence that charge was stored in the upper plate of the capacitor during the charging process? (Note: "Upper plate" refers to the orientation in the diagram.) Explain.

INVESTIGATION TWO: WHERE DOES THE MOVING CHARGE COME FROM?

2.6 Activity: Where was the charge located before it began to move?

1. Draw an arrow on Figure 2.6a to show where and in what direction charge moves during the charging process. Draw an arrow on Figure 2.6b to show where and in what direction charge moves during the discharging process.

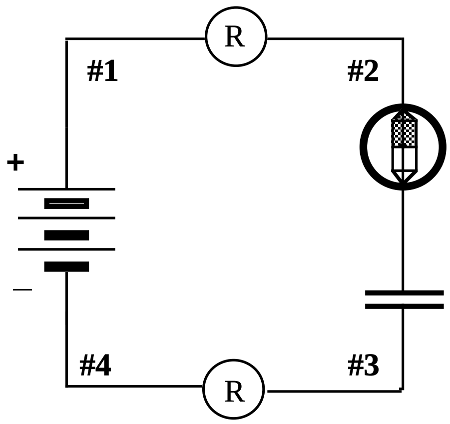


Figure 2.6a
CHARGING

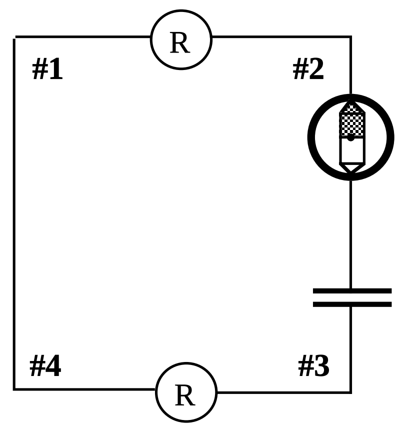


Figure 2.6b
DISCHARGING

2. Tape the compass to the table, and rotate the entire circuit in order to test the compass deflection under each wire (#1 - #4). Charge and discharge the blue capacitor. Carefully observe the direction (clockwise or counter-clockwise) and magnitude (amount) of the compass deflection under each wire. Record your observations in Table 2.6a.

TABLE 2.6a

	Charging Direction and Magnitude	Discharging Direction and Magnitude
Wire #1		
Wire #2		
Wire #3		
Wire #4		

3. Review the arrows you drew on Figure 2.6a and 2.6b to be sure they represent the direction of charge flow as indicated by the compass deflections above.

4. Is the same thing happening in every wire in the charging circuit? In the discharging circuit? What's the evidence?

5. Where do you think the charge comes from that lights the top bulb during capacitor charging?

6. Where do you think the charge comes from that lights the bottom bulb during capacitor charging?

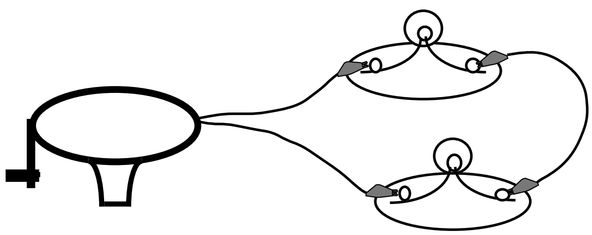
7. Where do you think the charge comes from that lights the bulbs during discharging?

8. 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? _______________

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

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



Remove the battery from the circuit you have been using in Activity 2.6, 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 2.7a.

Figure 2.7a
GENECON IN A CIRCUIT

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 may burn out the bulbs!

1. Remove 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" that is required to keep the Genecon turning at the same speed?

3. Do the bulbs light? What does this tell you about what a Genecon does?

Set up the circuit in Figure 2.7b, with only **ONE** D-cell in the battery holder. Carefully observe the brightness of the bulbs.

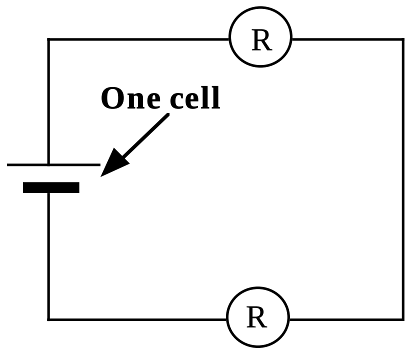


Figure 2.7b
CIRCUIT WITH ONE D-CELL IN BATTERY HOLDER

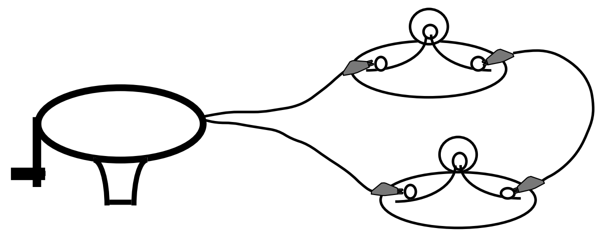


Figure 2.7c
CRANK GENECON TO PRODUCE SAME BRIGHTNESS

4. Observing the brightness of the bulbs in Figure 2.7b, crank the Genecon until the bulbs have the same brightness as with one D-cell (Figure 2.7c). During ten seconds, approximately how many turns of the crank do you have to make to do this?

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.

Prediction:

Try it — was your prediction correct?

2.8 Exercise: The Genecon

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

2. Where does the “energy” come from that’s needed to turn the Genecon crank and make charge move?

3. 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.

4. A hair dryer is a pump for air. Do a battery and a Genecon act like a pump for charge? Explain.

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

2.9 Activity: Charging an air capacitor

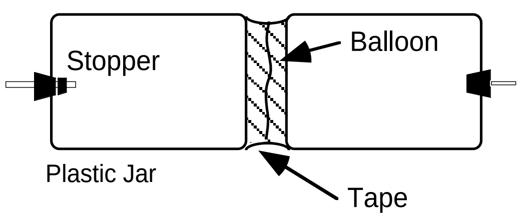


Figure 2.9a
NORMAL AIR CAPACITOR

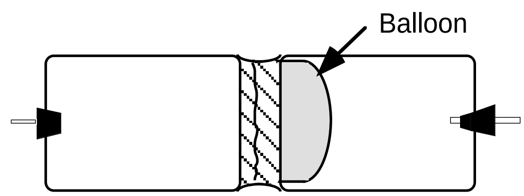


Figure 2.9b
CHARGED AIR CAPACITOR

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. Did any air flow <u>through</u> the capacitor? Explain your reasoning.

4. 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?

5. <u>Inhale</u> 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.

2.10 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 as the air that goes in? Explain.

2. Is there any similarity to the behavior of the 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.

What are the results?

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

2.11 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 <u>more than the normal amount</u> of charge in the plate, while removing some charge will result in there being <u>less than the normal amount</u> 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. 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)**

The next section will use these symbols with the same meanings Franklin gave them.

2.12 Commentary: Electrical energy

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 the ability to make something happen. We have identified a number of things which happen in circuits – charges move, compasses deflect, bulbs heat and give off light. What is the source of the energy that makes these things happen?

In most of the circuits we have observed, the source of the energy has been the battery. In some circuits, however, there was no battery present. When a capacitor discharges, it can make these same things happen, so it must also have been a source of energy, at least temporarily.

In some circuits, a Genecon was used, but the source of energy was that stored in muscles. The cranking action transformed the energy from muscle storage to the energy of moving charges and bulbs releasing light.

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 can be re-used and are called “rechargeable”. This is an incorrect term, however, since the batteries’ task was never to supply charge to the circuit – it was already there! These batteries would more properly called “re-energizeable”.

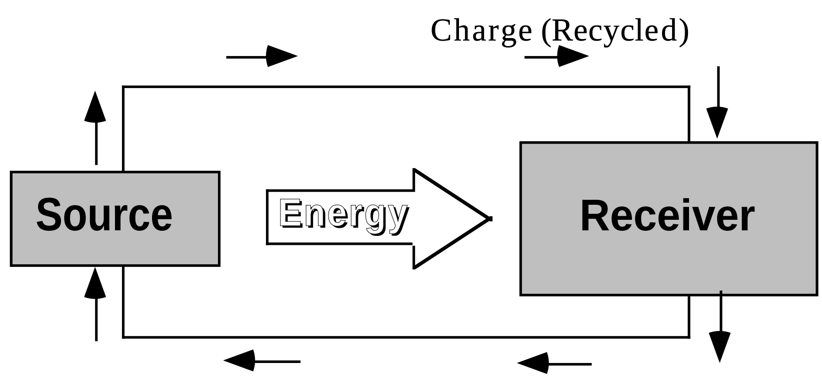


Figure 2.12
ENERGY FLOW DIAGRAM

In a circuit, charge originates in every conductor, and constantly <u>re-cycles</u> around the circuit. However, energy leaves the energy source and travels <u>one way</u>, leaving the circuit as heat or light energy from the bulbs (the receivers of the energy). The energy source might be the stored chemical energy in a battery, or the stored energy in muscles used to crank a Genecon, or other energy sources.

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. Describe the direction of charge flow in a circuit (based on the convention used in your lab work). Write your answer in terms of the positive (+) and negative (-) ends of the battery.

6. Consider a circuit with a Genecon, wires and bulbs. What is the source of charge while the bulbs are lit?

7. What causes the motion of charge while the bulbs are lit?

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. From the experiments you have done and the assumptions we have made, you now have an idea or <u>model</u> of the behavior of electricity. List the findings and assumptions that make up this model.

Section 3

WHAT DO BULBS DO TO THE MOVING CHARGE?

INTRODUCTION

How do light bulb filaments influence the movement of charge in a circuit? What does the brightness of a filament tell us about the movement of charge passing through the filament? What does the amount of time a filament is lit during capacitor charging and discharging tell us about the movement of charge into and out of the capacitor?

<u>INVESTIGATION ONE: WHAT DO FILAMENTS DO TO MOVING CHARGE?</u>

3.1 Activity: Comparing round and long bulbs

Charge a blue capacitor through <u>round</u> bulbs as in Figure 3.1a. Then discharge through these bulbs as in Figure 3.1b. **<u>Note the amount of time needed to discharge the capacitor.</u>**

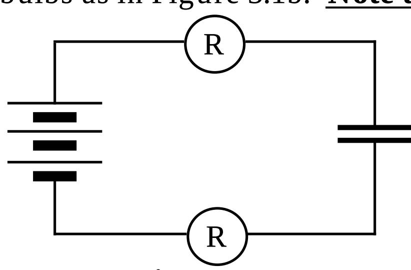


Figure 3.1a
STANDARD CHARGING CIRCUIT

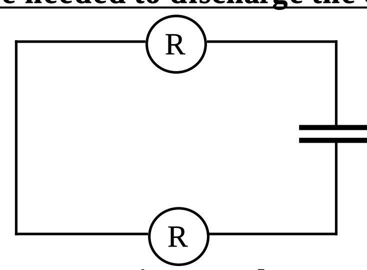


Figure 3.1b
DISCHARGING THROUGH ROUND BULBS

Charge the capacitor again. Remove the round bulbs with their sockets and replace them with <u>long</u> bulbs in two other sockets. Then discharge the capacitor through the long bulbs. Again – **<u>note the amount of time needed to discharge the capacitor.</u>**

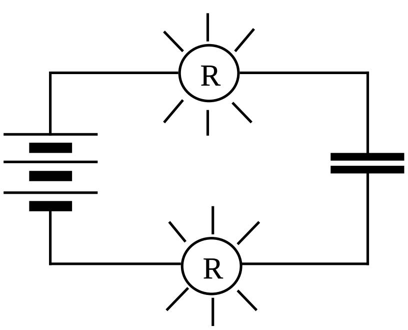


Figure 3.1c
STANDARD CHARGING CIRCUIT – ROUND BULBS

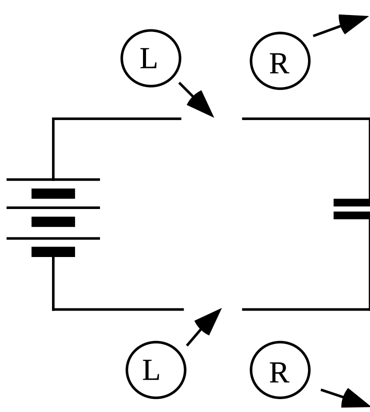


Figure 3.1d
SWITCHING BULBS

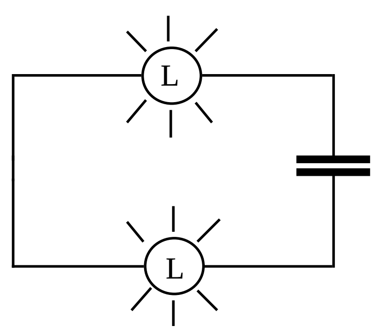


Figure 3.1e
DISCHARGING THROUGH LONG BULBS

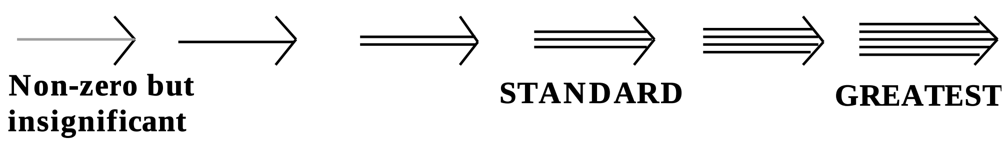
1. Compare the amounts of time that the long bulbs and the round bulbs remained lit during discharging.

2. Since the same round bulbs were used during charging both times, the same amount of charge must flow during charging and therefore during discharging both times. So how can we explain why the long bulbs remain lit for a different amount of time during discharging?

3. Which bulbs allow charge to flow through the wires at a greater rate -- round or long? What is the evidence?

4. Illustrate the directions and magnitudes of flow rates at the <u>beginning</u> of capacitor charging or discharging by placing one of the following arrowtails by each wire in Figures 3.1a through 3.1e.

Arrowtail Symbols for Flow Rates in Wires



The “**Standard**” flow rate is defined as the flow through bulbs in a circuit consisting of two round bulbs and a 3-cell battery pack.

3.2 Activity: Examining filaments under magnification

Compared to the other conducting wires in a circuit, the bulb filaments consist of very thin wire. In this activity you will be observing four different examples – round bulb filaments, long bulb filaments, support wires in bulbs, and the connecting wires.

Use the dissecting microscope or other magnifier provided by your teacher to look at the filaments in round and long bulbs. Compare these to the support wires attached to the filaments and the connecting wires from your kits; these are also know as wire ‘leads’ with alligator clips.

1. How do filament wires compare to support wires and / or connecting wires?

2. Compare the size of the filament wire for the round and long bulbs.

3. List the four types of wire in order from thick to thin – support wire, round and long bulb filaments, and connecting wire.

4. Which appears to provide the most difficult path for charge to follow? Which should be the least difficult? Explain why.

3.3 Activity: Detecting resistance of straws to air flow

Obtain two straws of the same length but with different diameters. Take a deep breath and observe the time it takes to exhale through the thicker straw. Now take a second deep breath and, using the same effort, completely exhale through the thin straw .

1. Compare the amounts of time it takes you to completely exhale.

2. Do you exhale more air through either straw? Explain your reasoning.

3. Repeat the activity with each straw and this time direct the flow of air from the straws onto the palm of your hand. What does your hand feel?

4. Now take a paper towel tube and cut it to the same length as the straws. Again, with the same effort from your lungs, exhale a full breath of air. How does the tube affect the time to exhale and the flow of air from your lungs?

5. Compare the times it takes to “charge” your lungs by inhaling through the straw, the stirrer and the paper towel tube.

6. Compare 1) the influence of bulb filament diameter on the rate of charge flow with 2) the effect of straw diameter on air flow.

3.4 Commentary: Resistance, conductance and flow rate

Early in our study of electric circuits, we classified objects and types of materials as either conductors or insulators. Most of the objects we tested were very good at allowing charge to flow (the conductors) **or** very good at blocking the flow (the insulators). In truth, most examples fall somewhere in between these two extremes and simply allow some flow to take place but at a reduced rate. We have called these mid-range examples resistors, and the property they exhibit is called RESISTANCE. All light bulb filaments are resistors. A resistor that allows charge to move through easily has low resistance, and one that hinders the flow of charge more strongly has high resistance. Electrical resistance is measured in terms of a unit called the OHM — named after the German physicist Georg Ohm. The physical design (size and shape) of these objects can have as much effect as the type of material itself. Copper is considered a good conductor; however, a copper wire that is very long and very thin may demonstrate a large degree of resistance.

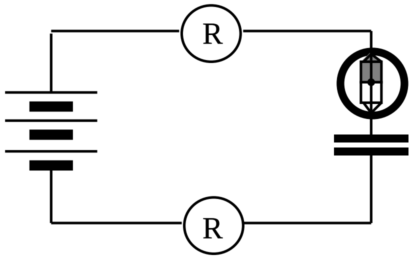
From another point of view, all resistors let charge through at some rate; and this leads to the inverse term of CONDUCTANCE. Conductance is a measure of how well something lets charge through. Just as resistance is a measure of how hard it is for charge to move, then conductance is a measure of how easy it is for the charge to move. As an inverse notion to resistance, the conductance value is measured in a unit called the **Mho**. Note that Mho is Ohm spelled backward.

Most text books use the term CURRENT to represent flow rate of charge in a circuit. Flow rate is measured in terms of a unit called the AMPERE — named after the French physicist André Ampere. **Flow rate – current – is not the same thing as speed or velocity.** Knowledge of the flow rate tells you how much charge passes through a point on a wire during each second, but provides no information at all about the speed of each bit of moving charge. Consider water flowing in a river. Over the course of a certain distance, the moving water will maintain the same flow rate if we assume no tributaries to add water or drains to remove water. But if the river bed becomes narrower or shallower, then the water must pick up speed in order to provide this same flow rate. Such a situation shows a change of speed without a change in the flow rate. In electric circuits it is the flow rate (the amount of charge per second), not the speed (the amount of distance per second), that we measure with a compass.

INVESTIGATION TWO: WHAT'S OBSERVABLE THAT SHOWS FLOW RATE?

3.5 Activity: Compass deflection and flow rate

Repeat the charging and discharging sequences from Activity 3.1, using a compass under one of the wires as shown below. Record the amount of deflection you observe for each charging and discharging circuit.



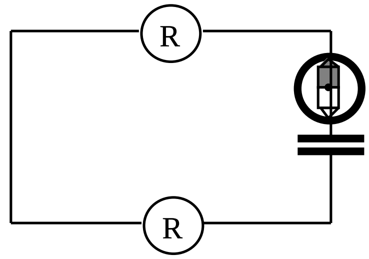
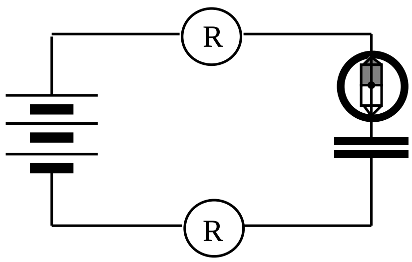


Figure 3.5a **Figure 3.5b**

CHARGING AND DISCHARGING THROUGH ROUND BULBS



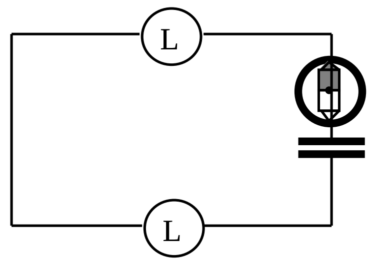


Figure 3.5c **Figure 3.5d**

CHARGING THROUGH ROUND AND DISCHARGING THROUGH LONG BULBS

1. Which bulbs allow greater compass deflection during **discharging**?

2. Can compass deflection be used as an indicator of flow rate in wires? Explain.

3.6 Activity: Bulb brightness and flow rate

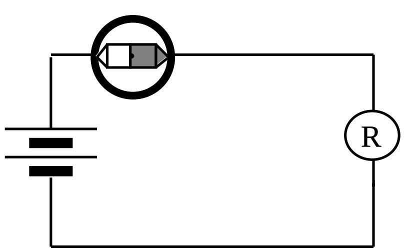


Figure 3.6a

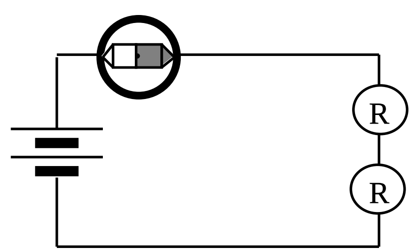


Figure 3.6b

Before you set up the circuits shown in Figure 3.6a and Figure 3.6b, **predict** what you expect to observe. Notice that only 2 cells are used in the battery pack.

Prediction:

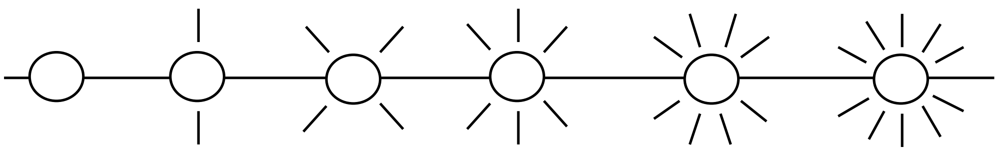
1. How do the compass deflections compare in the two circuits?

2. How do the bulb brightnesses compare in the two circuits?

3. Can bulb brightness be used as an indicator of flow rate in wires? Explain.

3.7 Activity: Use of multiple representations

In Activity 3.1, we used a convention of arrowtails to indicate the flow rate of charge. We will now begin using a convention of starbursts drawn around the bulbs to indicate brightness.



Note that bulb brightness is indicated by the number of rays drawn for each bulb – not by the length or thickness of the rays.

1. On the circuit diagrams in Activity 3.5 above, draw multiple shaft arrowtails as described in Activity 3.1 to indicate the flow rate in each wire.

2. Draw starbursts on the diagrams to indicate the relative brightness of the bulbs.

INVESTIGATION THREE: OVERALL RESISTANCE OF BULB COMBINATIONS

3.8 Activity: Series Circuits

Before you set up the circuits below (Figure 3.8a, b, c) – **predict** what you will observe.

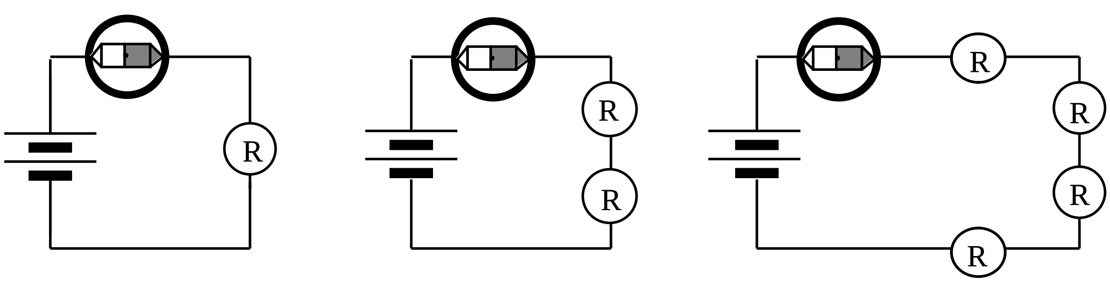


Figure 3.8a **Figure 3.8b** **Figure 3.8c**

Prediction:

Note that you are using <u>only 2 cells</u> in the battery pack. Construct the circuits and observe.

1. What does the compass deflection imply about the flow rate as the number of bulbs increases?

2. Comment on the brightness changes as the number of bulbs increases. What does this tell us about the flow rate through each bulb in a given circuit?

3. Draw arrowtails and starbursts on Figures 3.8a,b,c.

3.9 Activity: Stirrers in series

From your teacher, obtain four thin plastic coffee stirrers and a few inches of masking tape. Tape two of the stirrers together end to end with about an inch of tape to make a new straw twice as long. An easy way is to place two stirrers together at one end of the tape and then roll them toward the other end of the tape. Be careful to keep the ends of the straw open and avoid gaps that might leak. Set this pair aside.

1. To gain additional insight with a series, pick up one of the single thin stirrers and blow through it. Record the time to exhale a single breath of air.

2. Now take the pair of stirrers and with a new breath of air, record the time to exhale through two stirrers.

3. Finally tape all four stirrers together and measure the time needed to exhale.

4. Explain how the length of a conducting tube will influence the rate of flow through it.

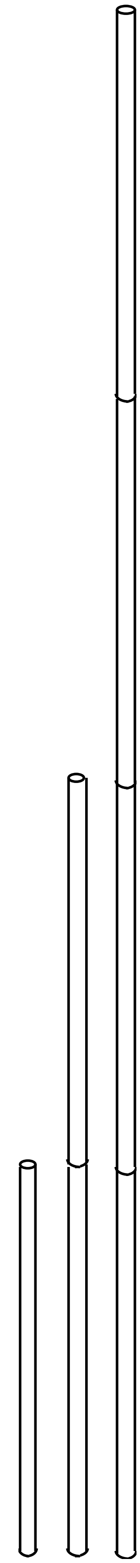


Figure 3.9
STIRRERS
IN 'SERIES'

3.10 Activity: Discharging through parallel bulbs

Charge a capacitor fully through two round bulbs, and discharge through a single long bulb as shown in Figures 3.10a and 3.10b.

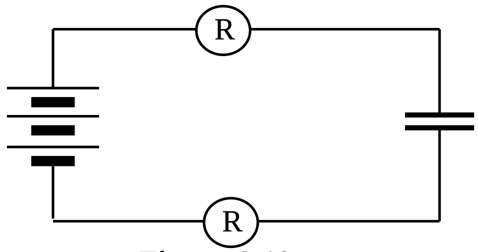


Figure 3.10a

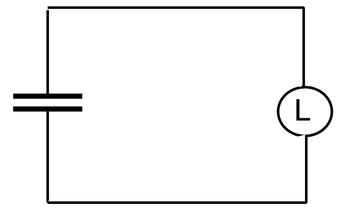


Figure 3.10b

1. Observe the brightness and record the approximate amount of time needed for the long bulb to go out.

Repeat the charging process, but then discharge the capacitor using two long bulbs connected in <u>branches</u> that allow the flow of charge from the top capacitor plate to split into two separate paths. This method of adding bulbs produces what is called a "parallel" circuit — because the flow occurs in side-by-side branches. (Figures 3.10c,d).

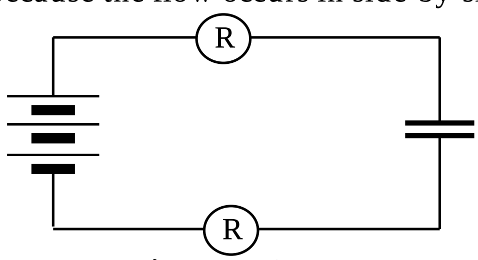


Figure 3.10c

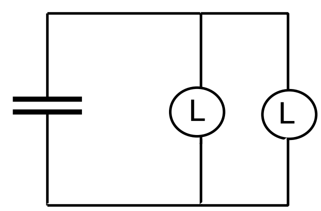


Figure 3.10d

2. Record the time for the long bulbs to go out. Compare the brightness of the two long bulbs with the bulb in 3.10b.

3. Finally, charge the capacitor and discharge through four long bulbs as in Figure 3.10f. Record the time for the bulbs to go out. Compare the brightness of the four bulbs during the discharge with the single bulb in 3.10b.

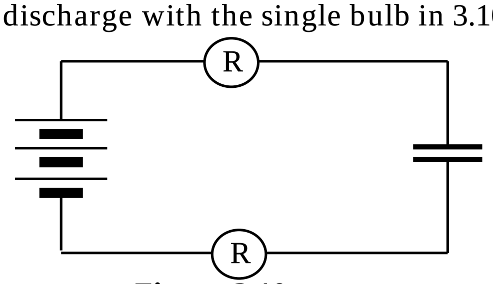


Figure 3.10e
STANDARD CHARGING THROUGH ROUND BULBS

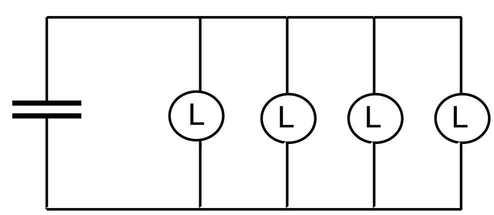


Figure 3.10f
DISCHARGING THROUGH 4 PARALLEL LONG BULBS

4. Does the addition of more bulbs in parallel make capacitor discharging seem more difficult or easier? What is the evidence?

5. Compare the brightness – and therefore the flow rates – in each of the four long bulbs.

6. Suppose you wanted to replace the bulb in Figure 3.10b with a single bulb that would allow the capacitor to discharge in the same amount of time as the four long bulbs in Figure 3.10f. Would you look for a bulb that had greater resistance or less resistance than a long bulb? Would that bulb have greater conductance or less conductance than a long bulb?

7. **Predict**: How might the filament of such a bulb differ from a long bulb filament. Explain your reasoning.

3.11 Activity: Stirrers in parallel

We can sense this same phenomenon with air flow through straws. Obtain four thin stirrers. Again, for reference, take a breath and exhale through a single thin straw. Notice the time it takes for the air in your lungs to flow through the stirrer. Now place two stirrers side by side or in parallel and exhale through both at once.

1. Does it seem that the two straws are more difficult or easier than one straw?

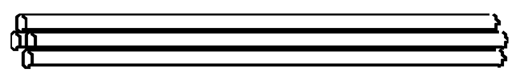


Figure 3.11
FOUR 'PARALLEL' STIRRERS

Finally place all four straws in your mouth as a small bundle and exhale a full breath.

2. How do four stirrers in parallel compare to a single thick soda straw?

3. If you were forced to breathe and exhale through four straws for a full day, describe how you would prefer to have them arranged – in series or in parallel? Explain your reasoning.

3.12 Commentary: Overall resistance of series and parallel combinations

The increased difficulty we experience when we breathe through a longer tube is typical of the effect that a greater length of wire will have where charge is trying to flow. This leads to the idea that "longer is harder". Adding more resistors in series creates the same effect as making a longer single resistance, which provides more overall resistance.

In contrast, adding more resistors **in parallel** creates the same effect as a wider or thicker single resistance, which provides less total resistance. We could also say that there is more total conductance. Here is a useful way to think about the distinction between series and parallel:

- In a **series** circuit all of the moving charge passes through every resistor. Every part of the charge is resisted every time it passes through a resistor.

- In a **parallel** circuit the moving charge is split into parts. Each part will pass through only one resistor, so its motion will be resisted only once.

A summary of the last four activities indicates that multiple resistors affect charge flow and air flow in a similar manner, as follows:

More in series	**—>**	**acts like single longer resistor**	**—>**	**makes flow harder**
More in parallel	**—>**	**acts like single wider resistor**	**—>**	**makes flow easier**

INVESTIGATION FOUR: DO THE CONNECTING WIRES HAVE RESISTANCE?

3.13 Activity: The effect of a wire in a circuit

We have looked at some cases where a few bulbs have been arranged either in series or in parallel. We have shown that the thin bulb filament wires have significant resistance. By contrast, the thick connecting wires have practically no resistance at all – an extremely large conductance. What will happen if more connecting wires are added to a circuit?

Start with a simple standard circuit as shown in Figure 3.13a below. Observe the bulb brightness and think about the implied flow rate. Draw arrowtails and starbursts on the diagram as appropriate.

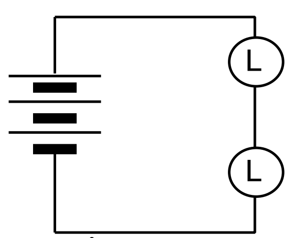


Figure 3.13a

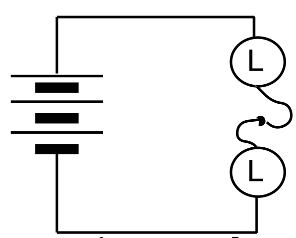


Figure 3.13b

Now prepare to break the circuit between the two bulbs and add an additional length of wire as in Figure 3.13b. First, **predict** what you will observe.

Prediction:

Make the connection and observe the effect on the two long bulbs. Explain your observations.

Return to the original circuit, and prepare to add the extra wire in parallel across the lower bulb, as in Figure 3.13c.

Predict what will happen when the connections are actually made.

Prediction:

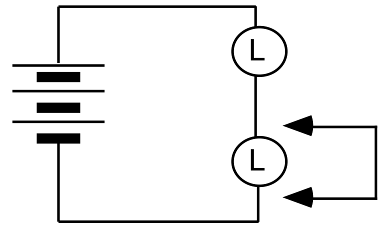


Figure 3.13c

Complete the connection. What kind of arrowtails and starbursts will correctly represent the observed effects now? What kind of arrowtail should you place by the added wire? Add them to the diagram.

Discuss the underlying principles that would lead to these conditions. How could you find out if your explanation is correct?

3.14 Activity: Confirming the resistance of wire

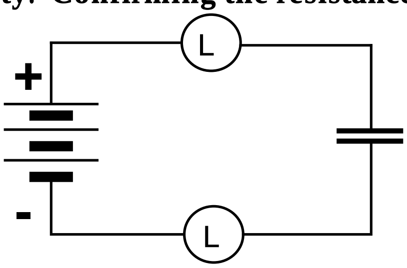


Figure 3.14a

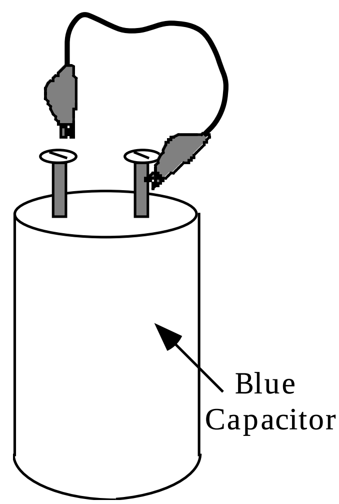


Figure 3.14b

Before you set up these circuits, predict what you will observe when you follow the instructions below.

Charge a blue capacitor through two long bulbs as in Figure 3.14a. Then 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 possible. Remove the battery from the circuit, return the capacitor, and discharge through the bulbs.

1. What do you predict you will observe?

Prediction:

2. Describe your results and explain what this investigation indicates regarding the resistance of the connecting wire.

SUMMARY EXERCISE

1. If the same capacitor were discharged through two different types of bulbs, what can you conclude about the bulbs which stay lit the least amount of time?

2. Which has the thickest filament – a high-resistance or a low-resistance bulb?

3. What are two observations which can be used to indicate flow rate?

4. When more bulbs are added to a circuit, is there always more total resistance as a result? Explain.

5. What experiments suggest that wires have essentially zero resistance?

Section 4

WHAT MAKES CHARGE MOVE IN A CIRCUIT?

INTRODUCTION

Why does capacitor charging stop **--** even though a battery is still trying to make charge move? What makes charge move during capacitor discharging **--** even though there is no battery to cause movement? Clearly, the complete story of why charge moves in circuits has to involve more than just batteries. In this section you investigate the <u>non</u>-battery causes of charge movement in circuits.

<u>INVESTIGATION ONE: DOES A CAPACITOR BEHAVE LIKE A BATTERY?</u>

4.1 Activity: Circuit with "dueling" batteries

Begin with a circuit that has one 3-cell battery, a compass and 2 round bulbs (Figure 4.1a. Observe the compass deflection.

Next add an opposing battery – one that is oriented in the opposite direction. The battery holder should contain only 1 cell. (Figure 4.1b) Predict what you will observe when you complete the circuit in Figure 4.1b.

Prediction:

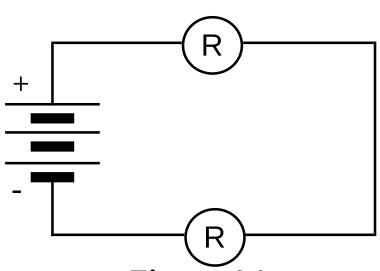


Figure 4.1a

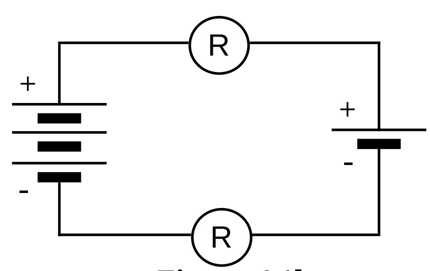


Figure 4.1b

ADDING A "DUELING" BATTERY CELL ON THE RIGHT

1. Draw arrowtails on Figure 4.1a to indicate standard flow rate through each bulb, and starbursts to show standard brightness for each bulb. Then draw arrowtails and starbursts on Figure 4.1b to represent what you observed. How do the brightnesses and flow rates differ from Figure 4.1a?

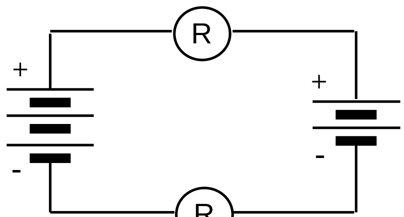


Figure 4.1c

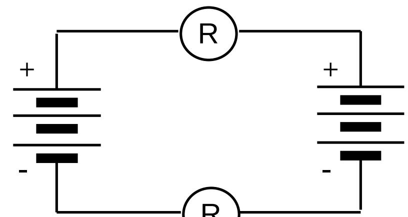


Figure 4.1d

ADDING MORE CELLS TO THE "DUELING" BATTERY

2. Draw arrowtails and starbursts on Figure 4.1c. How does the flow rate and bulb brightness differ from the previous two circuits?

3. Draw arrowtails and starbursts on Figure 4.1d. How does the flow rate and bulb brightness differ from the previous two circuits?

4. Comparing all 4 circuits, what can you conclude about the flow rate in a circuit that has <u>opposing</u> batteries? What is the evidence supporting your conclusions?

Conclusion	**Evidence**

5. From your observations of all four circuits, how would you describe <u>what batteries do</u> in a circuit? What is the evidence?

4.2 Activity: A closer look at capacitor charging

Charge a large silver capacitor through two long bulbs, using a 3-cell battery as in Figure 4.2 -- and with a compass under one of the wires. Carefully observe the brightness of the bulbs and the compass reading. Then discharge the capacitor with a wire, and observe the compass until the capacitor is completely discharged..

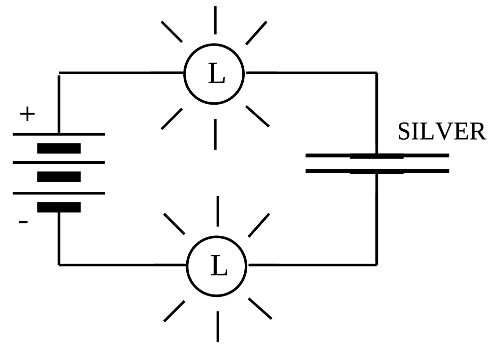


Figure 4.2
CHARGING A LARGE SILVER CAPACITOR

1. Draw arrows on Figure 4.2, to show charge flow in all parts of the circuit while the bulbs are lit. Don't use special arrowtail widths – just show <u>directions</u>.

2. How does the brightness of the bulbs change <u>during</u> capacitor charging? How does the compass reading change over time? What do these observations tell you about the <u>rate</u> of charge flow through the bulbs?

3. Compare what you observe in these two situations:

- while the large silver capacitor is charging in circuit 4.2
- when 1, then 2, then 3 opposing cells were added on the right in 4.1b,c,d

4. Is what a charging capacitor makes happen in this circuit anything like what a dueling battery makes happen? Explain your thinking.

4.3 Commentary: Comparing capacitor behavior with battery behavior

The pattern of bulb lighting we have just observed in a circuit with a charging capacitor is like bulb lighting in a circuit with a dueling battery. This similarity helps build a model of what causes flow in circuits. Here is the similarity:

CHARGING A CAPACITOR **---** Bulbs become progressively dimmer over time as the charging progresses.

ADDING OPPOSING CELLS **---** Bulbs become progressively dimmer each time an opposing D-cell is added.

In both of these situations, observing the bulbs change from "bright" to "dim" to "out" tells us that the flow rate is decreasing. This similarity of effect shows that a charging capacitor behaves like a battery which

- is getting stronger and stronger over time, and
- opposes the 3-cell battery that's charging the capacitor

During discharging, the bulbs again change from "bright" to "dim" to "out". The unopposed capacitor is now behaving like a battery that

- is getting weaker and weaker over time, and
- pushes in the same direction it pushed during charging

To summarize: During both charging and discharging, the capacitor behaves like a battery whose strength is determined by the amount of excess (+) or depleted (-) charge in the plates.
A charged capacitor pushes the charge that exists in the wires connected to it in a direction away from the (+) plate, toward the (-) plate.

4.4 Exercise: Why does capacitor charging eventually stop?

1. What is happening in the 'upper' and in the 'lower' capacitor plates during charging?

2. Observations of the bulbs and compass indicate that the capacitor charging eventually stops. Speculate: Why doesn't it continue?

INVESTIGATION TWO: WHAT HAPPENS WHILE A CAPACITOR CHARGES?

4.5 Activity: Experimenting with an already-charged capacitor

Charge a blue capacitor through two long bulbs, using a 3-cell battery as shown in Figure 4.5a. **Use a compass under one of the wires to monitor direction of flow.**

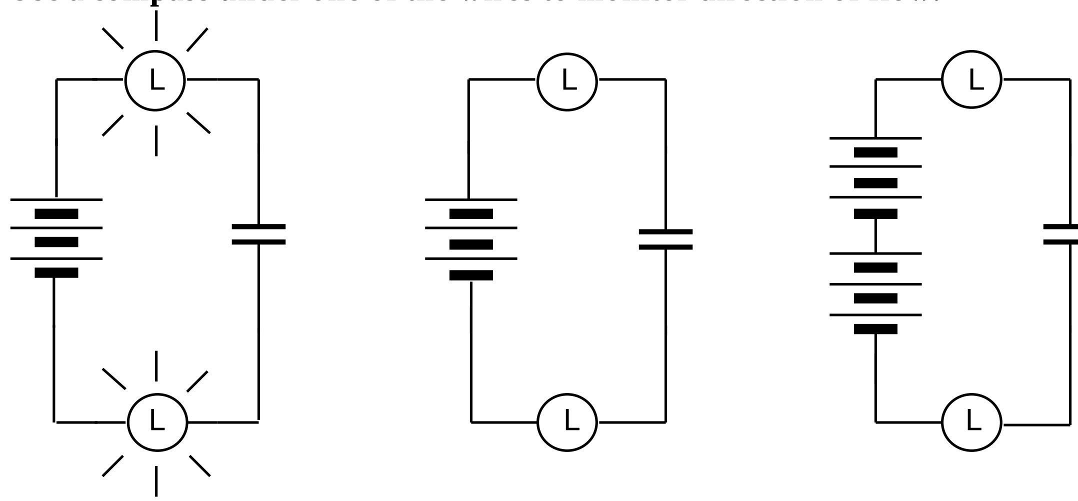


Figure 4.5a
CHARGING

Figure 4.5b
CHARGING COMPLETED

Figure 4.5c
ADDED BATTERY

1. Draw arrows on Figure 4.5a to show charge flow in all parts of the circuit while the bulbs are lit. Don't use special arrow widths -- just show directions.

2. Figure 4.5b shows the capacitor after it has been charged. Draw (+) signs by the plate that has gained charge, and (-) signs by the plate that has lost charge.

Next, imagine that you have opened the circuit and placed a second battery pack in the loop as shown in Figure 4.5b. Don't actually do this right now. Just think about what might happen if the already-charged capacitor is suddenly connected to a stronger battery with 6 cells.

3. **Predict:** Will the bulbs light again if you add the second 3-cell battery pack and close the circuit? Why or why not?

Now add the second battery pack as shown in Figure 4.5b, with the positive end of one battery pack connected to the negative end of the other one. Make sure the compass is under one of the wires.

4. Did the bulbs light? If they did, draw an arrow on Figure 4.5c to show the direction charge was moving everywhere during the second bulb lighting.

5. Did additional charge go into the (+) capacitor plate and out of the (-) plate? What is the evidence?

Now, remove both batteries from the circuit and connect the free ends of the wires to each other to form a closed circuit -- with a compass still under one wire.

6. What did you observe, for bulbs and compass? Explain why this happened.

Demonstration:

The teacher will now charge a capacitor with one battery pack as in Figure 4.5a, then add a second pack as in Figure 4.5c, and then add a third battery pack to the circuit.

7. How many times do the bulbs light?

8. Why do you think bulb lighting **stops** each time?

4.6 Activity: Exploring air as an analogy

In Section 2 an air capacitor provided insight into non-battery origins of charge in electric circuits. In this activity an air capacitor provides insight into non-battery causes of movement in circuits.

In the previous activity we found that a battery can push additional charge into a capacitor plate that is already "full". We can make a similar situation for air by

(a) connecting two syringes that are already filled with air

(b) pushing some of one syringe's air into the other syringe

Set up the apparatus shown in Figure 4.6a by pulling the plunger of syringe A all the way out, pulling the plunger of syringe B half-way out, and connecting the 2 syringes with a short length of clear tubing.

One person should hold plunger B steady to mimic the charge-holding region of a capacitor plate, while a partner pushes on plunger A to mimic stronger pushing by a battery.

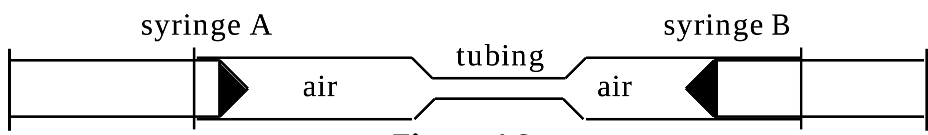


Figure 4.6a
SYRINGES CONTAINING AIR CONNECTED BY TUBING

1. Can you push air from syringe A into syringe B?

2. Describe how hard you have to push on plunger A, as you drive more and more air into syringe B.

3. Describe how much force you must exert to keep plunger B from moving while plunger A is being pushed in.

4. How does the air pressure change as syringe A's plunger is pushed in?

5. Let go of syringe A's plunger, and describe what happens. Then start over and let go of syringe B's plunger.

6. Using the connected syringes, air provides a model for explaining the observed electrical behavior in the circuit of Figure 4.5c? What are a) the advantages, and b) the limitations of this model?

4.7 Commentary: Compression, concentration, and trying-to-expand

When you pushed plunger A inward, the air in the syringes was compressed into a smaller volume. The air responded to this compression by <u>trying to expand</u>. The evidence for trying-to-expand was clear: When you released plunger A, you saw it being <u>pushed back out</u> by the compressed air.

Increased <u>concentration</u> -- particles more tightly packed -- is the reason compressed air tries to expand. But making the volume smaller is not the only way to increase the concentration.

When you pump air into a car tire, you increase the concentration by <u>adding more air</u> in a given volume. You are creating the same basis for trying-to-expand. The proof is that the extra air will <u>expand out through any hole</u> you make in the tire.

You can perform a "thought experiment" that combines volume reduction with adding more: Visualize a tire that's full of normal air. Then visualize this air being compressed into <u>part</u> of the tire. Finally, visualize more air being pumped into the part that was left empty when the volume of the original air was reduced.

The fact is that air tries to expand <u>no matter how</u> you make it more concentrated. The term "compressed air" is generally used for <u>all</u> trying-to-expand situations.

4.8 Commentary: The "electric pressure" idea

Compare extra charge being pumped into a capacitor plate (by a battery) with extra air being pumped into a tire: As charge flows in, the concentration of charge in the plate increases. You can imagine the charge in the plate being compressed to make room for more -- like air in the tire being compressed to make room for more.

Does compressed charge try to expand back out of the plate through a wire -- like compressed air expands back out of the tire through a hole? If compressed charge behaves the same way as compressed air, then the following events will happen:

- Increasingly strong reverse pushing by increasingly compressed charge in the (+) plate will make the battery less and less able to pump more charge into the plate. That will make the bulbs get progressively dimmer during capacitor charging.

- When the battery is removed, compression in the (+) plate will push charge in the reverse direction and discharge the capacitor. Decompression will weaken the reverse pushing and make the bulbs dimmer over time during discharging.

These bulb dimming predictions were in fact observed. The observations provide evidence that compressed charge in circuits really does behave like compressed air.

AIR PRESSURE is the name given to the effort to expand by compressed air. The name ELECTRIC PRESSURE is the same effort by compressed charge.

Electric pressure is measured in terms of a unit called the VOLT -- named after the Italian scientist Alessandro Volta, who introduced the concept in 1778.

INVESTIGATION THREE: HOW IS ELECTRIC PRESSURE INFLUENCED BY A BATTERY?

4.9 Commentary: Proposed model of how a battery pushes on charge

Suppose a battery moves charge internally as depicted in Figure 4.9a -- out of its bottom terminal and into its top terminal. The consequences of this movement are shown in Figure 4.9b -- charge depletion (-) in the bottom battery terminal and charge compression (+) in the top terminal. Figure 4.9c shows the presence of below-normal LOW pressure in the bottom terminal (created by depletion) and above-normal HIGH pressure in the top terminal (created by compression).

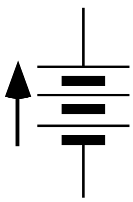


Figure 4.9a
CHARGE MOVED INTERNALLY BY THE BATTERY

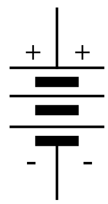


Figure 4.9b
COMPRESSION (+) IN TOP TERMINAL ALONG WITH DEPLETION (-) IN BOTTOM

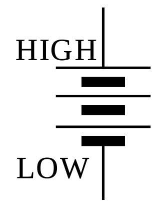


Figure 4.9c
RESULTING HIGH PRESSURE IN TOP & LOW IN BOTTOM

Figure 4.9c describes a proposed model of how a battery pushes on charge in wires connected to it. This model needs to be tested -- to find out how well it works.

But Figure 4.9c calls our attention to a role for below-normal electric pressure in circuits. Example: What does this LOW pressure do during capacitor charging?

We need to find out how below-normal air pressure behaves before we can test a battery model that involves below-normal electric pressure.

4.10 Activity: How below-normal air pressure behaves

Figure 4.10 shows an air capacitor with both sides open to the atmosphere through a glass tube in each side. There is atmospheric pressure in each side, which we will call NORMAL air pressure.

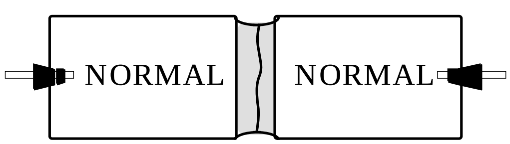


Figure 4.10
AIR CAPACITOR OPEN BEFORE INVESTIGATION

1. Blow air in through the glass tube in one side of an air capacitor, and hold the extra air inside by closing the tube with a finger. Draw a sketch of the air capacitor above, and label the pressure in each side as NORMAL or HIGH or LOW.

2. Explain why the membrane between the two sides changes shape.

3. Inhale air out of the other side of the air capacitor, and hold the depletion inside by closing the tube with a finger. Draw a new sketch of the air capacitor, and label the pressure in each side as NORMAL or HIGH or LOW.

4. Explain why the membrane between the two sides changes shape.

5. What do your observations tell you about the comparative ability of:

(a) Above-normal pressure to push toward NORMAL pressure?

and

(b) NORMAL pressure to push toward below-normal pressure?

4.11 Exercise: Testing the pressure-creating model of a battery

Consider a battery described by the model proposed in Activity 4.9. Suppose this battery is connected in a circuit with an uncharged capacitor. Before the circuit is closed, both capacitor plates will have a normal amount of charge. So they will be at NORMAL electric pressure when the circuit is closed as shown in Figure 4.11.

Use the air analogy test the predictions of the proposed model of a battery. Be sure to include the role of LOW (below normal) electric pressure -- the analog of LOW air pressure, which you investigated using an air capacitor in Activity 4.10.

1. Set up circuit 4.11 and observe bulb lighting during capacitor charging. According to the proposed model, what makes the top bulb light?

2. According to the proposed model, what makes the bottom bulb light?

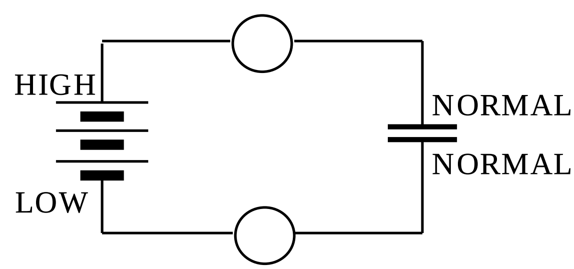


Figure 4.11
THE MOMENT CHARGING BEGINS

3. According to the proposed model, why do the bulbs become dimmer over time?

4. According to the proposed model, why does charging eventually stop?

INVESTIGATION FOUR: A WAY TO VISUALIZE PRESSURES IN A CIRCUIT

This investigation introduces the use of colors to represent electric pressure values in circuits. Color-coding a circuit enables you to visualize pressure differences as the causal agents that determine where and when charge moves.

4.12 Commentary: Color coding for electric pressures in a circuit

Electric pressures can be indicated on circuit diagrams by using colors to represent pressures on a relative scale. The following coloring system will be used:

RED	**HIGHEST Above Normal**
ORANGE	**Above Normal**
YELLOW	**NORMAL**
GREEN	**Below Normal**
BLUE	**LOWEST Below Normal**

Rules For Color Coding

1. A battery maintains highest electric pressure in the metal terminal labeled (+) and lowest electric pressure in the terminal labeled (-). Therefore:

- **Use RED for the (+) battery terminal and wires directly connected to it.**
- **Use BLUE for the (-) battery terminal and wires directly connected to it.**

2. Use YELLOW to represent normal electric pressure due to the normal amount of charge that exists in a connecting wires and uncharged capacitor plates before the wires are connected to a battery.

3. Battery terminal colors transfer to connecting wires as soon as the wires touch. Use only one color throughout each wire -- and throughout any group of wires that touch each other -- as well as throughout any capacitor plate connected to it.

4. Use different colors for the two wires connected to opposite sides of a lit bulb, because a pressure difference is needed to cause charge flow through a filament that resists flow. The colors may change over time during a transient process.

5. Do not color light bulbs -- because a lit bulb filament does not have the same pressure at all points. For the same reason, do not color the interior of a battery.

4.13 Commentary: Why wires are given uniform colors

A battery terminal transfers its electric pressure to a wire -- everywhere in the wire -- as soon as the wire touches it. Why???

The wire does not resist charge flow to any significant degree. So charge flow into or out of the wire will equalize the pressure everywhere within it -- and with the battery terminal -- in a super-fast transient process.

When a wire is connected to a capacitor plate, the plate has so much more metal than the wire that very little charge needs to leave or enter the plate in order to make the pressure in the wire equal to that in the plate. Therefore the pressure-equalizing process will not appreciably change the pressure in the plate.

4.14 Activity: Why wires are given uniform colors

Place one end of a soda straw against the skin of your arm or hand. Blow air into the straw at the other end -- then suck air out.

1. How much time elapsed between blowing air into the straw and feeling its pressure on your skin? How much time did it take to suck the air out?

2. For how long did the pressure keep changing after you first felt a change?

3. How much air do you feel you pushed into the straw, or sucked out of it, in order to change the pressure -- compared with the amount you blow in to supply air flow through an open straw?

4. If a wire is to charge flow as a straw is to air flow, what can you conclude about how much time it takes a wire to reach uniform pressure throughout the wire?

4.15 Exercise: Color coding the circuit for capacitor charging

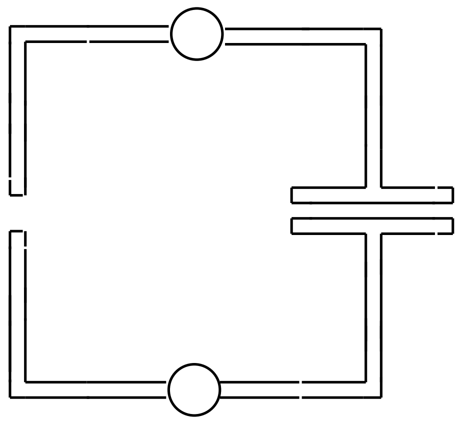


Figure 4.15a
NO BATTERY

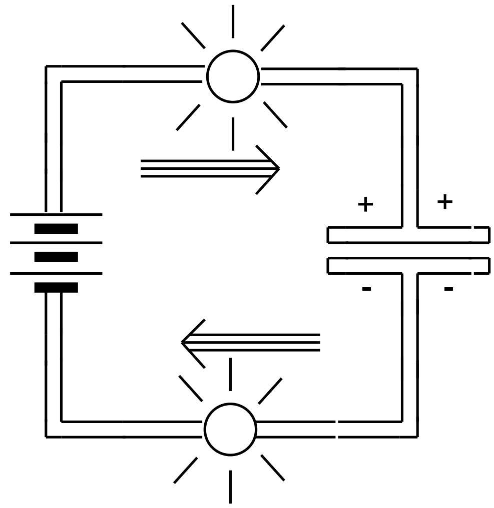


Figure 4.15b
CHARGING BEGINS

Color the battery terminals, the wires, and the capacitor plates in the diagrams in Figures 4.15a and 4.15b as you read the explanations that follow. Figure 4.15a shows a circuit containing a capacitor and two light bulbs. Since the circuit has no battery, the original NORMAL pressure in the wires and capacitor plates has not been altered. That's why the wires and plates are all colored YELLOW.

In Figure 4.15b, a battery has just been inserted into the circuit. The (+) terminal of the battery is a place that the battery keeps at HIGH electric pressure, and so it is colored RED. The red-to-yellow pressure difference will instantly push extra charge into a non-resisting wire attached to the battery's (+) terminal --- enough charge to raise the pressure in that wire to the same RED value as the battery terminal. Because the light bulb <u>resists</u> movement of charge, hardly any charge will have moved through the upper bulb and into the top capacitor plate during the negligible amount of time it takes the wire to reach RED pressure. Because an enormous amount of extra charge is needed to raise the pressure in the very large top capacitor plate, it and the wire attached to it are still at essentially the original YELLOW pressure.

The (-) terminal of the battery is a place that the battery keeps at LOW electric pressure, and so it is colored BLUE. The yellow-to-blue pressure difference will instantly push charge out of a non-resisting wire attached to the battery's (-) terminal --- enough charge to lower the pressure in that wire to the same BLUE value as the battery terminal. Because the light bulb <u>resists</u> movement of charge, hardly any charge will have moved out of the bottom capacitor plate and through the lower bulb during the negligible amount of time it takes the wire to reach BLUE pressure. Because an enormous depletion of charge is needed to lower the pressure in the very large bottom capacitor plate, it and the wire attached to it are still at essentially their original YELLOW pressure.

The pressure difference in the two wires connected to a bulb is what <u>drives charge through the bulb</u>. A large enough pressure difference will drive a flow rate that is great enough so that friction between the moving charge and the material of the filament will make the filament hot enough to glow. The glow is what you see when a bulb "lights up", but the <u>pressure difference in the wires</u> is what drives the flow that makes the bulb lighting happen.

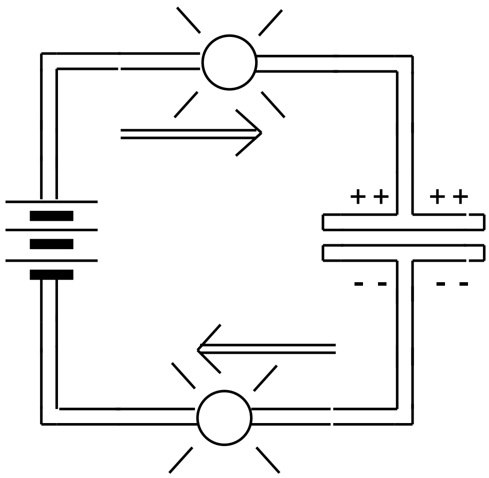


Figure 4.15c
CHARGING CONTINUES

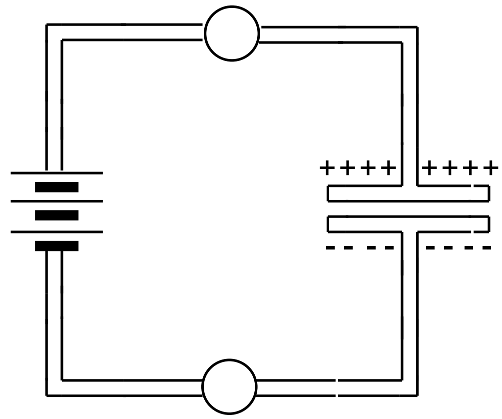


Figure 4.15d
CHARGING COMPLETED

Figure 4.15c shows the situation after enough charge has moved through each bulb to significantly change the amounts of charge in the capacitor plates. The increase of charge in the top plate has raised the pressure there to ORANGE, and depletion in the bottom plate has lowered the pressure there to GREEN. The wires attached to these plates will have the same colors (pressures) as the plates.

The red-to-orange and green-to-blue pressure differences are smaller than the earlier differences from red-to-yellow and yellow-to-blue. So the pressure differences driving charge through the bulbs are now smaller than they were earlier. These smaller pressure differences now drive charge through the bulbs at a lower flow rate. That reduces heat from friction in the filament, and makes the bulbs appear dimmer.

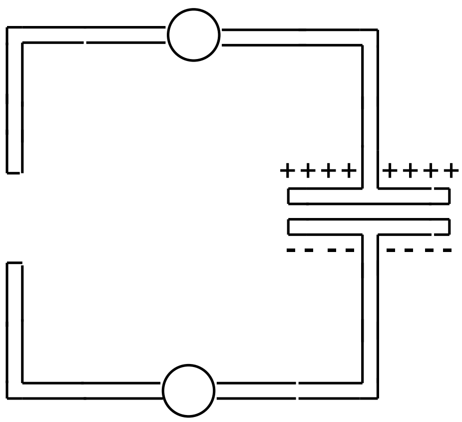
In Figure 4.15d, enough charge has been driven through the top bulb so that the pressure in the (+) capacitor plate has become equal to the HIGH pressure in the (+) terminal of the battery. So that plate and the wire connected to it are now colored RED. Also, enough charge has moved through the bottom bulb so that the pressure in the (-) capacitor plate has become equal to the LOW pressure in the (-) terminal of the battery. So this plate and the wire connected to it are now colored BLUE.

Now, notice that there is no longer any pressure difference in the pair of wires connected to either bulb. Since pressure differences are needed to drive charge through filaments that resist flow, there is no further charge flow through the bulbs. The bulbs are not lit, and the process of capacitor charging has stopped.

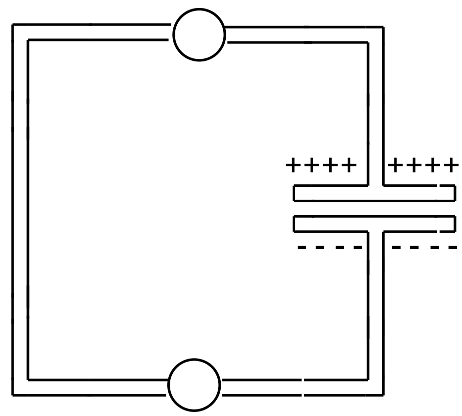
4.16 Activity: Color coding the circuit for capacitor discharging

Figures 4.16a, b, c, d show the situation at selected times during discharging of the capacitor. The number of (+) and (-) symbols show the degree of compression or depletion of charge in the capacitor plates.

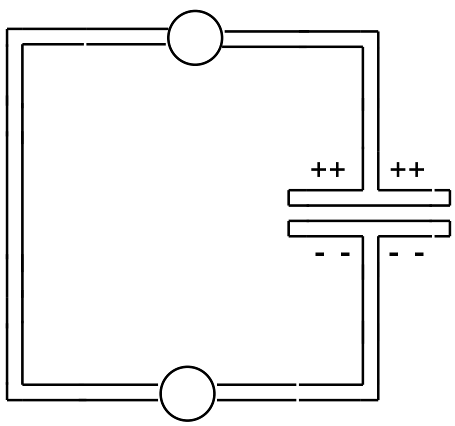
1. Draw starbursts on Figures 4.16a, b, c, d to show bulb brightnesses, and arrows to show the flow rates that cause bulb lighting. Show the distribution of pressures that make charge move by coloring capacitor plates and wires.



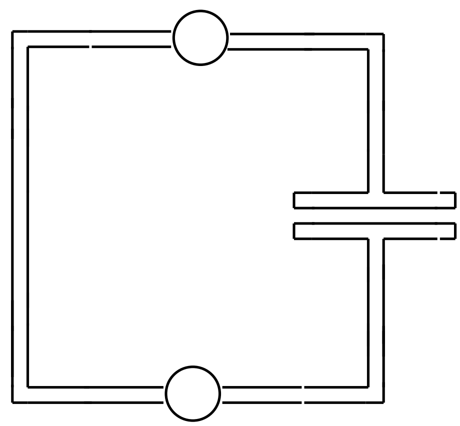
BATTERY REMOVED
Figure 4.16a



DISCHARGING BEGINS
Figure 4.16b



DISCHARGING CONTINUES
Figure 4.16c



DISCHARGING COMPLETED
Figure 4.16d

2. Which figure has the greatest pressure difference across the bulbs?

3. Which figure shows charge driven through the bulbs at the greatest flow rate?

4. In which figure do the bulbs become dim?

4.17 Activity: Color coding in circuits that don't have capacitors

Color each of the following circuit diagrams (Figures 4.17a through 4.17d). On the basis of your color coding, predict the direction of flow and the magnitude of the flow rate through each bulb by drawing arrowtails. Predict the relative brightness of each bulb in a given circuit by drawing starbursts. Be sure not to draw arrowtails and starbursts for bulbs that will not light at all.

In making predictions, keep in mind that the flow rate and brightness for each bulb is determined by the pressure difference across it. Equal pressure differences cause equal flow rates and brightness for identical bulbs, and a greater or lesser pressure difference causes greater or lesser flow rate and bulb brightness.

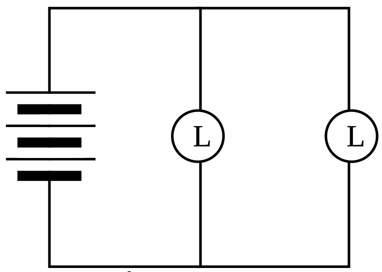


Figure 4.17a

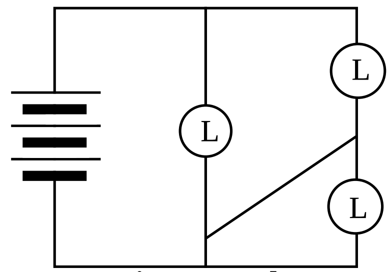


Figure 4.17b

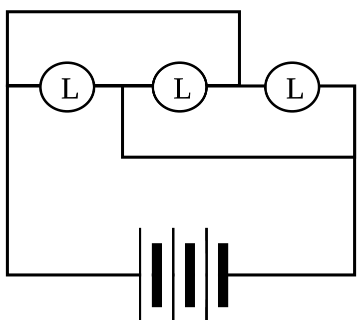


Figure 4.17c

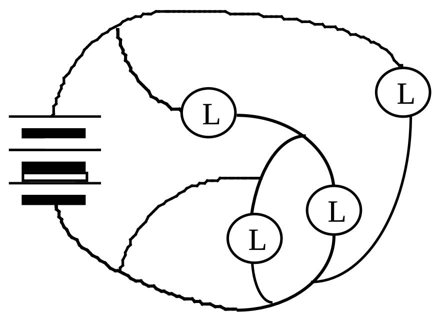


Figure 4.17d

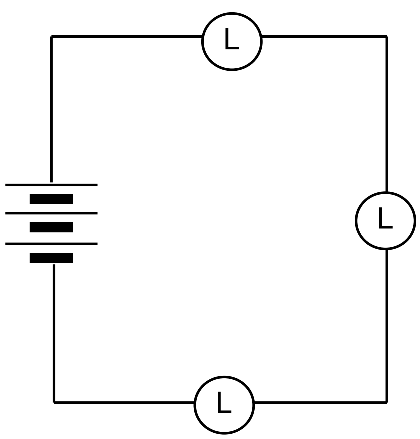


Figure 4.17e

After color-coding each diagram, construct the circuits to confirm your predictions. Use a compass to check your predictions about the directions of flow and the relative magnitudes of flow rate.

Making good predictions probably means that you have a good grasp of color coding and its relationship to charge flow. Be sure to resolve any differences between your predictions and your observations before you move on.

SUMMARY EXERCISE

1. Cite two examples of evidence that mobile charge in a circuit can be **compressed**.

2. What is meant by the term “electric pressure”?

3. How does a battery establish its pressure difference between the (+) and (-) terminals?

4. When color-coding, a wire is always a uniform color, and any wires it touches are the same color as well. What is the reasoning for this rule?

5. Using the term “pressure difference” explain why bulbs light.

6. In a circuit with identical bulbs, how can you use color-coding to predict the brightness of each bulb?

Section 5

HOW DO WIRES DISTRIBUTE ELECTRIC PRESSURE IN A CIRCUIT?

INTRODUCTION

The uniform pressure in a wire is represented by a uniform color. We learned in Section 4 how to assign colors to wires with one end touching a battery terminal or a capacitor plate. But what determines the pressure in a wire that does not touch a battery or a capacitor?

INVESTIGATION ONE: HOW DO PRESSURE CHANGES GET TO THE WIRES?

5.1 Activity: Four identical bulbs in series

Set up the circuit shown in Figure 5.1 using four D-cells.

1. Describe what you observe.

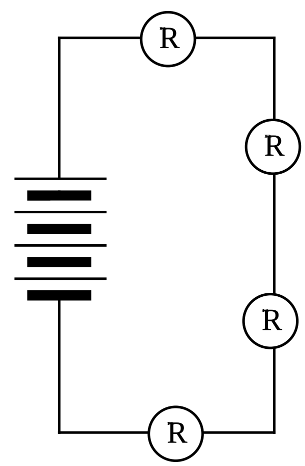


Figure 5.1
FOUR BULBS IN SERIES

2. Draw starbursts on the bulbs in Figure 5.1 to show the brightness of all bulbs. Draw arrowtails nearby to show the flow rates causing the observed brightness. Color code the wires to show the pressure differences that cause the flow rates.

3. Explain why you colored the wires in Figure 5.1 the way you did.

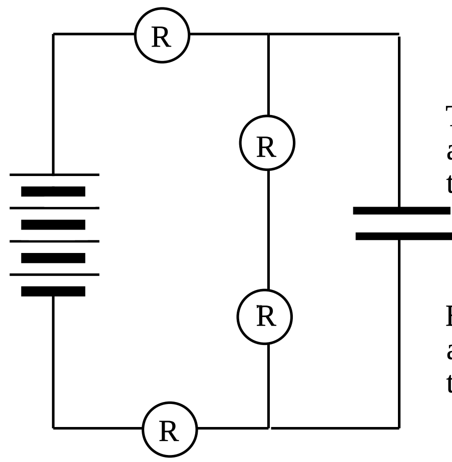
5.2 Activity: What causes pressure change in the wires?

In Figure 5.1, all wires had YELLOW (normal) pressure before they were connected in the circuit. The pressure in two of the wires changed to RED and BLUE because they were connected to the (+) and (-) battery terminals. But the colors of the wires that don't touch the battery can't be explained so easily. These colors show

- above-normal pressure in the top right wire
- below-normal pressure in the bottom right wire

To make the pressure go above YELLOW in the top right wire and below YELLOW in the bottom right wire, charge must have been compressed the first wire and depleted in the second. How did that compression and depletion happen? The process occurred too quickly to give us any observable clues.

We will slow the process down by adding a lot more metal to the top right and bottom right wires – using capacitor plates, as in Figure 5.2. A lot more charge will have to be compressed and depleted in these plates, in order to cause higher and lower pressure in the top right and bottom right wires. That will require a lot more time.



Top capacitor plate adds much more metal to the top right wire

Bottom capacitor plate adds much more metal to the lower right wire

Figure 5.2
CAPACITOR ADDED ACROSS 2 BULBS AT RIGHT

1. Set up the circuit in Figure 5.2 using a blue capacitor. Make the last connection at one of the battery terminals. Describe what you observe.

Repeat with a silver capacitor if one is available, to stretch out the time even more. Note that there's a <u>transient</u> process going on initially, until a steady-state is reached.

2. Draw starbursts on the bulbs in Figure 5.2 that show the brightness of each bulb <u>at the instant of connection</u>. Draw arrowtails that show the directions and rates of flow that are causing the observed brightness. Color code the wires to provide a picture of the pressure differences that cause these flows.

3. <u>At the instant of connection</u>:

a) Is there any movement through the wire between the two bulbs at the right?

b) Where is the charge that's passing through the top bulb going to?

c) Where is the charge passing through the bottom bulb coming from?

d) Is charge also passing through the battery?

Draw arrowtails on Figure 5.2 to illustrate your answers. Explain your reasoning.

4. Does the charge that has moved through the glowing bulbs cause any pressure changes in the circuit? Explain your reasoning.

5. <u>Predict</u>: What will happen to the electric pressure in the top right and bottom right wires as time goes on? Explain your reasoning.

Observe the circuit after the changes of bulb brightness have stopped.

6. What is the evidence that your prediction in question #5 was right or wrong?

5.3 Activity: What happens if the capacitor is not there?

Keep the circuit of Figure 5.2 in front of you, with all of its bulbs glowing in the final steady state.

1. Show the final condition of the circuit on Figure 5.3a below by drawing starbursts, arrowtails, wire colors and (if appropriate) + / - symbols on the capacitor plates.

Now take the capacitor away, without breaking the circuit through the bulbs.

2. Show the circuit's final condition without a capacitor by drawing all appropriate symbols again on Figure 5.3b.

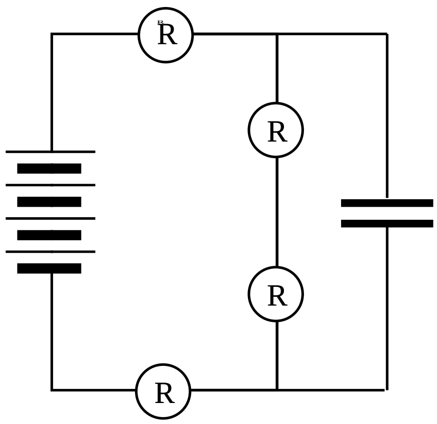


Figure 5.3a

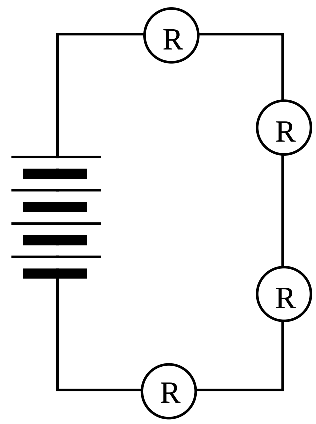


Figure 5.3b

3. Did you observe a change of bulb brightness when you removed the capacitor? Why do you think this was the case?

4 In Activity 5.1, the four-bulb circuit was connected without a capacitor. Was the final steady state any different?

5. How do you think the four-bulb circuit gets to its final steady state without a capacitor?

6. Why does the circuit require very much less time to reach the final steady state without a capacitor in the circuit?

5.4 Commentary: Transient process and steady state in a series circuit

A circuit that maintains steady flow rates has the same flow rate through all bulbs (or other resistors) that are connected in series.

Think about what would happen in a wire connecting two bulbs if different flow rates through these bulbs were to exist. Remember that the wire is already full of charge before any of the following happens.

1) More charge would be going into the wire through one bulb than is coming out of the wire through the other bulb.

2) This imbalance would cause compression of the charge in the wire, and would lead to a higher pressure in the wire.

3) The consequences of this pressure increase are very substantial:
- falling pressure difference across the inflow bulb makes inflow rate smaller
- rising pressure difference across the outflow bulb makes outflow rate larger
- flow rates through the bulbs are becoming more and more equal over time

The process that changes pressure in the wires eventually produces the same flow rate through every bulb connected in series. The flow rates through the series bulbs and the pressure values in the connecting wires will then remain steady. Describing the behavior of the process over time:

- It is transient – changing flow rates result from changing electric pressures.
- It is super-fast in ordinary circuits – because the wires contain very little metal where charges can accumulate.
- It can be observed – by adding a capacitor that has a lot more metal in its plates.

INVESTIGATION TWO: CAN SERIES PRESSURE DIFFERENCES BE UNEQUAL?

5.5 Activity: Non-identical bulbs in series

Set up the circuit in Figure 5.5. Connect the circuit 5 times – with the compass placed under a different wire each time. (Tape the compass in place and rotate the circuit over it.)

1. Write down what you observe about bulb brightness and compass deflection for the various parts of the circuit.

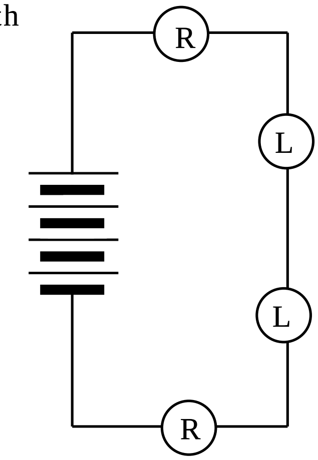


Figure 5.5
2 KINDS OF BULBS IN SERIES

2. What do you think is happening in the round bulbs?

3. Is there the same flow rate through all the bulbs? How do you know?

4. Is there the same pressure difference across all bulbs? How do you know?

5. What colors should we assign to the wires that don't touch the battery?

6. Color code the wires in Figure 5.5 in accordance with your answer to question 5. Draw arrowtails by the bulbs, which show direction and magnitude for flow rates driven by the pressure differences. Draw starbursts on the bulbs to represent the light coming out.

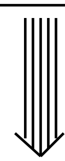
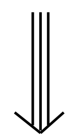
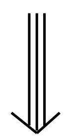
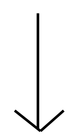
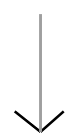
5.6 Commentary: Comparing currents in unlike bulbs

The flow rate through a bulb is determined by the pressure difference, which drives the flow. But the flow rate through a bulb is also determined by the bulb's resistance, which hinders movement through the bulb. The driving and hindering factors must be coordinated whenever you want to compare flow rates through unlike bulbs.

These two factors are coordinated visually by the arrows of different widths in Table 5.6. The columns indicate that the current through either kind of bulb decreases as the pressure difference across the bulb decreases. The rows indicate that, for the same pressure difference, a low resistance round bulb always allows a greater flow rate to pass through it than a high resistance long bulb does.

The table is especially useful for cases where a long bulb and round bulb have equal currents passing through them. Study Table 5.6 to determine what circumstances must exist in order for a round bulb and a long bulb to have exactly the same flow rate.

TABLE 5.6

Pressure Difference	Current Through Round Bulb	Current Through Long Bulb
Large		
Medium		
Small		

The table shows that there must be more pressure difference across the long bulb than across the round bulb in order for the flow rates to be equal. For example, a long bulb with a large pressure difference across it should have only about the same current through it as a round bulb with a medium pressure difference. Or a long bulb with a medium pressure difference across it should have only about the same current through it as a round bulb with a small pressure difference.

5.7 Activity: How did the top and bottom right wires get their pressures?

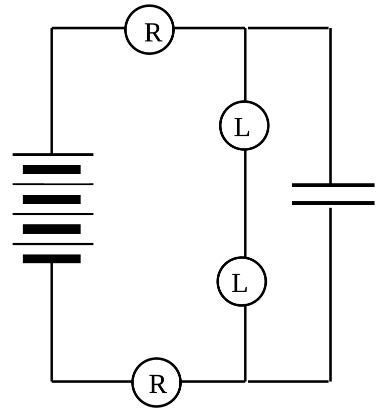


Figure 5.7
CAPACITOR ADDED ACROSS THE LONG BULBS

Set up the circuit in Figure 5.7 using a blue capacitor.
Make the last connection at one of the battery terminals.
Notice the difference between this circuit and Figure 5.2.

1. Describe what you observe.

2. Draw starbursts on the bulbs in Figure 5.7 that show the brightness of each bulb at the instant of connection.

Draw arrowtails that show the directions and rates of flow everywhere in the circuit. Color code the wires to provide a picture of the pressure differences that cause these flows.

3. Does the charge that has moved through the glowing bulbs cause any pressure changes in the circuit? Explain your reasoning.

4. Predict: What will happen to the electric pressure in the top right and bottom right wires as time goes on? Explain your reasoning.

Observe the circuit after the changes of bulb brightness have stopped.

5. What is the evidence that the pressure rose to a value higher than orange in the top right wire and fell to a value lower than green in the bottom right wire?

Now remove the capacitor from the circuit.

6. Do you observe any change of bulb brightness? Did you expect this result? Explain your reasoning?

5.8 Commentary: Series voltage division

Bulbs in series share the total pressure difference provided by the battery. But the previous activity shows they don't share it equally when they don't have equal resistance values. We have just seen that

• series bulbs with more resistance (long bulbs) get more pressure difference
• series bulbs with less resistance (round bulbs) get less pressure difference

We may draw a general conclusion for a circuit with resistors in series that has reached a steady-state condition:

> **There is more pressure difference across a larger resistance and less pressure difference across a smaller resistance.**

Scientists and engineers call this the principle of "series voltage division".

5.9 Exercise: Two non-identical bulbs in series

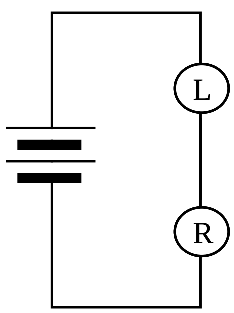


Figure 5.9a

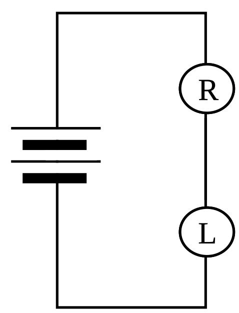


Figure 5.9b

LONG AND ROUND BULBS IN SERIES

1. Color code the wires in Figures 5.9a and 5.9b. Draw arrowtails to show the flow rates driven by the pressure differences.

2. Explain the reasoning behind your color coding decisions.

3. Draw starbursts to indicate your predictions for bulb brightness. Then construct the circuit to check your work.

INVESTIGATION THREE: HOW DO PARALLEL PATHS AFFECT A CIRCUIT?

5.10 Activity: Parallel pair in a series circuit

Set up the 3-bulb circuit in Figure 5.10a, with a gap for a fourth bulb to be added. Then add the fourth bulb to form the circuit in Figure 5.10b. To switch back and forth easily between Figures 5.10 a and b, you can add the fourth bulb and its socket, and simply lift the bulb to break the connection (5.10a).

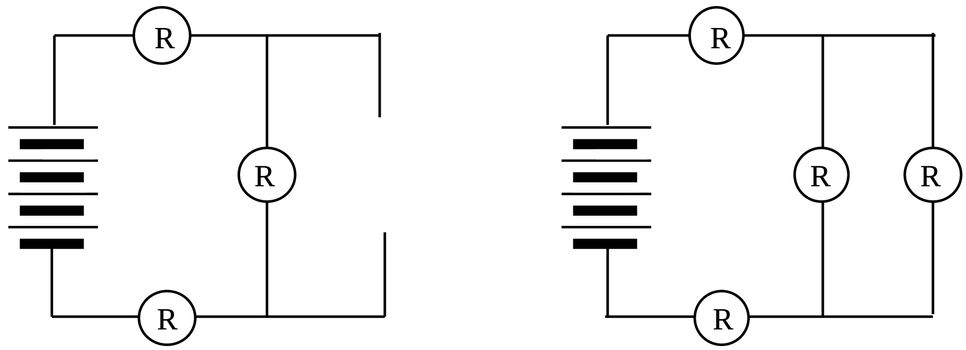


Figure 5.10a **Figure 5.10b**

2 BULBS IN SERIES WITH A PARALLEL PAIR

1. Write down what you observe about bulb brightness before and after you add in the 4th bulb to form a parallel pair at the right.

2. What do your observations indicate about flow rate through the top and bottom bulbs before and after you add the 4th bulb to form a parallel pair at the right?

3. What does this indicate about the overall resistance of the circuit after a bulb is added in parallel with an original bulb, compared to the overall resistance before?

4. What do your observations indicate about pressure difference across the parallel pair, in comparison with pressure difference across the top or bottom bulb?

5. What does this indicate about the overall resistance of the parallel pair of bulbs, compared to the resistance of an individual bulb?

6. What caused the pressure changes in the wires connected to the original middle bulb?

5.11 Commentary: Parallel resistance reduction

The previous activity shows that a parallel pair has less resistance than a single bulb. We will give the name "parallel resistance reduction" to this property of a parallel combination of resistors. You may wonder: How can two bulbs possibly have less resistance than one bulb? The way out of this puzzle is to note that:

- Parallel resistors provide more paths from a HIGH to a LOW pressure region. Resistance in other paths does not reduce the flow rate in an individual path.

- So a given pressure difference will drive a greater net flow rate from the HIGH pressure region to the LOW pressure region than it does through a single path.

We need a definition of RESISTANCE that takes into account the letting-through effect of parallel paths as well as the holding-back effect of the individual resistors.
From now on we will redefine resistance in terms of flow-permitting behavior:

"Less resistance" lets the same pressure difference drive a greater flow rate.

– OR –

"Less resistance" lets the same flow rate be driven by less pressure difference.

Our work in the previous activity produced two applications of these statements:

- The 4-bulb circuit with a parallel pair has less resistance than the original 3-bulb circuit because it lets the same pressure difference drive a greater flow rate through the circuit.

- The parallel pair has less resistance than either of the 2 single bulbs in series because it lets the same flow rate be driven through even though there is less pressure difference across the pair than there is across either series bulb.

5.12 Activity: Alternative definition of resistance

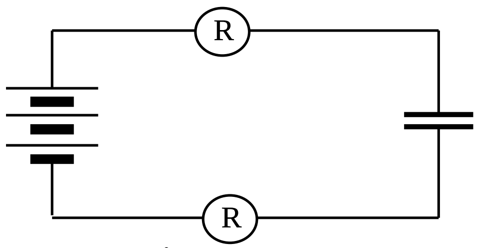
The definition of “resistance” developed in Activity 5.8 is based on comparing situations with the same flow rate through different types of bulbs. The definition could just as well be based on comparing situations with the same pressure difference.

1. Complete this alternative form of the definition by writing the word “greater” or the word “less” in each underlined space:

“More resistance” lets through _______ flow rate for a given pressure difference.

“Less resistance” lets through _______ flow rate a given pressure difference.

Use the standard charging circuit at the left to charge a silver capacitor – three times. Discharge first through 1 long bulb, then through 2 parallel long bulbs, then through 4 parallel long bulbs.



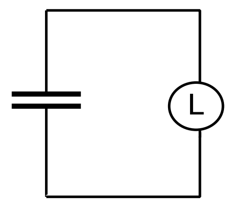
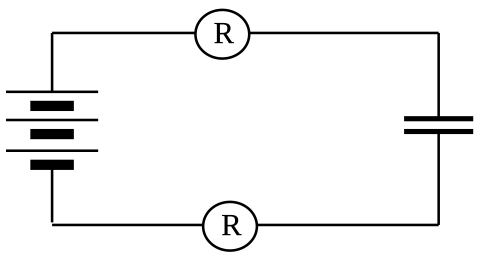


Figure 5.12a
STANDARD CHARGING CIRCUIT

Figure 5.12b
DISCHARGING



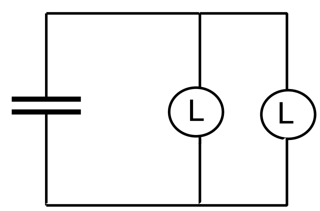
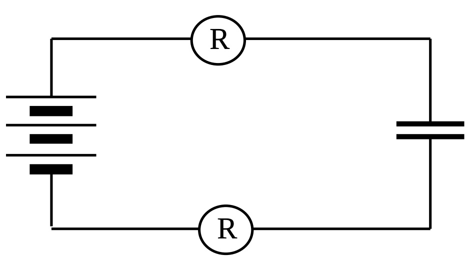


Figure 5.12c
DISCHARGING



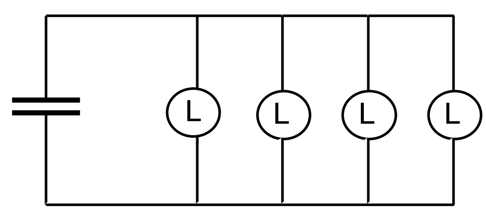


Figure 5.12d
DISCHARGING

2. Rank the three bulb combinations in Figures 5.12b, c, and d according to lighting time (shortest to longest).

3. Rank these bulb combinations according to resistance, based on lighting time.

4. Rank the three bulb combinations in Figures 5.12b,c,d according to flow rate.

5. Rank these bulb combinations according to resistance, based on flow rate.

5.13 Activity: Shorting wires and short circuits

Set up a circuit with a round and a long bulb in series, as in Figure 5.13a. Observe carefully as you make three modifications: First connect a long bulb in parallel with the long bulb, then a round bulb, and then just a wire in parallel with the original long bulb as shown in 5.13a, b, and c.

In each case, add the parallel wire by tapping it into the circuit (touch a segment of a bulb socket). Particularly in 5.13c, the round bulb will become stressed so tap briefly to make your observations.

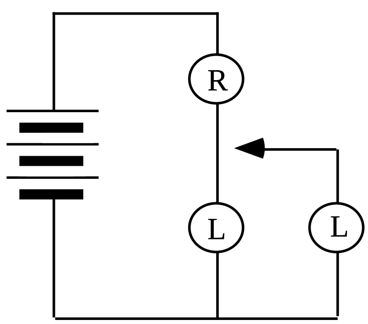


Figure 5.13a

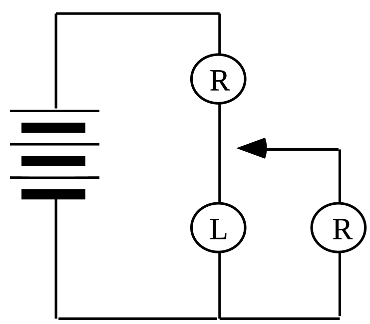


Figure 5.13b

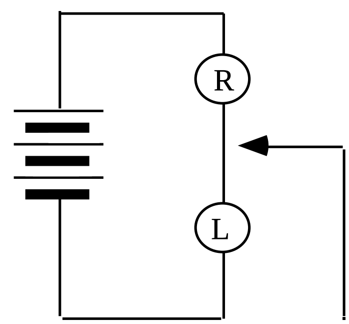


Figure 5.13c

1. Color code each of the circuits. Draw arrowtails to indicate flow directions and rates through each bulb as determined with a compass.

2. How does the brightness of the top round bulb change during the progression of parallel branches? Explain why this happens.

The wire across the long bulb in Figure 5.13c is called a "shorting wire," a "short circuit," or just a "short." Since this wire cannot sustain a pressure difference, it causes both sides of the long bulb to have blue pressure. The pressure difference across the bulb is therefore zero, and all of the flow must go through the wire.

5.13 Commentary: How does adding branches lower resistance?

It seems to defy common sense that adding ***more*** resistors to part of a circuit can make ***less*** equivalent resistance. But that's exactly what happens when resistors are added in parallel. Thinking about steady-state flow in the circuit of three identical bulbs shown in Figure 5.13 can help make sense of this idea.

You'll need to keep a couple of things in mind about steady-state flow:

1) Each wire in the circuit is <u>filled</u> with mobile charge, and <u>all</u> of this charge is being driven forward by differences of <u>pressure</u> in the wires.

2) Different pressures were established by <u>compression and depletion</u> in the wires, during a brief transient stage at the instant of connection.

You can visualize the flow pattern by thinking of a moving collection of "little bits." Figure 5.13 shows four bits (small black circles) entering the single series bulb at the top, at the same time that four other bits are entering the parallel pair at the bottom.

Note that the pressure differences are pushing <u>only two</u> bits through each bulb in the parallel pair, while pushing <u>all four</u> bits through the single series bulb. So charge is moving <u>at only half the rate</u> through each parallel bulb as through the single series bulb.

How much pressure difference is required to drive a stream of charge at half the rate through one bulb as through another identical bulb? The answer is:

Only half as much pressure difference is needed!

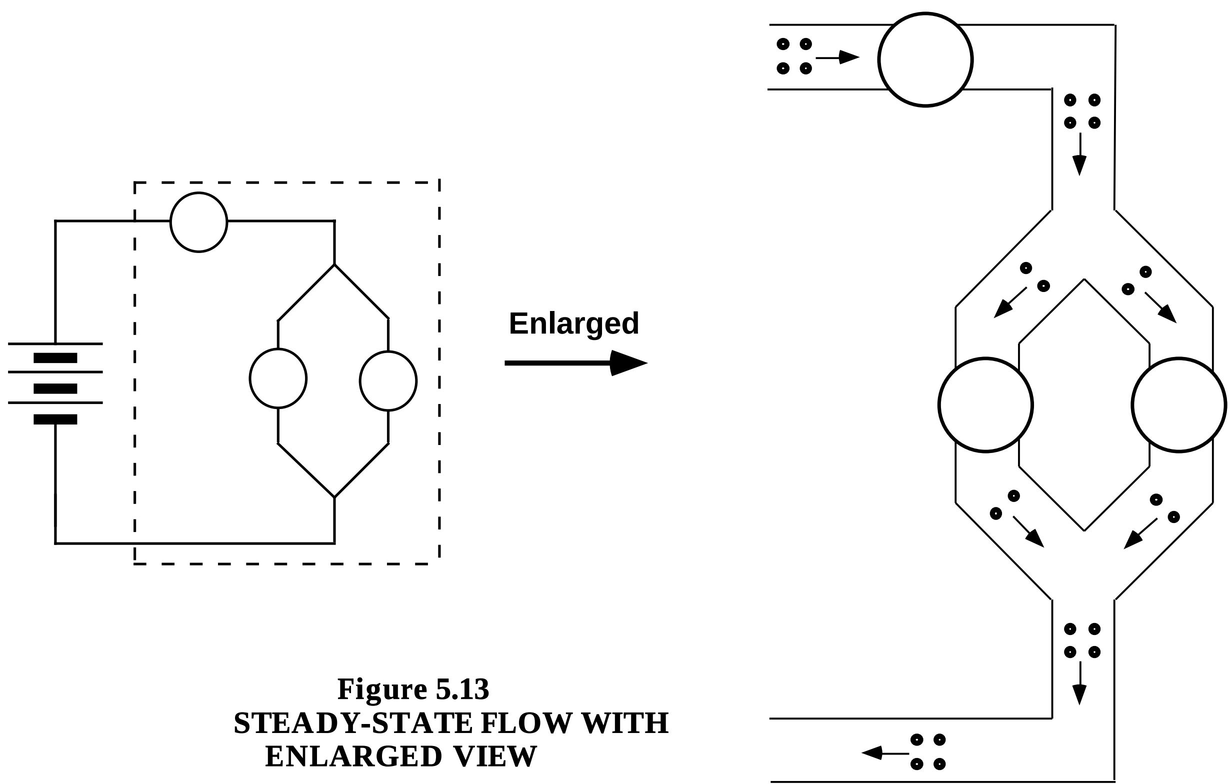


Figure 5.13
STEADY-STATE FLOW WITH ENLARGED VIEW

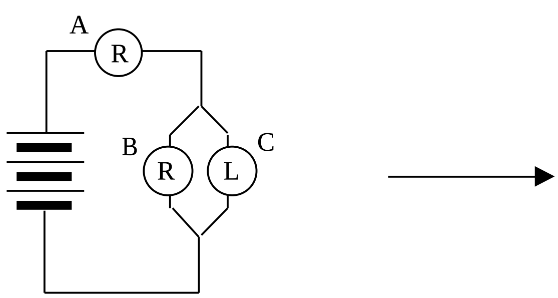
What does it seem like is happening when you take one resistor, put another one in parallel with it, and discover that you need only half as much pressure difference to push the same flow rate through the pair?

It seems like the original resistance is cut in half!

Another way of saying this is that two parallel resistors have the same effect on charge flow as a single resistor with half as much resistance**.**

5.14 Activity: Non-identical bulbs connected in parallel

The ideas we have been developing will now be used to analyze the circuit in Figure 5.14. You will find it useful to connect the two round bulbs in series first, and then to observe how the brightness of the top round bulb A changes when the long bulb C is added in parallel with the bottom round bulb B.



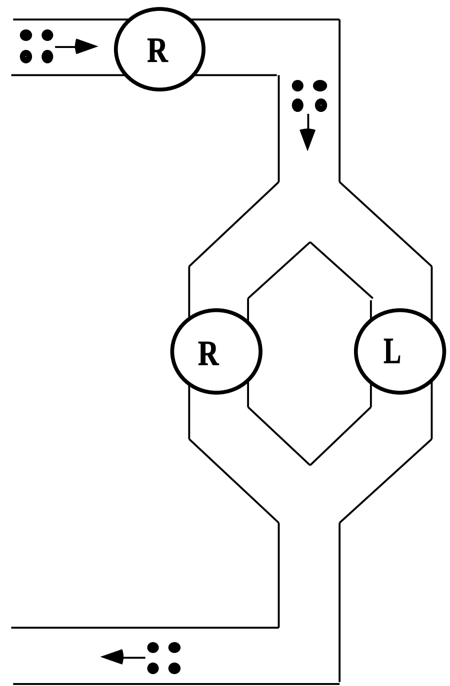


Figure 5.14
PARALLEL COMBINATION CIRCUIT

1. Does the parallel combination behave as if it has a greater or a smaller equivalent resistance than a single round bulb? How do you know?

2. Use the enlarged circuit at the right in Figure 5.14 to diagram the path of charges as they move through the parallel branches. Explain your reasoning.

3. Use a compass to check your answer. What do you observe?

4. Which has the greater pressure difference across it — round bulb A or the two bulbs in parallel? Explain.

5. Color code the circuit using the idea of voltage division.

INVESTIGATION FOUR: WHAT FACTORS INFLUENCE BATTERY VOLTAGE?

A battery influences pressure differences in flow paths connected to it. Can flow paths influence the pressure difference ("voltage") in the terminals of a battery?

5.15 Activity: Do flow paths influence pressure difference in battery terminals?

Connect a long bulb to the terminals of a 2- cell battery. Place the bulb on the left of the battery, as shown in Figure 5.15a.

As other conducting paths are added on the right of the battery, as shown in Figures 5.15b and 5.15c, observe what happens to the brightness of the bulb on the left. If the brightness changes, flow through the added path has influenced the pressure difference in the battery terminals. If the brightness stays the same, that flow through the added path had no effect on the pressure difference in the terminals.

Add an extra flow path at the right of the cell as in Figure 5.15b and observe the long bulb. Next add a different flow path as in Figure 5.15c by **briefly tapping** the wire to one of the battery terminals. Circuit 5.15b uses a high resistance bulb to obtain the smallest possible flow rate in the extra path, while circuit 5.15c uses a simple wire with practically no resistance to obtain the largest possible flow rate.

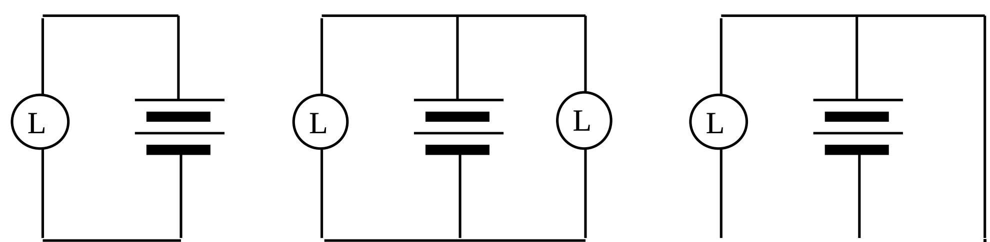


Figure 5.15a **Figure 5.15b** **Figure 5.15c**

1. What happened to the brightness of the bulb on the left when you added an extra flow path to form circuit 5.15b? What happened to the brightness of this bulb when you added a different extra flow path to form circuit 5.15c?

2. Draw starbursts on the three circuit diagrams to show bulb brightness, and draw arrowtails to show flow rates through the battery and through all flow paths.

3. What happened to the pressure difference in the battery terminals when you added the extra flow path in circuit 5.15b? What happened when you added the extra path in circuit 5.15c? What is the evidence?

People familiar with electric circuits will say that the added wire in circuit 5.15c is a “shorting wire”, which “short circuits” the battery (reduces its voltage to zero).

5.16 Commentary: Flow paths influence pressure difference in battery terminals

Circuit 5.15c demonstrates that a shorting wire can reduce the pressure difference across the battery terminals to zero. This drastic reduction of pressure difference is presumably a consequence of a wire with no resistance allowing charge to flow rapidly out of a battery’s HIGH pressure terminal and into its LOW pressure terminal.

Can flow through the non-zero resistance of a bulb filament also influence the pressure difference in the battery terminals? The answer is YES. Consider the cell diagram in Figure 5.16a:

- The shaded interior region represents compounds inside the cell that (a) contain mobile charge and (b) try to push this charge upward.
- The black regions represent High and Low pressure terminals where a pressure difference due to compression and depletion tries to push the same charge downward.

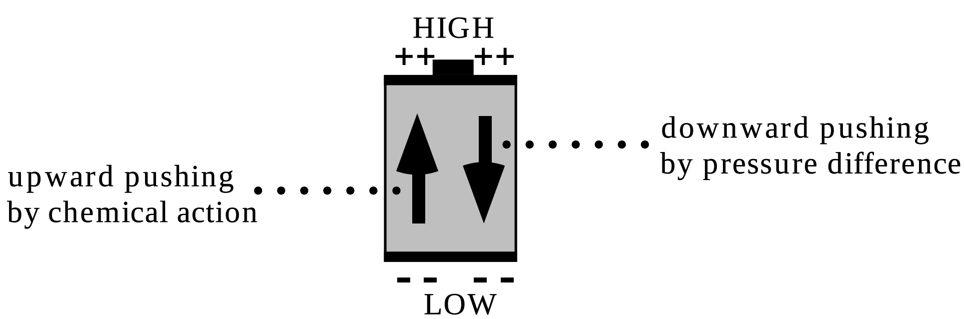


Figure 5.16a
PUSHES IN OPPOSITE DIRECTIONS CANCEL OUT IN
A CELL WHERE THERE IS CHARGE BUT NO FLOW

When a cell is not connected in a circuit, there is no flow through it. The upward and downward pushes have equal magnitude and cancel each other out.

This picture changes when a cell is connected to a flow path. Activity 5.15 showed that charge flow in a shorting wire connecting the battery terminals can <u>reduce the pressure difference</u> in the terminals. Study the diagrams below (Figure 5.16b, c, and d).

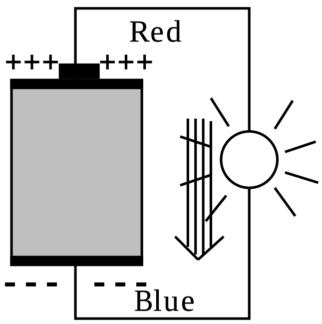


Figure 5.16b
AT THE MOMENT OF CONNECTION

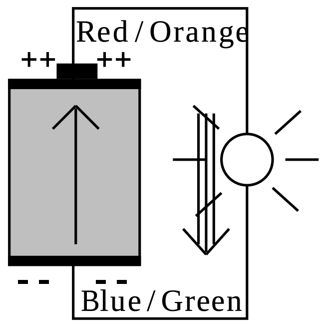


Figure 5.16c
JUST A LITTLE WHILE LATER

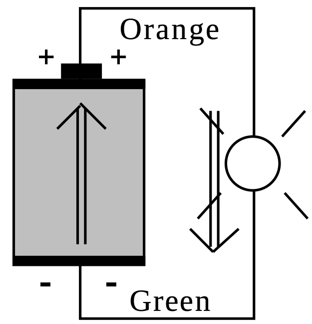


Figure 5.16d
NO MORE CHANGES AFTER A LONG TIME

<u>Figure 5.16b</u>: Pressure difference in the cell terminals starts driving HIGH-to-LOW flow through the bulb at the instant of connection.

<u>Figure 5.16c</u>: Flow through the bulb reduces pressure difference in the terminals, and weakens downward pushing by pressure difference in the battery terminals. This allows chemical action to start driving charge upward through the cell.

<u>Figure 5.16d</u>: Falling pressure difference in the battery terminals drives falling flow rate through the bulb and lets chemical action drive growing flow rate through the cell. The two flow rates eventually become equal, and result in:

- steady reduced pressure difference in the battery terminals
- same steady flow rate everywhere in the circuit
- steady bulb brightness

These bulb lighting changes ordinarily happen so quickly that they cannot be observed.

5.17 Activity: How does battery voltage depend on resistance in the flow path?

In Activity 5.15, we found that connecting a flow path to the battery terminals that has practically no resistance (just a wire) will reduce the pressure difference across the terminals all the way down to zero. This activity is a repeat of Activity 5.15 using a round bulb to give the added flow path a resistance that is intermediate between a long bulb and a wire.

Set up the circuit in Figure 5.17a, and then connect an extra flow path with a round bulb as indicated in Figure 5.17b.

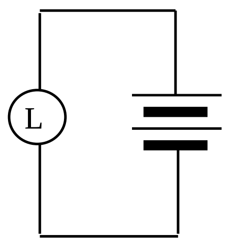


Figure 5.17a
STANDARD CIRCUIT

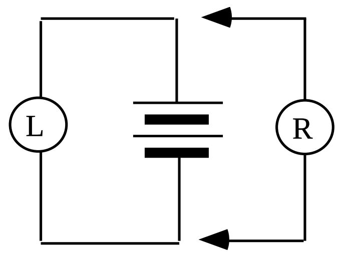


Figure 5.17b
ADD NEW FLOW PATH WITH A ROUND BULB

1. What happened to the brightness of the long bulb when a single round bulb was added? Compare this with what happened with a long bulb in the added path (Activity 5.15b).

2. Predict what would happen if you were to repeat the experiment using a group of 3 parallel bulbs as indicated in Figure 5.17c, instead of using a single round bulb.

Prediction:

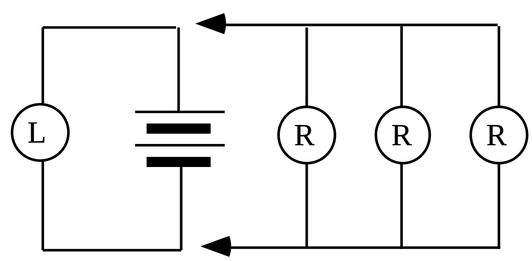


Figure 5.17c
EXTRA PATH WITH THREE PARALLEL ROUND BULBS

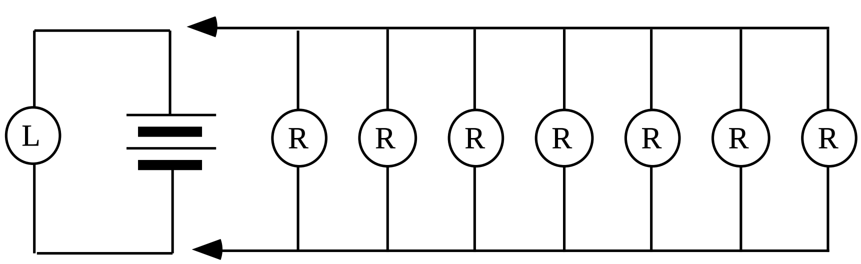


Figure 5.17d
EXTRA PATH WITH SEVEN PARALLEL ROUND BULBS

What do you think would happen if you used a group of 7 parallel bulbs, as indicated in Figure 5.17d?.

Prediction:

Construct the circuit in Figure 5.17a to test your predictions. (If you choose to construct 5.17b, you will need to borrow sockets from another lab group.))

3. What do you observe?

4. What happened to the pressure difference in the battery terminals when one round bulb was used? When 3 parallel bulbs were used? When 7 parallel bulbs were used? What is the evidence?

5. Describe in words the relationship of (a) pressure difference a battery maintains in its terminals to (b) resistance in a flow path connected to the terminals.

5.18 Activity: Does the internal resistance of the battery also have an effect?

When a battery is connected in a circuit, the chemical reactions that drive charge flow are changing its compounds into new compounds that have <u>greater resistance</u>.

Your teacher will give you 2 cells that are "run down" due to long use, and have substantially more resistance than the relatively fresh cells you have been using. Use these 2 cells to do the experiments indicated in Figures 5.18a, 5.18b, and 5.18c.
Then repeat the experiments using your fresh cells.

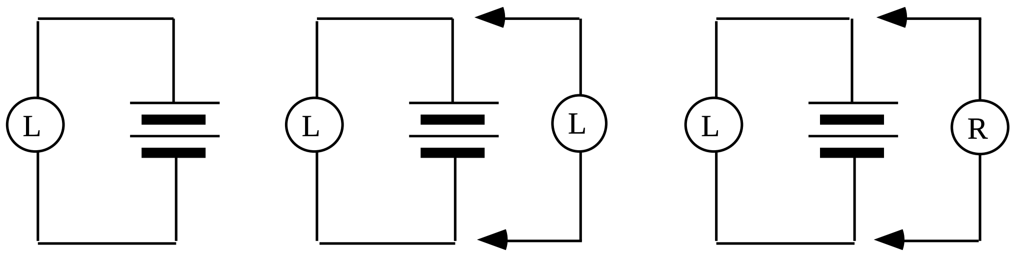


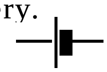
Figure 5.18a **Figure 5.18b** **Figure 5.18c**

1. What do you observe when you use the high resistance "run down" cells?

2. Compare this with what happens when you use the low resistance fresh cells.

5.19 Commentary: Including the complete battery model in a circuit diagram

Our model of a battery now includes <u>two</u> properties:

(1) CHEMICAL ACTIVITY — tries to drive charge through a battery.
This effort is represented on circuit diagrams by the symbol 

(2) INTERNAL RESISTANCE — hinders movement through the battery
This is represented on circuit diagrams by the resistance symbol 

If internal resistance did not exist, a cell could be represented on a diagram by the symbol for property (1) alone — just as we have been doing until now. We may continue to do this in situations where the resistance in the flow path is so large (R>>r) that property (2) does not have an appreciable effect on the battery voltage.

Figures 5.19a, 5.19b, and 5.19c show how to include property (2) in circuit diagrams when the external resistance is not so large. Since chemical activity maintains red-to-blue pressure difference in battery terminals when there is <u>no</u> flow, the symbol for chemical activity should be colored red-to-blue in situations where flow <u>does</u> occur. When there is no flow through the battery, the terminals should also be colored red and blue. In a circuit where flow is occurring, however, there should be a less-HIGH color in the (+) terminal and a less-LOW color in (-) terminal.

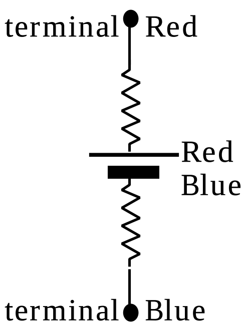


Figure 5.19 a
ISOLATED CELL

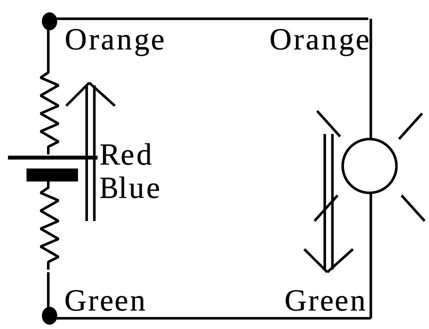


Figure 5.19b
IN CIRCUIT WITH FLOW

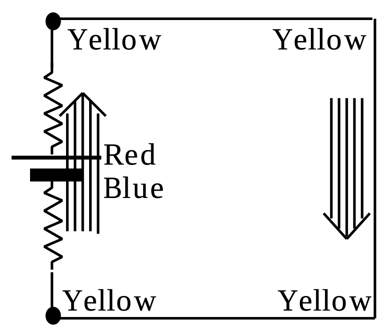


Figure 5.19
SHORT CIRCUITED

SUMMARY EXERCISE

1. A circuit containing three identical bulbs in series will have equal flow rates through all bulbs when the steady state is reached. Will it have equal flow rates through each bulb in the transient stage at the instant the connection is made? Explain with a diagram.

2. A single long bulb is connected to a fresh battery. When a second long bulb is added in parallel to the first bulb, there is an (Increase, Decrease, or No Change) in:

a) the electric pressure difference across the battery terminals ________

b) the electric pressure difference across the first bulb ________

c) the flow rate of charge through the battery ________

d) the flow rate of charge through the first bulb ________

3. Is the overall resistance of a series combination more than the resistance of any single bulb in the combination? Why or why not?

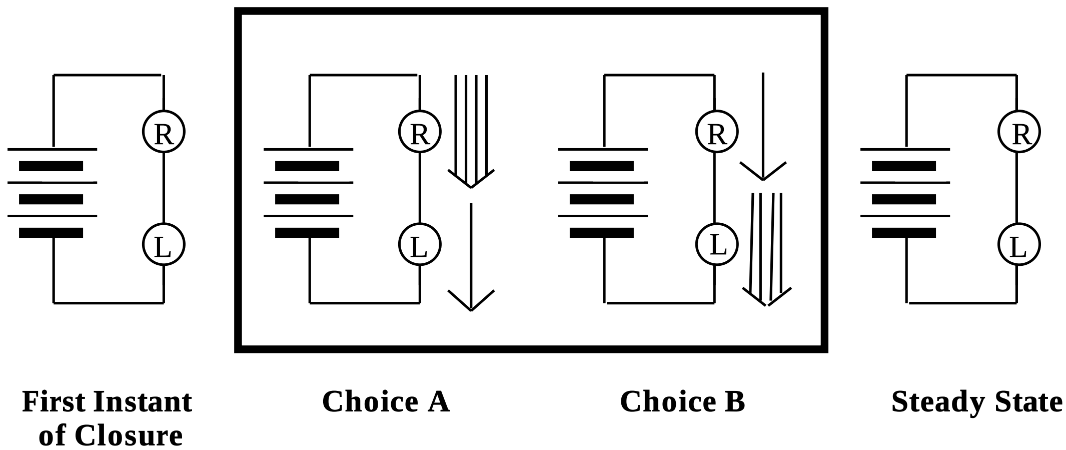
4.. Is the overall resistance of a parallel combination more than the resistance of any single resistor in the combination? Why or why not?

5. How does the flow rate of charge into a parallel circuit divide –

a) if all branches of the circuit have the same resistance?

b) if different branches have different resistance values?

6. Does Choice A or Choice B provide the best representation of the transient process that occurs after the circuit is closed? Explain your reasoning.



7. A simple circuit contains a battery and a single light bulb. What effect does adding a wire in parallel with the light bulb have on –

a) the electric pressure difference across the bulb?

b) the flow rate of charge through the bulb?

c) the pressure difference across the battery terminals?

Section 6

HOW ARE VALUES OF CIRCUIT VARIABLES MEASURED?

INTRODUCTION

People who use electric circuits for practical purposes often need to measure quantitative values of electric pressure difference and flow rate of charge. To do this they use instruments called “voltmeters” and “ammeters.” In this section you will investigate the behavior of these instruments. You will then combine these instruments in a circuit to measure the resistance of circuit components.

6.1 Commentary

Your teacher will provide you with an instrument labeled “voltmeter” and with another labeled “ammeter.” The circuit diagram symbol for a voltmeter is a box labeled “V”, and the symbol for an ammeter is a box labeled “A”.

There are two main types of voltmeters and ammeters: The “analog” type has a number line scale and a movable pointer, while the “digital” type provides a numerical readout. Your teacher will demonstrate the proper use of the instruments available in your classroom. Please note that connecting them directly to a battery can often damage ammeters. **Follow instructions carefully**!

Do not connect an ammeter in any circuit until your teacher has shown you how to do this properly.

<u>INVESTIGATION ONE: WHAT DOES A "VOLTMETER" DO?</u>

The readout of an instrument labeled "voltmeter" is intended by the manufacturer to tell you the electric pressure difference between any two points on a circuit to which it is connected. In this investigation you will investigate the <u>actual</u> behavior of your voltmeter.

6.2 Activity: Testing the voltmeter qualitatively

Each diagram below is shown with a pair of extra wires connected to two points on a circuit. Figure 6.2a shows a voltmeter connected to the free ends of one of the pairs of extra wires. Do not build the circuit yet; just study the diagrams.

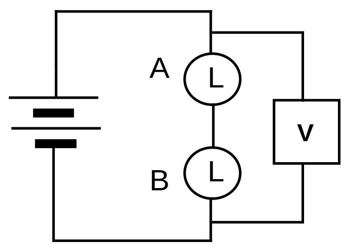


Figure 6.2a
VOLTMETER CONNECTED ACROSS A PAIR OF BULBS

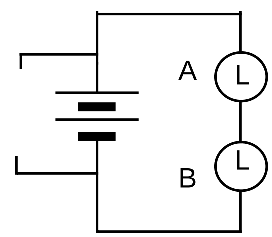


Figure 6.2b
EXTRA WIRES CONNECTED TO BOTH SIDES OF THE BATTERY

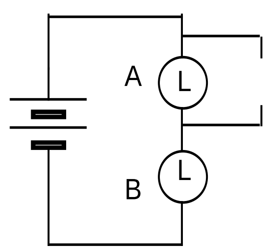


Figure 6.2c
EXTRA WIRES CONNECTED TO BOTH SIDES OF UPPER BULB

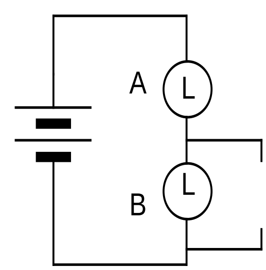


Figure 6.2d
EXTRA WIRES CONNECTED TO BOTH SIDES OF LOWER BULB

1. Color code each of the diagrams above, including the extra wires.

2. Based on the color code, is there a pressure difference across the voltmeter in Figure 6.2a? Do you think it is equal or unequal to the pressure difference across the pair of bulbs? Why?

Suppose the voltmeter shown in Figure 6.2a is connected to the free ends of the extra wires in each of the other circuits . Try to envision the pressure difference in these wires as <u>acting on</u> the voltmeter, and the meter reading as telling you how the voltmeter is <u>responding to</u> this action.

3. How would you predict the pressure difference that acts on the voltmeter when it is connected across the battery as in Figure 6.2b – compared with the pressure difference that acts on it when it is connected across the pair of bulbs as in Figure 6.2a? Should these pressure differences be the same or different?

4. **Predict** how these pressure differences will compare:

a) across bulb A (as in Figure 6.2c) compared to the battery (Figure 6.2b)?

b) across bulb B (as in Figure 6.2d) compared to the battery (Figure 6.2b)?

c) across bulb A (Figure 6.2c) compared to across bulb B (Figure 6.2d)?

6.3 Commentary

The symbol for the quantitative value of electric pressure is "**V**". The symbol "Δ**V**" will be used for the difference between two electric pressure values.

The unit for expressing quantitative values of electric pressure and of electric pressure difference is the **VOLT**. Values of electric pressure difference are measured by a voltmeter in volts. D-cells are designed to maintain their (+) terminals at 1.5 volts electric pressure higher than their (-) terminals.

6.4 Activity: Testing the voltmeter quantitatively

1. Color code the wires for the circuit diagram in Figure 6.4a, using red-to-blue for the pressure difference maintained by the battery between its terminals. Do not connect the voltmeter yet.

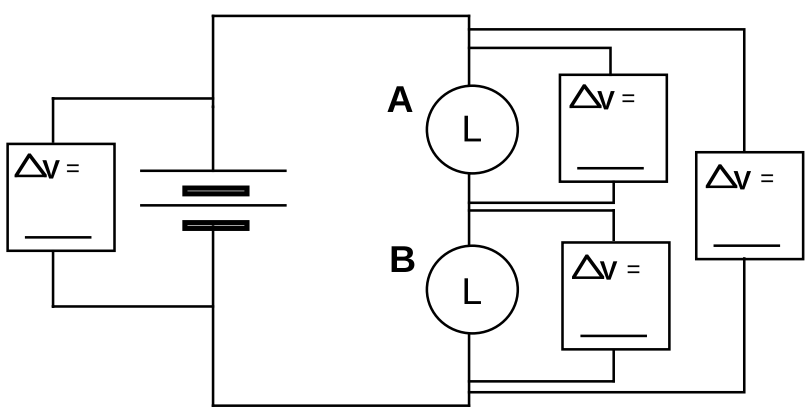


Figure 6.4a
VOLTMETER READINGS

2. **Predict** how many volts of electric pressure difference your red-to-blue color difference corresponds to in this situation where the battery consists of two D-cells connected in series. Explain.

3. Your teacher will provide a voltmeter. Connect the voltmeter to each of the locations indicated in Figure 6.4a, and record the readings provided by this instrument in the corresponding spaces on the figure.

4. What evidence do you observe in these instrument readings that your voltmeter is actually measuring the differences of electric pressure that exist in the circuit between the various pairs of points to which it is connected?

5. Now color code the wires for the circuit diagram in Figure 6.4b, which has two <u>different</u> kinds of bulbs.

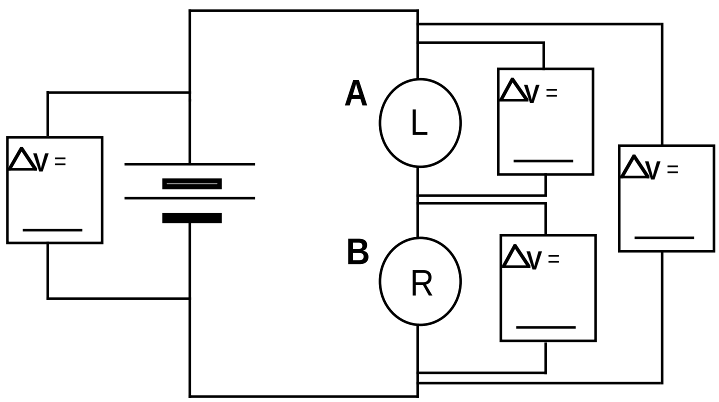


Figure 6.4b
VOLTMETER READINGS WITH TWO DIFFERENT BULBS

6. Set up the circuit in Figure 6.4b. Use your voltmeter to measure the pressure difference at each of the locations shown, and record the readings in the spaces provided on the figure.

7. **Predict**: Considering the voltmeter readings for bulb A and for the battery, what would you predict is the pressure difference across bulb B? Explain your reasoning.

8. Use the voltmeter to test your prediction for bulb B. Does the brightness of bulb B also confirm the prediction? Explain.

9. Construct the circuit shown in Figure 6.4c. Measure the pressure differences across each of the parts of the circuit indicated in the diagram, and record the readings in the spaces provided.

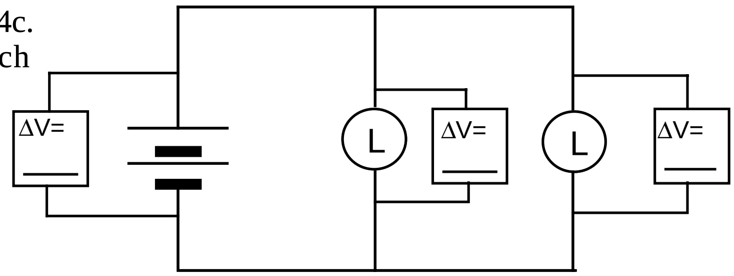


Figure 6.4c
VOLTMETER READINGS IN PARALLEL BRANCHES

10. How do the three pressure differences compare?
How would they compare if the battery and the bulbs were connected in a series circuit?

Activity 6.5: Investigating voltmeter resistance

1. Connect the circuit shown in Figure 6.5a. Describe the observed behavior of both the bulb and the voltmeter

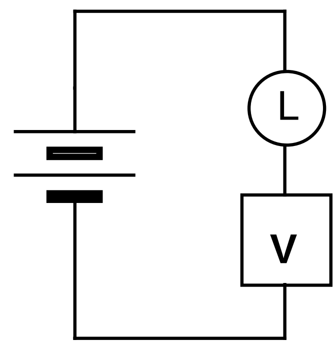


Figure 6.5a
VOLTMETER CONNECTED IN SERIES

2. What do your observations tell you about the resistance of a voltmeter?

3. Speculate why a voltmeter would be designed with that resistance?

4. Why isn't a voltmeter normally connected to a circuit as in Figure 6.5a?

INVESTIGATION TWO: USING A VOLTMETER WITH A CAPACITOR

6.6 Activity: Pressure difference during charging and discharging

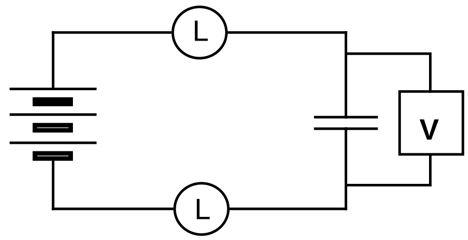


Figure 6.6a
VOLTMETER CONNECTED ACROSS A CAPACITOR

1. Color code the diagram above as a circuit in which the capacitor is fully charged.

2. Set up the circuit; observe the voltmeter while the capacitor is charging. Describe what you observe for the voltmeter reading as the capacitor is charging while the long bulbs are lit.

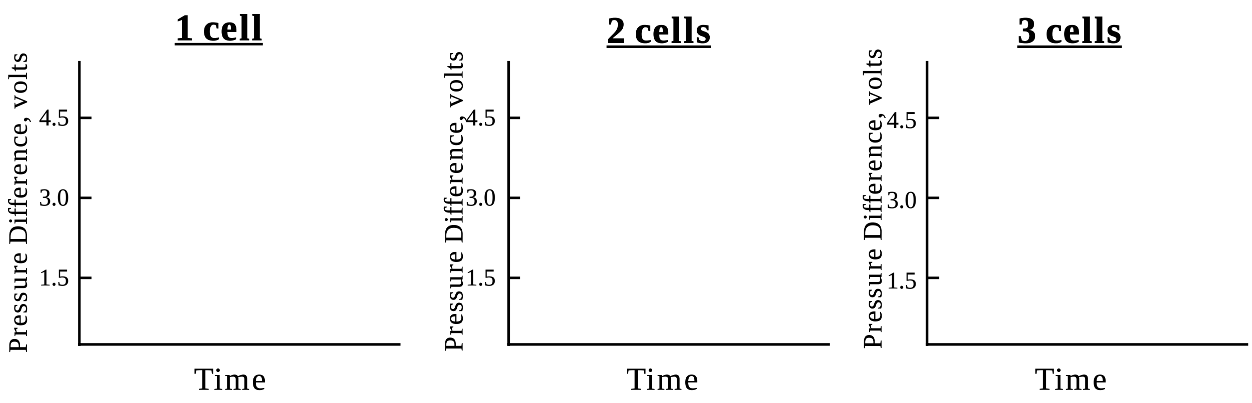
3. What do you think the voltmeter is "sensing", or responding to, in the wires connected to it? What is it sensing in the capacitor plates connected to the wires?

4. Remove the battery from the circuit, but do not connect the free ends of the wires. What happens to the voltmeter reading? What is the voltmeter "sensing" now?

5. Now, reconnect the free ends of the wires and observe the voltmeter reading while the capacitor discharges. What happens to the voltmeter reading during capacitor discharging? Why is this happening?

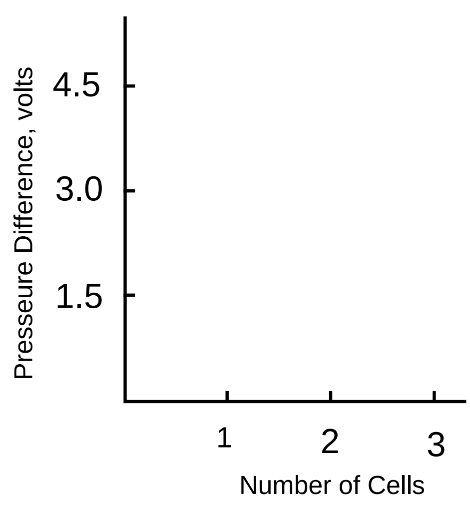
6. Repeat the charging-discharging process a few times, and sketch a graph of pressure difference as a function of time <u>during capacitor charging</u>. Investigate the variations using one cell, two cells and three cells in your battery case. Sketch each approximate graph below.

Approximate Graphs of Pressure Difference vs. Time



7. Draw a bar graph of the maximum pressure difference as a function of the number of cells.

Maximum Pressure Difference vs. Number of Cells



8. According to your observations, what do you think determines the amount of the maximum pressure difference in a circuit?

INVESTIGATION THREE: WHAT DOES AN AMMETER DO?

DO NOT BEGIN THIS INVESTIGATION UNTIL YOUR TEACHER HAS DESCRIBED HOW TO USE AMMETERS WITHOUT DAMAGING THEM.

6.7 Activity: Testing the ammeter in series circuits

1. Using <u>two</u> D-cells in the battery and two long bulbs, connect each of the circuits shown below. Observe the reading of the ammeter in each case. How do the meter readings compare?

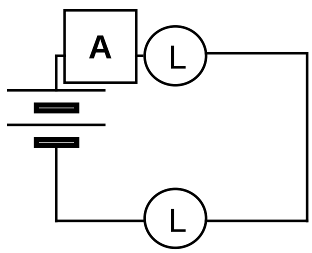


Figure 6.7a

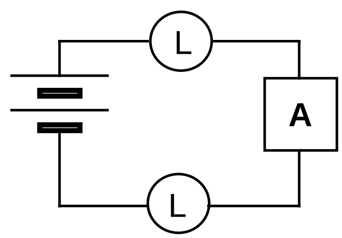


Figure 6.7b

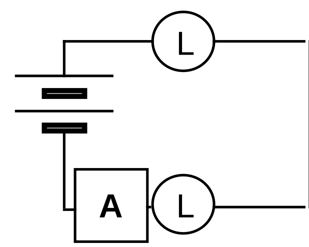


Figure 6.7c

SERIES CIRCUITS WITH AMMETER

Now, replace one of the long bulbs in Figure 6.7c with a round bulb, as in the figures below. Move the ammeter around the circuit as in the previous activity.

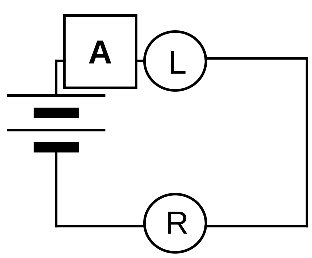


Figure 6.7d

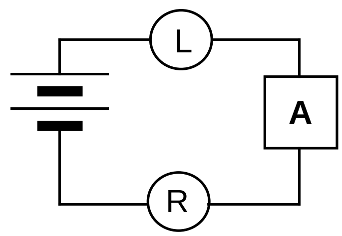


Figure 6.7e

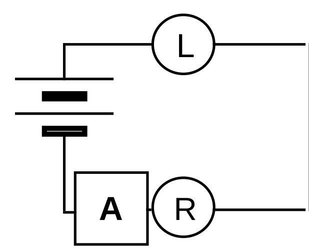


Figure 6.7f

CIRCUITS WITH AMMETER AND TWO TYPES OF BULBS

2. Explain the difference in ammeter readings from the values observed in the previous exercise (Question 1).

6.8 Commentary

The symbol for the quantitative value of flow rate is "**I**" The rate of flow through a circuit component is commonly called the "current" through that component.

The unit for expressing quantitative values of current is the **AMPERE** — often shortened simply to **AMP**. Values of current are measured by an ammeter in amperes (or amps).

6.9 Activity: Testing the ammeter in parallel circuits

Set up the circuit as shown in Figure 6.9a using two cells in the battery case.

1. Insert the ammeter at each of the locations indicated by a current symbol (I) in Figure 6.9a. Record the readings provided by this instrument in the corresponding spaces on the figure — labeled I_1, I_2, I_3, and I_4. (I_1 and I_4 represent the current in the 'trunk' of the circuit, and I_2 and I_3 represent the current in the 'branches'.

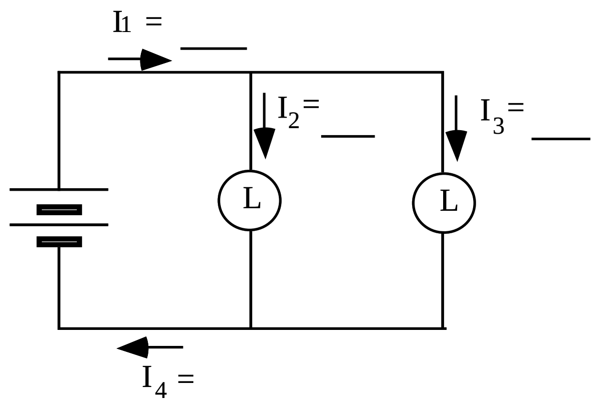


Figure 6.9a
INSERTING AMMETER AT FOUR DIFFERENT LOCATIONS

2. What evidence do you have that the ammeter is accurately measuring the flow rates that exist in all parts of the circuit?

6.10 Activity: Investigating ammeter resistance

1. **Predict**: Suppose you were to "short circuit" the long bulb in Figure 6.10a using a wire as shown in the diagram. That would, in effect, remove the long bulb's resistance from the circuit. How would you expect the ammeter's reading to change?

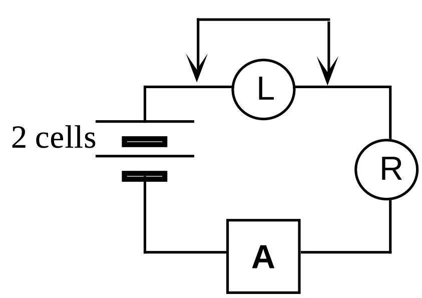


Figure 6.10a
SHORTING OUT ONE BULB

2. Set up the circuit and do the experiment. Was your prediction correct? What did you observe?

3. Now connect the circuit shown in Figure 6.10b. Compare the meter reading change to what you observed in the previous investigation.

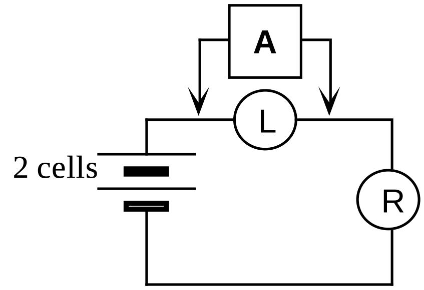


Figure 6.10b

4. Considering the change in bulb brightness for the long and the round bulb, does the ammeter act like a short circuit?

5. What can you conclude about the resistance of the ammeter? Explain.

6. Why would an instrument designer plan to manufacture an ammeter with this resistance?

7. Speculate why it is easy to damage an ammeter.

INVESTIGATION FOUR: HOW DO WE MEASURE RESISTANCE?

Besides light bulb filaments, there are circuit components called “resistors” (usually made of carbon), that hinder charge flow but do not emit light. These can be obtained with just about any resistance value. In this section you will learn how to measure resistance.

6.11 Commentary

The symbol ”**R**“ is used for the quantitative value of the resistance of a circuit component. The unit for expressing resistance values is the **OHM** (symbol Ω). In circuit diagrams, resistors are indicated by the symbol at the right.

Resistor Symbol

Measuring the resistance of a circuit component requires both a voltmeter and an ammeter. The procedure is as follows:

(a) Connect the resistor to a battery.
(b) Use a voltmeter to measure the voltage across the resistor in volts.
(c) Use an ammeter to measure the current through the resistor in amperes.
(d) Calculate the ratio of voltage to current: Voltage / Current = a value.
(e) This value represents the amount of resistance in ohms.

This calculation can be expressed by means of the following important equation:

$$\textbf{Resistance} = \frac{\textbf{Voltage}}{\textbf{Current}} \qquad \text{or in symbols} \qquad \mathbf{R} = \frac{\Delta \mathbf{V}}{\mathbf{I}}$$

This equation says that the ratio of Δ**V** to **I** represents the amount of resistance **R** in a resistor**.** It says that the amount of resistance **R** in a resistor is equivalent to the amount of pressure difference Δ**V** that must be applied across the resistor for flow rate **I** to be pushed through a given resistor. That makes sense, because a large resistance value does require a large pressure difference to drive flow rate through the resistor.

The equation indicates that one ohm is equivalent to one volt per ampere. Note that nothing in the definition prevents the resistance from being variable — for example, the resistance value of a component might turn out to be different if it is in a circuit with high voltage compared to one with low voltage.

6.12 Activity: Measuring resistance

Your teacher will provide two carbon resistors, referred to as **Rx** and **Ry.**.

Set up the circuit shown in Figure 6.12, with R_X as the resistance.

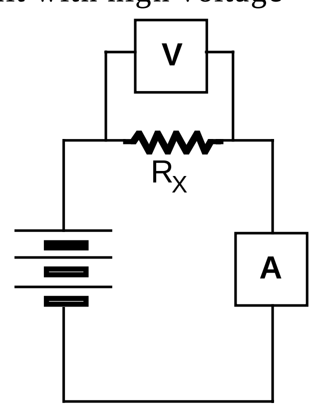


Figure 6.12
CIRCUIT FOR DETERMINING RESISTANCE

1. Using 1 cell, then 2 cells, and then 3 cells, measure the pressure difference Δ**V** across the resistor labeled $\mathbf{R_x}$ and simultaneously the current through $\mathbf{R_x}$. Then replace $\mathbf{R_x}$ with $\mathbf{R_y}$, and repeat the measurements. Record the data in the table below. Then calculate the resistance in ohms for each resistor at each voltage value. Be sure to record the meter readings accurately.

TABLE 6.12

	$\mathbf{R_x}$			$\mathbf{R_y}$		
Cells	**Pressure Difference (volts)**	**Flow Rate (amps)**	**Volts / Amps (ohms)**	**Pressure Difference**	**Flow Rate (amps)**	**Volts / Amps (ohms)**
1						
2						
3						

2. Compare the values you found for $\mathbf{R_x}$ when using three different driving voltages. Are the values approximately the same?

What about the values for $\mathbf{R_y}$?

Important:

If a resistor has the same value of resistance when measured at different voltages, we say that the resistor obeys Ohm's law.

3. Does the resistor labeled $\mathbf{R_x}$ obey Ohm's law? Does the one labeled $\mathbf{R_y}$?

6.13 Activity: Resistance of a long bulb

1. Design a circuit to determine the resistance of a long bulb. Sketch your circuit below and have your teacher check it.

2. After your circuit has been approved, make the necessary measurements. Determine the resistance of a long bulb at different voltages. Record your data and calculations below.

The resistance of a long bulb is _________ ohms at _________volts.

The resistance of a long bulb is _________ ohms at _________volts.

The resistance of a long bulb is _________ ohms at _________volts.

3. Does a long bulb obey Ohm's Law? (Suggestion: To answer this question, plot a graph of pressure difference vs. flow rate at different voltages.)

6.14 Commentary: The "equivalent resistance" idea

Suppose you have some boxes, with terminals connected to combinations of bulbs inside the boxes. Each box will behave like a resistor, and the resistance of the box is called the "equivalent resistance" of the bulbs contained in it.

In Figures 6.14a and 6.14b, the shaded areas labeled A and B represent two such boxes. The equivalent resistances of the boxes can be compared by connecting them to the same battery and measuring the flow rates that the battery voltage drives through them.

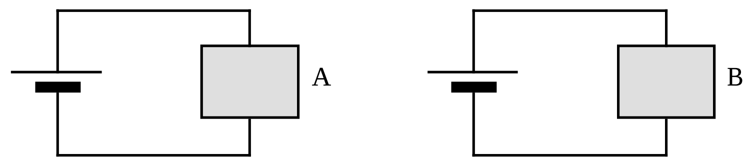


Figure 6.14a **Figure 6.14b**
CIRCUITS WITH EQUIVALENT RESISTANCES

6.15 Activity: Equivalent resistance for parallel and series resistors

In Figures 6.15a and 6.15b, the shaded areas indicate that we will be comparing the equivalent resistance of two long bulbs in parallel with the equivalent resistance of a single round bulb. Do not set up these circuits until you have answered questions 1 and 2.

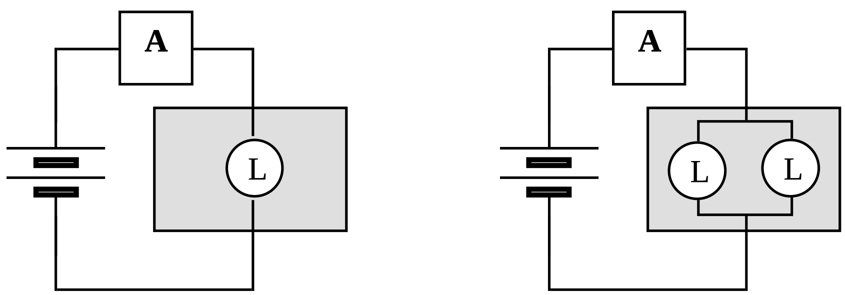


Figure 6.15a **Figure 6.15b**
COMPARING EQUIVALENT RESISTANCES

1. Explain how observing the ammeter readings will enable you to decide if the equivalent resistance of two bulbs in parallel is greater than, less than, or equal to the resistance of a single bulb.

2 What does your intuition tell you about the equivalent resistance of two bulbs in parallel compared to the resistance of a single bulb?

3. Now, connect your battery as in Figure 6.15a and then as in Figure 6.15b. How does the equivalent resistance of the two parallel bulbs in circuit 6.15b compare to the resistance of the single bulb in circuit 6.15a? What is the evidence?

Remove the pair of bulbs and reconnect them in series, as in Figure 6.15c. Then connect your battery as in Figure 6.15a and then as in Figure 6.15c.

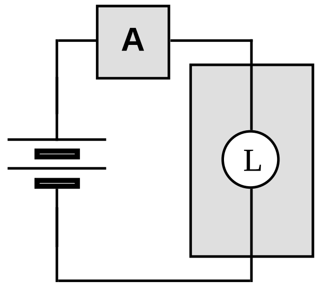


Figure 6.15a

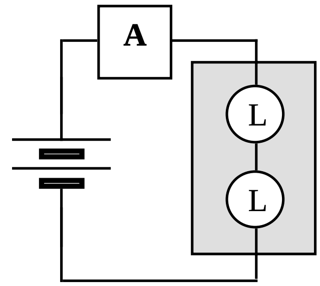


Figure 6.15c

COMPARING EQUIVALENT RESISTANCES

4. How does the equivalent resistance of the two series bulbs in circuit 6.15c compare to the resistance of the single bulb in circuit 6.15a? What is the evidence?

5. Color-code the circuits in Figures 6.15a, 6.15b and 6.15c below, and use the colors to explain the ammeter readings observed in 6.15b and 6.15c, compared to 6.15a.

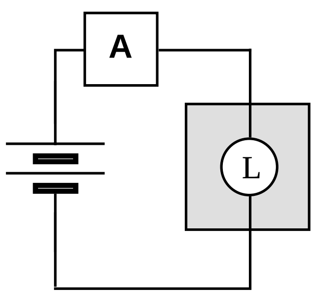


Figure 6.15a

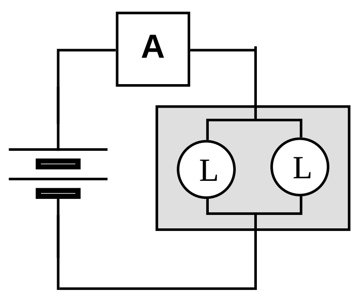


Figure 6.15b

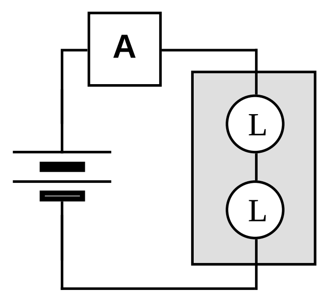


Figure 6.15c

6.16 Activity: Influence of internal resistance on battery voltage

Set up the circuit in Figure 6.16. Use a compass to check the flow direction in each wire, and draw arrows to show the flow direction through each battery and bulb.

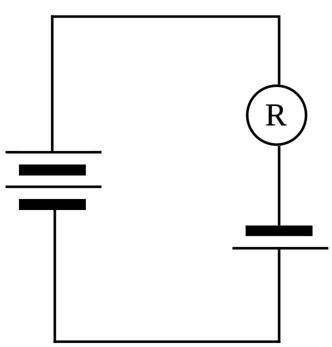


Figure 6.16

You will use a voltmeter to measure ΔV across the single cell and then across the 2-cell battery:

(a) before you connect the circuit, and

(b) after you connect the circuit.

1. Before connecting the circuit, the magnitude of ΔV is a result only of the chemical activity within the battery, symbolized by $\mathcal{E}$. What is the value of the chemical activity strength $\mathcal{E}$

(a) for the 2-cell battery?

(b) for the 1-cell battery?

2. Once the circuit is closed and current begins to flow, the pressure difference across the battery terminals changes. Compare the measured values of ΔV in a closed circuit with the value of $\mathcal{E}$

(a) for the 2-cell battery?

(b) for the 1-cell battery

3. How do your voltage measurements correlate with flow directions through the two batteries?

6.16 Activity: What are the variables that determine energy transfer?

Set up the circuit in Figure 6.16a, and then the circuit in Figure 6.16b. The bulbs in these circuits are getting energy from a battery. The evidence is that they give out energy as light when the battery is connected to them.

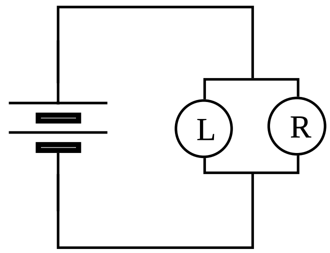


Figure 6.16a

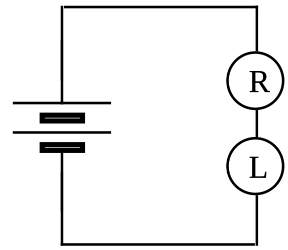


Figure 6.16b

1. Which bulb in circuit 6.16a is getting energy from the battery at a greater rate? What is the evidence?

2. One of the bulbs in 6.16a is getting more energy per second than the other. Is this because there is more current through the bulb? Is it because there is more voltage/pressure difference across the bulb?

3. Which bulb in circuit 6.16b is getting energy from the battery at a greater rate? What is the evidence?

4. One of the bulbs in 6.16b is getting more energy per second than the other. Is this because there is more current through the bulb? Is it because there is more voltage/pressure difference across the bulb?

6.17 Commentary: What is "power"? What is a "watt"?

Activity 6.16 above shows that the rate of energy transfer to a bulb is determined by two variables:

(1) CURRENT -- the flow rate of charge passing through the bulb

(2) VOLTAGE -- the pressure difference that drives the flow rate

We would like to find out how these variables combine to determine the rate of transfer of energy when both of them are varying. We will use the professional term POWER for rate of transfer of energy.

"POWER" MEANS AMOUNT OF ENERGY TRANSFERRED PER SECOND.

Energy transferred to a bulb comes from a battery or some other energy source. When we need to distinguish between transfer to one part of a circuit and from some other part, we will use the terms POWER INPUT and POWER OUTPUT.
The unit of power is the WATT. The magnitude of the watt is defined as follows:

When a 1 volt pressure difference drives a 1 ampere flow rate through a bulb, the rate of transfer of energy to that bulb is defined to be 1 WATT of power.

Figure 6.17 shows a "unit" cell connected to a "unit" bulb. Chemical activity in this imaginary cell maintains a 1 volt pressure difference in its terminals, and the resistance of this special bulb allows the cell to drive a 1 ampere flow rate through it. The symbol P is used for amount of power input. Therefore, P = 1 watt for a unit bulb lit by a unit cell, illustrated in Figure 6.17.

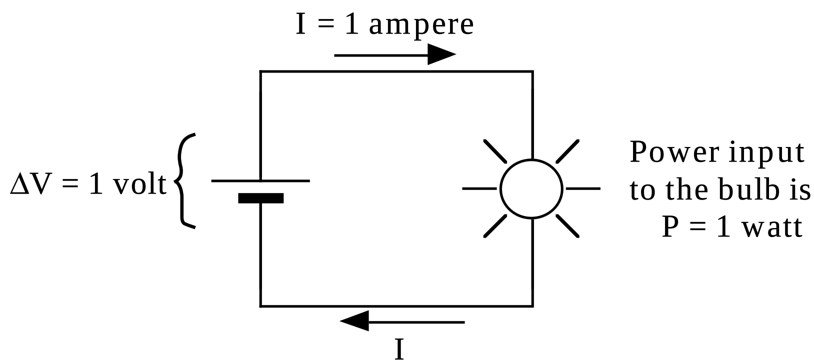


Figure 6.17
DEFINING ONE WATT OF POWER INPUT TO A BULB

"Unit" cells and bulbs cannot be bought in stores, but they make circuit diagrams especially easy to analyze. This can will help us find out how current and voltage combine to determine power input to resistors.

6.18 Activity: How do current and voltage jointly determine power transfer?

We can use the definition of the watt provided in Figure 6.17 to determine the power input to a box that contains any combination of "unit" bulbs. Figures 6.18a and 6.18b show how "unit" cells in series can provide 1 volt across each bulb in a variety of different combinations that let different battery voltages drive different currents through different boxes.

Two shaded boxes with different combinations of "unit" bulbs are shown in Figures 6.18a and 6.18b. Here's how to determine magnitudes of the variables:

POWER input to a box	- is equal to -	number of "unit" bulbs in box
CURRENT through the box	- is equal to -	number of parallel paths in box
VOLTAGE that drives current	- is equal to -	number of "unit" cells in battery

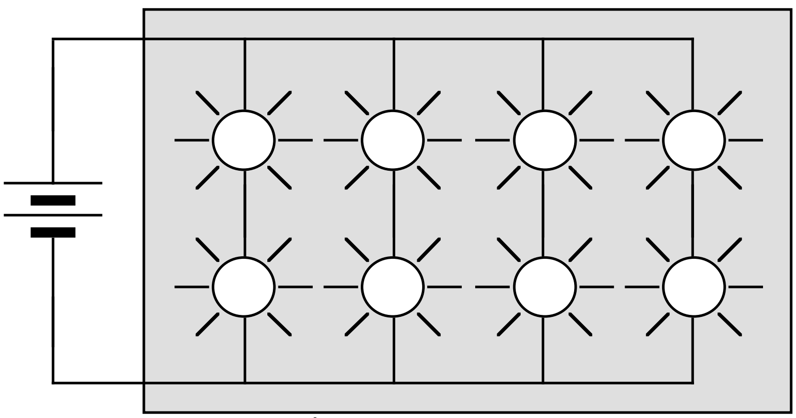


Figure 6.18a
BOX WITH 8 UNIT BULBS

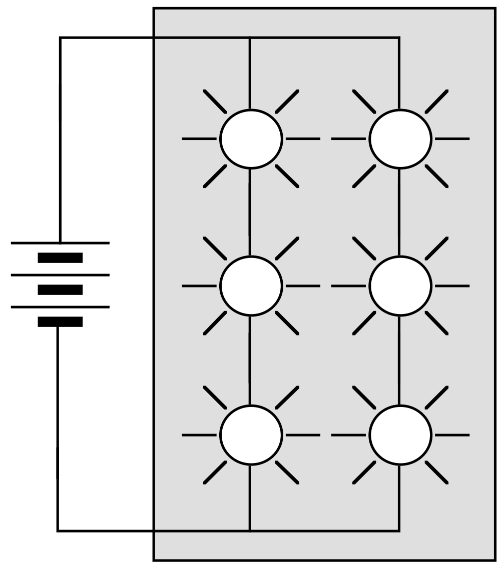


Figure 6.18b
BOX WITH 6 UNIT BULBS

Imagine an arrowtail with one shaft drawn next to each bulb in Figures 6.18a and 6.18b, representing a 1 ampere flow rate through each bulb.

1. On Figures 6.18a and 6.18b, draw arrowtails to represent current into and out of the shaded boxes. Draw one shaft in the arrowtail for each ampere.

2. Near each shaded box in Figures 6.18a and 6.18b, write

P = <u>?</u> (a number for watts of power input to the box.)

Near each arrowtail, write

I = <u>?</u> (a number for amperes of flow rate into and out of the box.)

Near each battery, write

ΔV = <u>?</u> (a number for volts of pressure difference across the box.)

3. Look at the numbers you placed on Figures 6.18a and 6.18b. Write an equation that describes the <u>pattern of relationship</u> between P, I, and ΔV.

6.19 Activity: Power Input vs. Power Output

The power transfer relationship **P = I • ΔV** is valid for input to identical bulbs lit to identical brightness. But does it apply to all bulb combinations? And does it apply to output from batteries as well as input to light bulbs?

Figure 6.19 shows a circuit with two unlike bulbs.

1. Use meters to make appropriate measurements and calculations in order to complete Table 6.19 below.

2. Does the Power Output equal the total Power Input in this circuit? Comment.

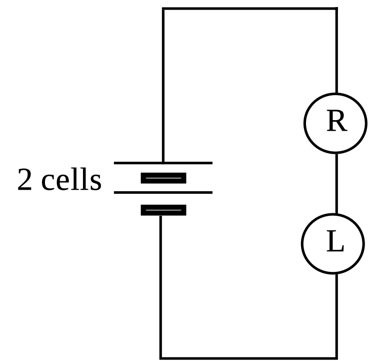


Figure 6.19

TABLE 6.19

Circuit Components	**ΔV**	**I**	**Power Output from Battery**	**Power Input to Each Bulb**
Battery				X
Round Bulb			X	
Long Bulb			X	
		TOTALS		

6.20 Activity: Circuit with more than one battery

Figures 6.20b and 6.20c have an extra single cell that is not present in Figure 6.20a. The single cell in 6.20c is a "dueling" battery, with orientation reversed from 6.20b.

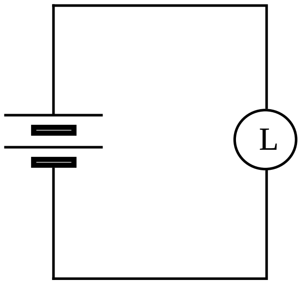


Figure 6.20a

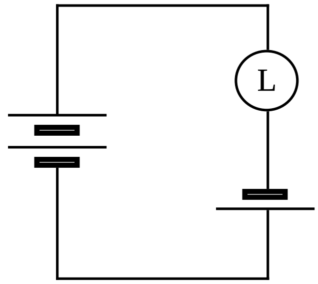


Figure 6.20b

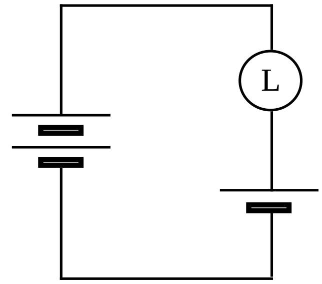


Figure 6.20c

1. Are both batteries giving energy to the bulb in 6.20b? What is the evidence?

2. Are both batteries giving energy to the bulb in 6.20c? What is the evidence?

3. Could the single cell in 6.20c be getting energy from the stronger 2-cell battery? Explain your reasoning.

Using meters, make appropriate measurements from the circuit in Figure 6.20b only and complete Table 6.20.

Table 6.20

Circuit Components	ΔV	I	Power Giving	Power Receiving
2 Cell Battery				X
Single Cell				?
Bulb			X	
		TOTALS		

4. Does the power output in this circuit equal the power input? Explain.

5. Is the circuit in Figure 6.20b “re-energizing” the single cell? Explain.

6.21 Activity: Energy storage in capacitors

You may be able to answer the following questions from previous experience. If not, try doing the experiments first.

1. When a capacitor is being charged through light bulbs, is some of the energy stored in the battery being transferred to the capacitor as well as to the bulbs? What is the evidence?

2. Compare this situation to pushing a plunger into an air syringe and then letting the plunger go.

3. Compare the amount of energy stored in a silver capacitor with the amount stored in a blue capacitor that has been charged with the same battery. What is the evidence?

SUMMARY EXERCISE

1. Explain what electrical quantity each of the two meters measures, and what units are used for the measurement.

Ammeter:

Voltmeter:

2. In terms of experimental measurements, how is resistance defined? What units are used for measuring resistance?

3. A good measuring instrument should have as little interference as possible on the system being measured. For both an ammeter and a voltmeter, describe:

a) whether the resistance of an ammeter and a voltmeter is high or low, and why:

Ammeter:

Voltmeter:

b) how the meter should be connected in a circuit in relation to the circuit elements:

Ammeter:

Voltmeter:

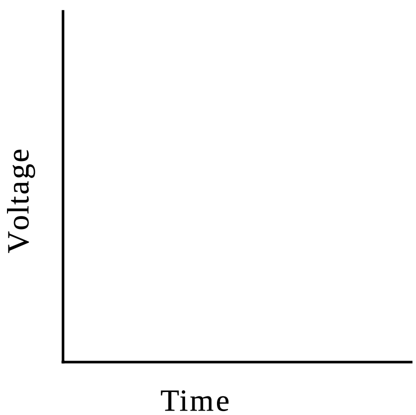
c) why each meter needs to have its particular resistance to be a good measuring device:

Ammeter:

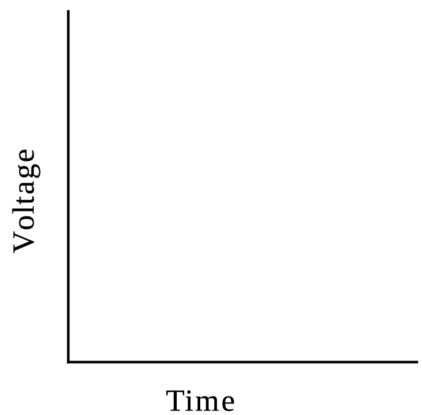
Voltmeter:

4. Describe how the resistance of the X and Y resistors was affected by the different voltages you used. Describe how the resistance of the long bulb was affected by the different voltages you used. Compare the behavior of the two kinds of devices. Does each type of device obey Ohm's law?

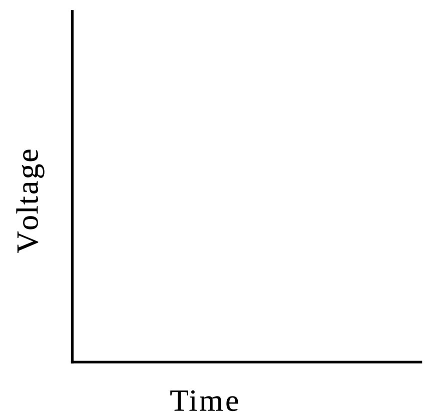
5. For a circuit containing a battery, two bulbs and a capacitor in series, sketch graphs describing how the voltage across each element and the current through each element will behave during the charging of the capacitor.



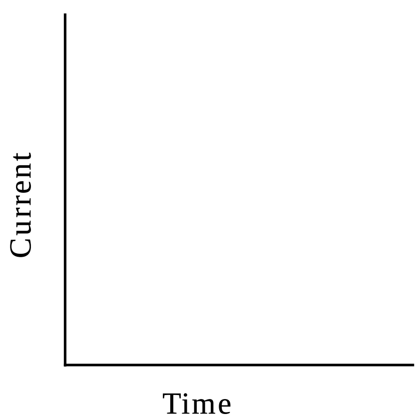
Capacitor



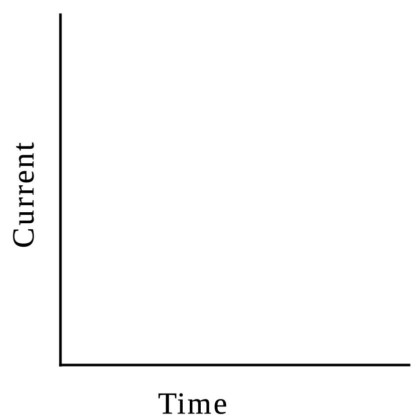
Battery



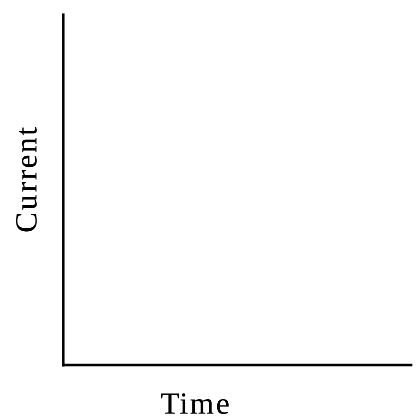
Light Bulbs



Capacitor



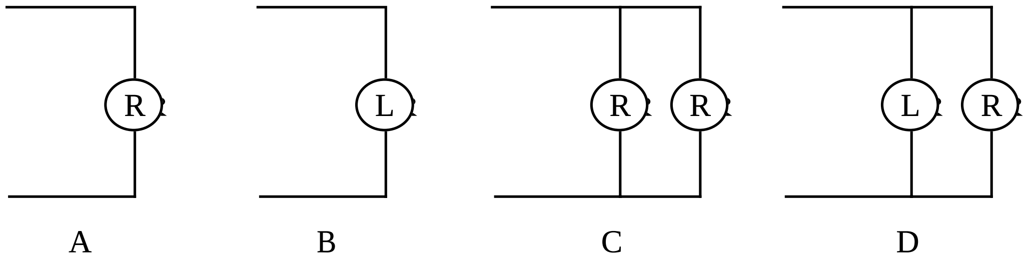
Battery



Light Bulbs

6. Consider the equivalent resistance of each of the following four combinations of bulbs. List each in order from the least resistance to the greatest resistance.

Then devise a method and build circuits to check your answers.



7. Power is the rate of energy transfer, so which household bulb would be brighter: a 100-watt or a 60-watt bulb? Explain.

8. Which bulb (a 100-watt or a 60-watt) has the largest resistance? Use the relationship $P = \Delta V \cdot I$ in your explanation.

9. Compare a rechargeable battery and a capacitor:

a) In what ways are they similar?

b) In what ways are they different?

Section 7

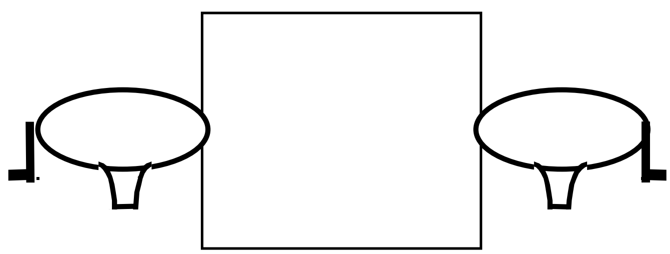
WHAT IS THE RELATIONSHIP BETWEEN MOTORS AND GENERATORS?

INTRODUCTION

To the best of your ability, define the following two terms:

(1) Generator:

(2) Motor:



Genecon A **Genecon B**

TWO GENECONS IN ONE CIRCUIT

Connect the wires from two Genecons to each other. Hold the Genecons up by their handles or by their bodies (not by their cranks). Allow the cranks room to rotate.

Turn the crank on Genecon A and observe how Genecon B responds. Then turn the crank on B and observe how A responds. **CAUTION: Do not try to turn both cranks at the same time!**

One of the Genecons is acting as a motor and the other is acting as a generator. Try to improve the definitions you gave above, based on your observations of this circuit.

INVESTIGATION ONE: WHAT IS THE MOTOR EFFECT?

7.1 Activity: Observing the motor effect

Place a single Genecon in a circuit with a single D-cell and two wires, as in Figure 7.1a. Place a compass under the wire connected to the (+) terminal of the battery. Hold the Genecon by the handle or by the body (but not by the crank) Add a second D-cell and then a third D-cell – as in Figures 7.1b and 7.1c. Always keep the compass under the wire.

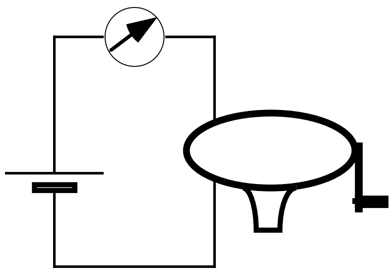


Figure 7.1a
1 CELL AND A GENECON

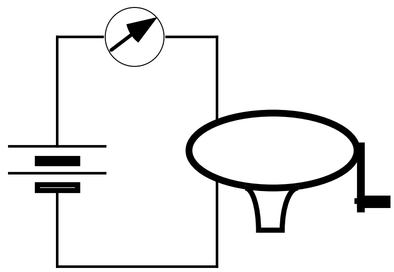


Figure 7.1b
2 CELLS AND A GENECON

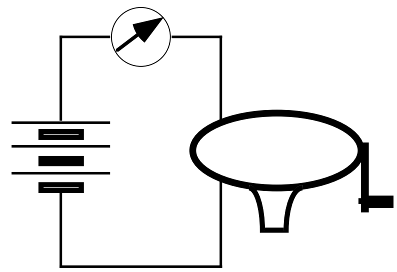


Figure 7.1c
3 CELLS AND A GENECON

1. How is the flow rate in the circuit affected by adding cells? How do you know?

2. How is the speed of rotation of the Genecon crank affected by the flow rate?

7.2 Activity: The force on charge near a magnet

In earlier sections we observed the deflection of a compass needle near a current-carrying wire. Since the compass needle is a small magnet, this shows that charge moving in a wire exerts a force on a nearby magnet.

The reverse is also true: A magnet exerts a force on nearby moving charge. This force is what makes the coiled wires in a Genecon rotate when you use a battery to make charge move through the wires. We can observe this force acting on charge moving in a wire by suspending a current-carrying wire over a magnet.

Use a flexible insulated wire about 1.5 meters long. Place the magnet on a flat surface, and suspend the wire so that the middle is hanging just above the magnet as shown in Figure 7.2.

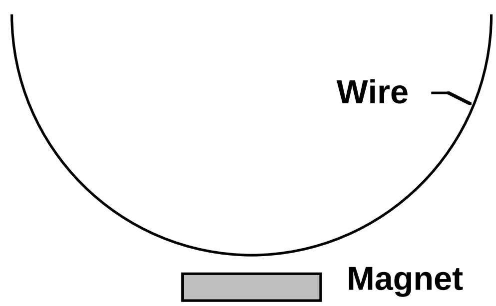


Figure 7.2
WIRE SUSPENDED OVER A MAGNET

1. Using a 3-cell battery, tap the connection to complete the circuit. What do you observe?

2. How is this like a motor? How is it different from a motor?

INVESTIGATION TWO: WHAT IS THE GENERATOR EFFECT?

7.3 Activity: Observing the generator effect

Connect the terminals of a single Genecon to a long bulb in a socket, as shown in Figures 7.3a and 7.3b. Place a compass under one of the wires. **DO NOT BURN OUT THE BULB!**

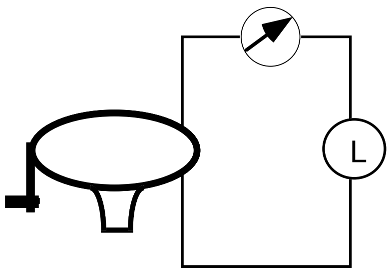


Figure 7.3a
SLOW CRANKING

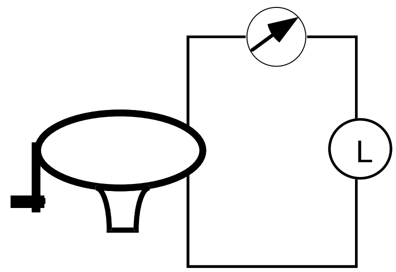


Figure 7.3b
FAST CRANKING

1. State in words what you observe when you turn the crank at different rates?

2. State in words how turning the crank must affect pressures in the Genecon terminals.

3. Draw starbursts and arrowtails on Figures 7.3a and 7.3b to show what you observed. Color code the wires to show the pressures that make this happen.

7.4 Activity: A simple generator

It is quite simple to generate charge flow in a circuit without batteries, a capacitor or even a Genecon. You will need –

1) a coil of wire with the ends attached to a galvanometer to detect charge flow

2) a magnet (bar magnet or flat cylinder magnet or horseshoe magnet)

1. Try as many ways as possible to move the magnet and the coil relative to each other to produce charge flow. Describe the orientation and motions that generate the greatest flow rate.

2. Instead of a coil of wire, try swinging a single wire back and forth near a strong magnet (just the opposite of Activity 7.2). Are you able to detect charge flow with a galvanometer attached to the ends of the wire? What is the advantage of using a coil?

INVESTIGATION THREE: HOW CAN A GENECON BE BOTH A MOTOR AND A GENERATOR?

7.5 Activity: The Genecon's interior

How is it that the same device can be both a motor and a generator? Lets find out what's inside a Genecon that gives it this 'dual personality'.

1. Bring a compass near a Genecon and move it all around the exterior. What do you observe?

2. What does this indicate about the interior of the Genecon?

It would be helpful to open up the metal cylinder inside the plastic casing of the Genecon and find out how it works – but that would destroy it. Rather than ruin a working Genecon, we will use a cheap surplus motor unit that is nearly identical to the metal cylinder inside the Genecon.

3. Bring a compass near the metal cylinder you obtain from the teacher. As you move the compass all around the exterior, what do you observe?

As you open the metal cylinder, notice that there are 1) two internal magnets, and 2) a set of wire coils attached to a shaft which allows the coils to rotate in the space between the two magnets. The magnets in the motor are curved to fit inside the cylinder.

Use a compass to identify which face of each magnet from inside the cylinder is the north pole. The north pole will attract the end of a compass needle that normally points geographically southward. The south pole will attract the end of the needle that normally points geographically northward. (This pole is often painted.) Mark the north pole surface of each magnet with tape, marker, or paint. Move the compass around near a Genecon, to verify that there really is a north pole on one side of the metal cylinder inside it and a south pole on the opposite side.

4. Hold each of the two curved magnets near each other.

   a. Try placing the two north poles together. What do you observe?

   b. Place the two south poles together. What do you observe?

   c. Place a north and a south together. What do you observe?

7.6 Commentary: A common cause of motor and generator behavior?

A battery connected to a Genecon drives charge through the wires that are attached to an interior shaft. There appears to be a sideways push on the moving charge that makes the wires containing the charge rotate – which makes the shaft they are attached to rotate with the wires. This rotation of a shaft is called the “motor effect”. A motor is a device which converts electrical energy into mechanical energy. It converts the energy of charges moving through an electrical pressure difference into the mechanical energy of the turning crank. The motors inside fans, blenders and electric shavers all require a source of electrical energy and they produce motion.

When you turn the Genecon crank, the wires attached to it must move with it. The wires are always full of charge, and this charge moves with the wires. There appears to be a sideways push on the moving charge that drives charge flow through the wires. The flow moves charge out of one Genecon terminal and into the other, producing HIGH electric pressure in one terminal and LOW electric pressure in the other terminal. This creation of an electrical pressure difference is called the “generator effect”. A generator is a device which converts mechanical energy into electrical energy. It converts the energy of turning the crank into the energy which pushes charges around the circuit.

A motor and a generator are exact opposites of each other! The Genecon can behave as either a motor or a generator, depending on what is the cause and what is the effect.

	Cause	**Effect**
MOTOR:	Charges moving through a wire near a magnet, while a battery is attached	Sideways force on charges makes wire move; motor turns
GENERATOR:	Wire moving near a magnet, while the crank is being turned	Sideways force makes charges move through wire

INVESTIGATION FOUR: WHAT IS A MAGNETIC FIELD?

7.7 Activity: Searching for a pattern in the space near a magnet

With this page flat on your lab table, place a bar magnet over Figure 7.7. Place a compass near the magnet, and move the compass around. Notice how the compass needle points in different directions at different places near the magnet.

1. Describe in words the directions the compass points –

a) near the magnet's south pole.

b) near the magnet's north pole.

c) at places that are equal distances from the poles.

Figure 7.7
BAR MAGNET

2. Draw a set of short arrows at various places around the bar magnet diagram (Figure 7.7), which show the direction the north end of the compass points in the area surrounding the compass. Draw a large enough number of arrows to show the pattern of arrows in the space near the magnet. Check with your partner, to see if both of you are seeing the same pattern of arrows.

3. Place a sheet of paper (or an acetate transparency) over a bar magnet; sprinkle iron filings on the paper, and tap the paper gently until a pattern of filings is formed. These filings are slivers of iron that behave much like tiny compass needles. Because there are so many of them, they show you the pattern of arrows in much greater detail.   Describe that pattern and compare it to the pattern you observed in question 2.

7.8 Commentary: Magnetic vectors and magnetic field

The pattern of arrows that you have observed shows there is a pattern of something in space surrounding a magnet, and that this "something" has a direction at every point in that space. This pattern of directions represents **magnetic vectors**, whose directions are shown by your compass. A pattern of magnetic vectors over the whole space surrounding a magnet represents the MAGNETIC FIELD of the magnet.

In the model we are building, a magnetic field is the invisible "something" by which a magnet acts on other objects in the surrounding space. The magnet does not need to actually touch the objects it acts on – its magnetic field is doing the touching on its behalf. In a Genecon, the magnetic field of a pair of magnets acts on moving charge in wires that are situated in the space between the magnets.

7.9 Activity: The magnetic field inside a Genecon

Flat magnets with poles on their faces are like very short bar magnets. Stand one on edge on a piece of paper, and use a compass to investigate the magnetic field pattern in the space around it. Place the compass on the paper, and notice the direction of the needle. Then lift the compass off the paper and mark a small arrow to represent the direction of the magnetic vector at that point – the direction the north end of the compass needle points. Repeat this procedure at various places around all sides of the magnet.

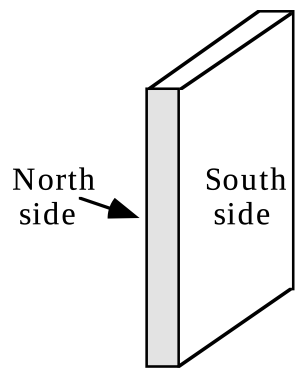


Figure 7.9a
SINGLE FLAT MAGNET

1. Describe in words the pattern of magnetic vectors represented by the arrows.

To investigate the field pattern in the space **between** the pair of magnets in a Genecon, set up the situation showing Figure 7.9b. Place the magnets about two compass diameters apart. Tape may be needed to hold the magnets in place.

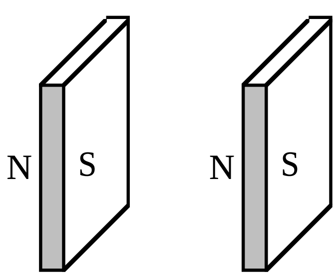


Figure 7.9b
MAGNET PAIR ORIENTED LIKE IN A GENECON

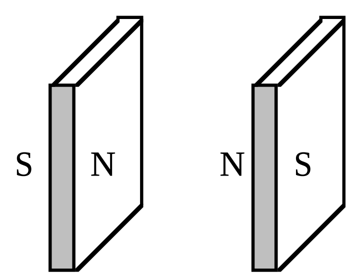


Figure 7.9c
ORIENTATION IF ONE MAGNET IS REVERSED

Place a compass at a variety of places between the magnets, and draw arrows that show directions of magnetic vectors at all those places. Keep drawing more arrows until there are enough to reveal the pattern of magnetic vectors in the magnetic field. Then reverse one magnet so that both north faces (or both south faces) are positioned opposite each other, and again investigate the magnetic vector pattern.

2. Sketch the magnetic vector patterns for both situations on Figures 7.9b and 7.9c.

3. Speculate why the magnets inside the Genecon are configured as in Figure 7.9b – and not as in Figure 7.9c.

Hold one magnet in each hand and push same poles together – and then reverse one magnet and push opposite poles together.

4. Compare what you feel when you do this with the vector patterns in Figures 7.9b and Figure 7.9c. How do these patterns help describe what you feel? Explain.

INVESTIGATION FIVE: COMPARING MOTOR EFFECTS AND GENERATOR EFFECTS

7.10 Activity: The force on charge moving in a magnetic field

In Activity 7.2 you investigated the motion of a current-carrying wire near a magnet. As you closed the circuit so that charges began to move in the wire, you observed the wire move. Set up the same equipment and analyze that motion in more detail.

Place the magnet on a flat surface with the **north face up**, and suspend the wire (approximately 1.5 meters) so that the middle of the wire is hanging just above the magnet as shown in Figure 7.10.

Connect the wire to a battery in order to cause conventional flow – briefly – from left to right through the wire:

1) connect the right end of the wire to the negative battery terminal
2) briefly tap the left end of the wire on the positive battery terminal

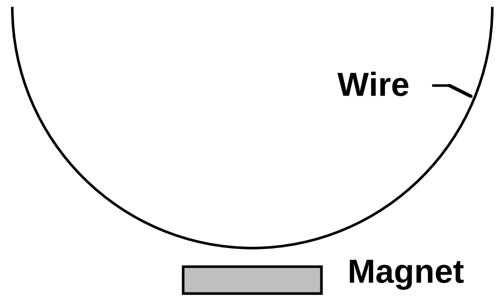


Figure 7.10
WIRE SUSPENDED OVER A MAGNET

Observe whether the wire moves **towards** or **away from** you. Record the observed movement of the wire on the first line of the fourth column of the table below. Leave the fifth column blank until later.

Table 7.10

Current Direction	Magnet	Magnetic Field Direction	Direction Wire Moves (toward or away)	Right Hand Rule Prediction
Left to Right	North Up	Up		
Right to Left	North Up	Up		
Right to Left	South Up	Down		
Left to Right	South Up	Down		

Reverse the direction of the current, and record the observed direction. Reverse the direction of the magnetic vectors by turning the magnet over so the north surface faces down and complete the table.

7.11 Commentary: The Right Hand Rule for Motors

There is a Right Hand Rule that can be used to predict the direction of the force on a current-carrying wire. Study the diagram at right; using the right hand, hold the forefinger straight while bending the other three fingers so that they are perpendicular to the palm, and extend the thumb out away from the palm. Thus the thumb, forefinger, and remaining three fingers will point in directions that are perpendicular to each other.

If the forefinger points in the direction of charge movement in the wire, and the three fingers point in the direction of the magnetic field vector at the place where the charge is located, then the thumb will point to predict the direction of the resulting force that acts on the charge moving in the wire.

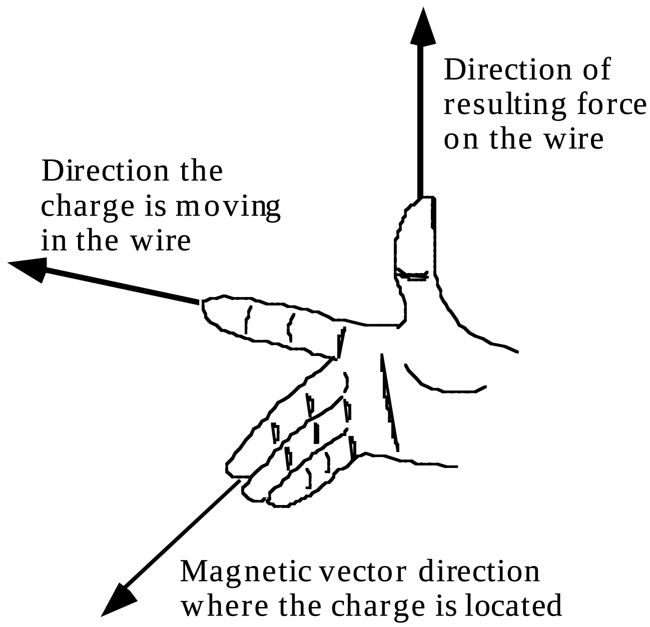


Figure 7.11
RIGHT HAND RULE – MOTORS

The three directions are mutually perpendicular. For example: If the charge is moving from east to west, and the magnetic vector points from north to south, then the force on the charge would be directed straight up.

7.12 Activity: Testing the Right Hand Rule for motors

Test this right hand rule by using it for each of the four cases in the table above (Table 7.10). Record its predictions in the last column of the table. If any of these predictions that are different from what you observed, repeat the observations. If there are still disagreements, check with your teacher.

7.13 Commentary: The Right Hand Rule for Generators

To use the Right Hand Rule for Generators, again hold your hand so that the forefinger, thumb, and remaining three fingers are each perpendicular to each other.

This time, however, the forefinger represents the direction the wire is moving through a magnetic field. The three fingers represent the vector direction of the magnetic field in which the wire and charges are located. The thumb direction will predict the direction of the force pushing on the charges in the wire.

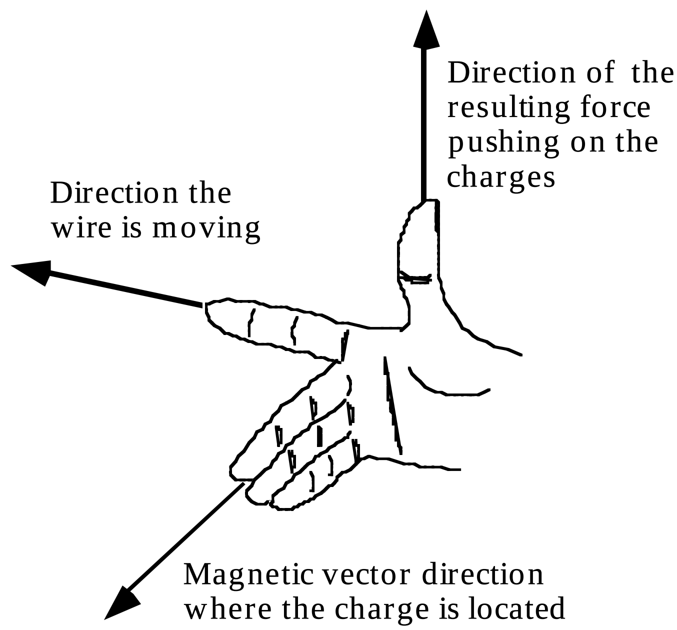


Figure 7.13
RIGHT HAND RULE – GENERATORS

7.14 Exercise: Applying the Right Hand Rule for generators

Study the diagrams below. Use the Right Hand Rule for generators to predict the direction of the generated charge flow based on the magnetic vector direction (north to south pole) and the direction the wire is moving. (The motion of the wire is down in the left diagram, and up in the right diagram.) Determine whether your prediction agrees with the diagrams.

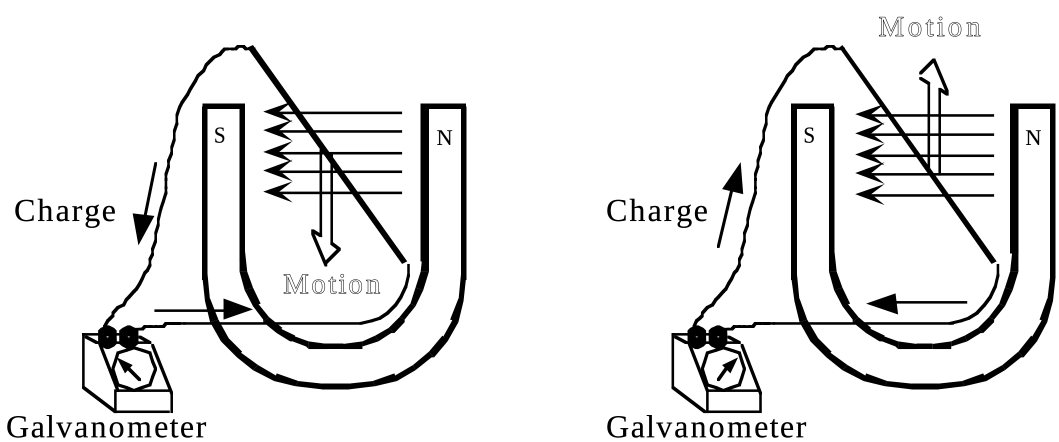
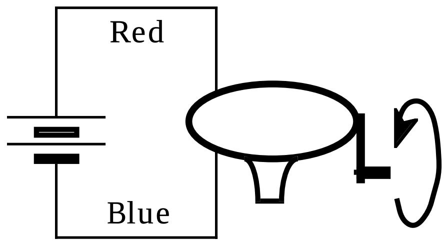


Figure 7.14
APPLYING THE RIGHT HAND RULE FOR GENERATORS

7.15 Commentary: Comparing the motor and generator effects

Motor effect

A Genecon operates as a motor when you make the shaft rotate by applying a pressure difference to the terminals. You have used a battery to apply a pressure difference.



Applying a pressure difference makes the motor shaft rotate.

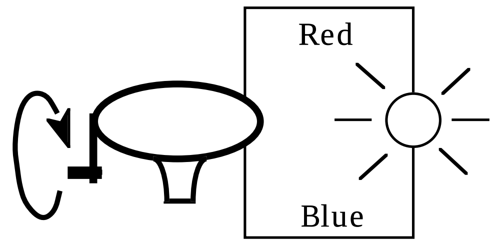
The pressure difference makes charge move <u>along wire segments</u> in coils that are attached to the motor shaft.

Over most of the length of each wire charge moves <u>perpendicular to magnetic vectors</u> in space between two magnets. This maximizes the strength of magnetic pushing on charge moving along the wire segments.

By the Right Hand Rule for Motors, charge that's moving along each wire segment is <u>pushed sideways to the segments</u>. Charge moving in different wire segments is pushed in directions that make the motor shaft rotate.

Generator effect

A Genecon acts as a generator when you create a pressure difference in its terminals by cranking to make the shaft rotate. You have used a bulb to detect the pressure difference.



Rotating the motor shaft creates a pressure difference in the terminals.

A rotating shaft makes charge that's always present in wires move <u>sideways through the wire segments</u>.

Over most of the region of rotation, segment, charge is being moved <u>perpendicular to magnetic vectors</u> in space between two magnets. This maximizes the strength of magnetic pushing on charge carried sideways to the wire segments.

By the Right Hand Rule for Generators, charge carried sideways by rotating wire segments is <u>pushed along the segments</u>. Charge is driven out of one terminal (at HIGH pressure), through series segments, to the other terminal (at LOW pressure).

How the magnets are involved

Magnets inside the Genecon motor cause both the motor effect and the generator effect by pushing charge in direction that is (a) <u>sideways to its direction of motion</u> and (b) <u>sideways to the magnetic vector</u> at the location of the moving charge. The right hand rule predicts the direction of the push in both cases.

Where the moving charge originates

If the wires were empty pipes, then coils of wire rotating in a Genecon that you are cranking would not carry any charge with them. There would then be no moving charge for the magnets to push sideways on. So there would be <u>no generator effect</u>. But we have seen that the generator effect really does exist. This is evidence that <u>mobile charge is always present in wires</u>.

SUMMARY	CAUSE	EFFECT
Motor	**Charge moving through wire in a magnetic field**	**Force on wire results in motion**
Generator	**Wire moving through a magnetic field**	**Force on charges results in current through wire**

7.16 Activity: A Genecon and a capacitor

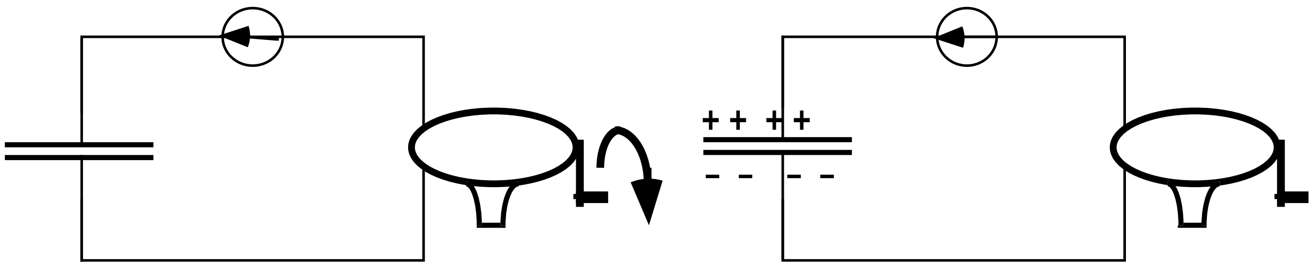


Figure 7.16
CHARGING AND DISCHARGING A CAPACITOR WITH A GENECON

1. You will 1) **charge** a capacitor, and then 2) **discharge** the capacitor through the Genecon.

Predict both of the following:

a) Predict the direction of the crank motion in both cases (same or opposite):

b) Predict the compass deflection in both cases (same or opposite):

2. Connect the two Genecon wires to a capacitor, one to each terminal. Place a compass under one of these wires, attach each of the wires to one of the leads from the Genecon, and use the Genecon to charge the capacitor. When the capacitor is fully charged, release the crank of the Genecon and note the direction the crank turns while the capacitor is discharging, Also note the direction of the compass deflection. What do you observe?

3. Use the idea of a <u>motor effect</u> also being present during the charging phase to explain what you observe.

INVESTIGATION SIX: DO GENERATORS TRIGGER THE MOTOR EFFECT? DO MOTORS TRIGGER THE GENERATOR EFFECT?

7.17 Activity: Looking for simultaneous effects

1. In this activity you will attach the Genecon to decreasing resistance in circuits. Predict whether it will FEEL easier or harder to turn the crank.

Prediction:

Connect a Genecon to a long bulb, and turn the crank until the bulb lights. Note the rate of rotation as the number of turns per some unit of time.

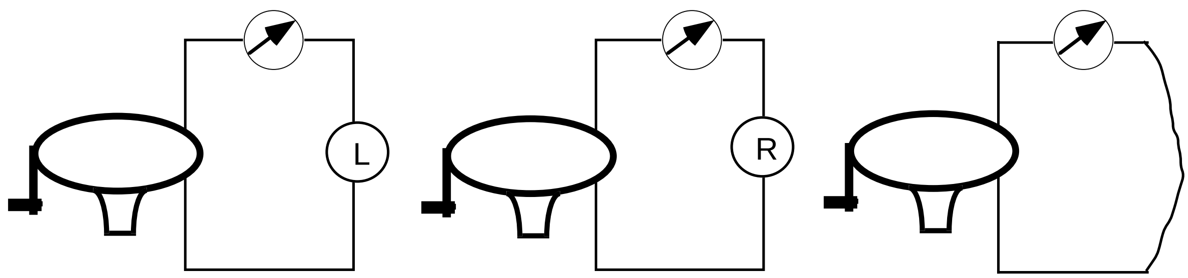


Figure 7.17
GENECON ATTACHED TO DECREASING RESISTANCE IN CIRCUITS

Replace the long bulb with a round bulb. Try to maintain the same rate of rotation as with the long bulb.

Replace the round bulb with a wire. Try to maintain the same rate of rotation as with the round bulb.

2. What did you observe about the difficulty of turning the crank? Does this make sense?

3. Charge flow driven through the wires in a Genecon by a battery causes a motor effect. Try to explain what you observe using the idea that flow driven through the same wires by the generator effect will also produce a motor effect.

7.18 Commentary: Why the motor and generator effects occur together

When you crank a Genecon, it produces a generator effect, which causes charge to move through the circuit – including movement through the Genecon itself. The charge moving through the Genecon produces a motor effect force, which <u>opposes the cranking</u>. The motor-effect force that opposes rotation in the Genecon is what makes the crank harder to turn.

Conversely, when the Genecon is cranked but disconnected there is no charge flowing. This can produce no motor effect so the crank is the easiest to turn.

A pressure difference applied to the Genecon terminals by a battery will make the motor shaft rotate (motor effect). But the rotating shaft will <u>also</u> affect the pressure difference in the Genecon terminals (generator effect). This suggests that the motor effect and the generator effect <u>always appear together</u>. It is not possible to have one without the other.

7.19 Commentary: Don't burn out your electric mixer

This shows an effect similar to that observed with "dueling" batteries in Section 4. The battery causes rotation of the wires in the Genecon by driving charge flow through these wires – the motor effect. But rotation of the wires in a magnetic field produces pushing that tries to drive charge through the wires in the reverse direction – the generator effect. The generator effect is <u>opposing the motor effect</u> caused by the battery.

The electric mixer in your kitchen is like a Genecon operating as a motor. When it is used to make whipped cream, the cream gets stiffer and makes the motor rotate slower. This reduces opposition to charge flow by the generator effect. Remember when your hand hindered rotation of the Genecon crank – reducing opposition by the generator effect and allowing a greater flow rate – making the bulb brighter?

The same thing is happening in the electric mixer. When anything makes it turn more slowly, opposition by the generator effect will be reduced and there will be a greater flow rate of charge moving through the wires in the mixer. This will heat up the wires in the mixer – which you might be able to smell because the heated insulation is throwing off fumes – and it could burn out the wires if the rate of rotation gets slowed way down.

The motor will give you two signals that you need to watch the cream whipping process more carefully. First, you will hear a different sound. The motor will "growl", as the greater flow rate pushes harder to turn the motor shaft (stronger motor effect). That is not necessarily cause for alarm. But if there is overheating, you will smell insulator fumes and should turn the mixer off until it cools down.

The same thing happens with electric drills. You can hear the motor “growl” as the drill bites into something that makes it harder to turn. But high quality drills are well protected against overheating, and serious problems are unlikely to occur.

A motor which is not turning almost acts like a short circuit for a brief instant when it is first turned on. For that first instant, there is a surge of current. This is why, if the kitchen lights and refrigerator are on the same circuit, the lights dim every time the refrigerator motor turns on.

A frequent summer problem involves the difficulty utility companies have in their attempts to turn their generators fast enough to maintain proper pressure differences in household wires. A decreased pressure difference results in slower operating motors in refrigerators and air conditioning units, which leads to the threat of overheating.

7.20 Activity: Interfering with the motor effect

Connect a battery, a Genecon, and a long bulb in series as shown in Figure 7.20a.
Hold the Genecon with the main axis vertical, and note the brightness of the bulb and the behavior of the Genecon.

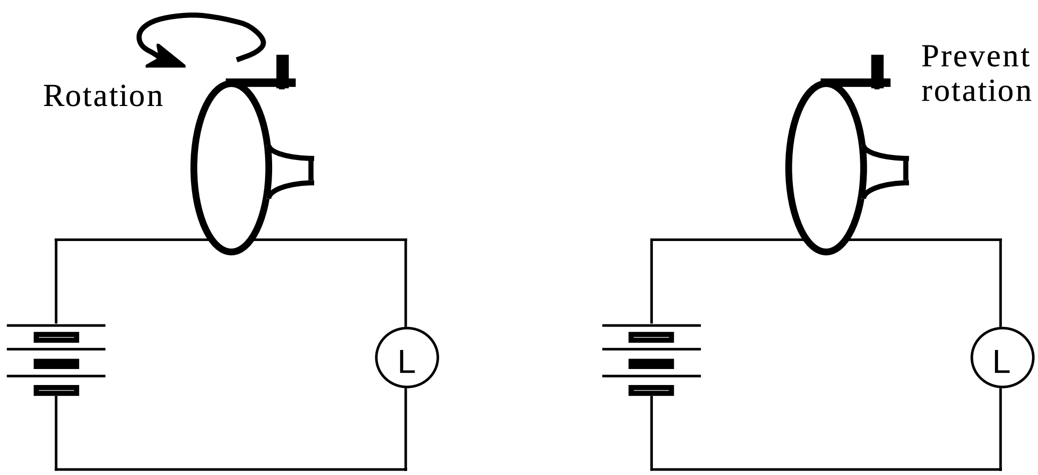


Figure 7.20a **Figure 7.20b**
MOTOR SHAFT IS ROTATING HAND PREVENTS ROTATION

1. Use your hand to prevent the Genecon crank from turning, as in Figure 7.20b. What happens to the bulb brightness when you hold the crank still?

2. The Genecon was turning because of the motor effect. Did you observe any evidence that the generator effect was also occurring? Explain.

Use your hand to make the Genecon crank turn faster in the same direction it is being turned by the battery, as in Figure 7.20c.

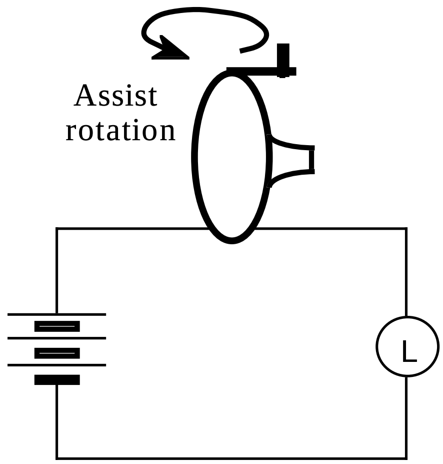


Figure 7.20c
CRANKING IN <u>SAME</u> DIRECTION

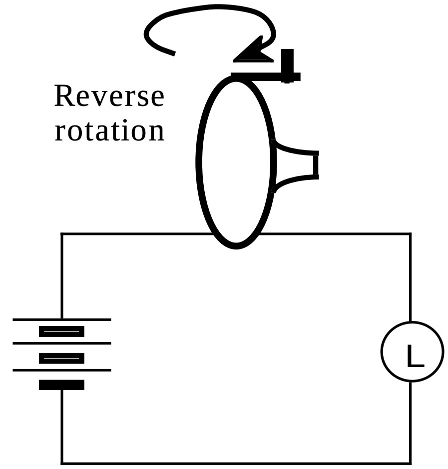


Figure 7.20d
CRANKING IN OPPOSITE DIRECTION

3. What happens to bulb brightness?

4. Use the idea that a generator effect is also present to explain what you observe.

Use your hand to turn the Genecon crank opposite to the direction it is being turned by the battery, as in Figure 7.20d.

5. What happens to the bulb brightness?

6. Use the idea that a generator effect is also present to explain what you observe.

INVESTIGATION SEVEN: MAKING A MODEL MOTOR FROM SCRATCH

7.21 Activity: Introduction to motors

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

a. Field magnet – a stationary magnet that establishes a magnetic field within which a coil rotates.

b. Armature (or rotor) – a coil of wire that rotates on an axis.

c. Commutator – a switching device attached to the armature. It changes the direction of charge flow through the armature in order to keep it rotating.

Constructing the motor:

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

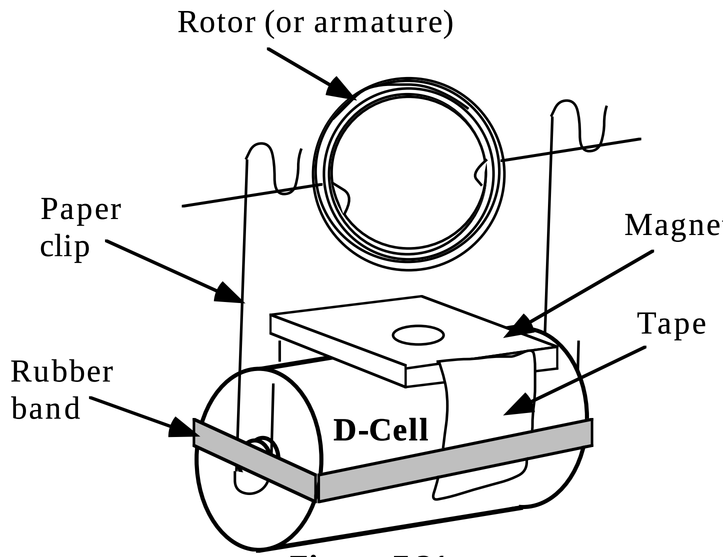


Figure 7.21a
FINAL MOTOR CONSTRUCTION

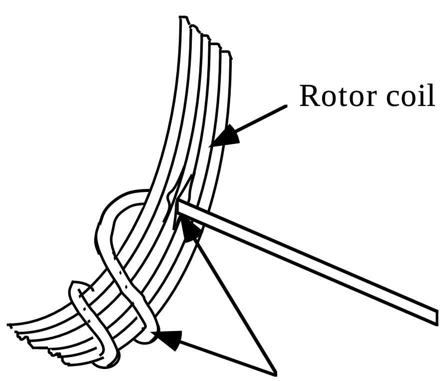


Figure 7.21b
THE ROTOR COIL

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.

5. Tape a flat magnet to a D-cell as shown in Figure 7.21a. (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 shown in the diagram. Attach them to the D-cell with a rubber band.

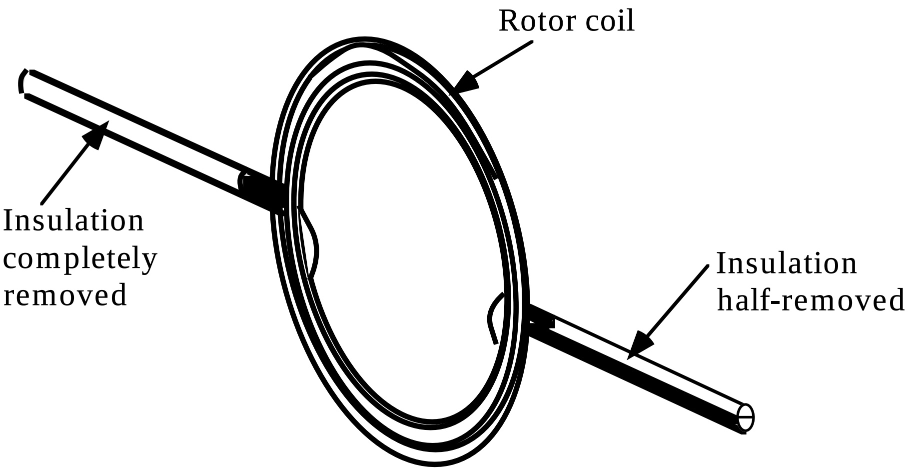


Figure 7.21c
ENLARGED VIEW OF COIL

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, current may not be flowing through the coil:

    a) Try spinning the coil while squeezing the clips against the battery for better contact.
    b) Check that the insulation is completely removed from the free ends of one wire and half of the second wire.
    c) Try your coil on someone else's battery and clips. If it spins, check your battery.

2. If the coil rocks back and forth but won't spin, check the balance of the coil. Adjust the free ends so they are carefully centered.

7.22 Exercise: Explaining the motor's activity

A motor is a device which converts electrical energy into mechanical energy (motion). Explain how your motor (from Activity 7.21) does so.

SUMMARY

1. Define motor and generator.

Motor:

Generator:

2. What does the term "magnetic field" describe?

3. The Right Hand Rule for Motors allows the 3-dimensional application of three mutually perpendicular effects – what are they?

4. How are the Right Hand Rules for Motors and Generators alike?

5. How are the Right Hand Rules for Motors and Generators different?

6. It may feel very difficult to crank a generator when it is attached to a very **low** resistance circuit. Explain this apparent contradiction.

7. In some situations, the motor effect and the generator effect can occur simultaneously. Cite at least one example.

Section 8

DOES ALL MATTER CONTAIN CHARGE?
WHAT ARE ELECTRONS?

INTRODUCTION

This section uses a new kind of bulb to resolve some basic questions: Do insulators contain charge? If so, is it ever mobile? What carries charge through the connecting wires and the battery? What carries charge through a lit neon bulb?

INVESTIGATION ONE: DOES THE GAS IN A NEON BULB HAVE CHARGE?

8.1 Activity: Testing neon gas at high voltage

A neon bulb has two wires that pass through the glass -- and in that respect it is like our long and round flashlight bulbs. But the wires terminate inside the bulb at two short metal rods, called “electrodes”. Between these electrodes there is only neon gas. There is no metal filament to provide a conducting path through the bulb from one electrode to the other.

Identify one of the electrodes by putting a small piece of masking tape on one of the bulb’s wires. Connect a yellow clip lead to the wire with the tape, and a green clip lead to the other wire. Clip four 9-Volt cells together in series, and then connect the free cell terminals to the clip leads as illustrated in Figure 8.1.

NOTE: Your neon bulb may have a resistor attached to it. If not, connect a large resistance in series with the bulb -- to make sure the bulb is not destroyed by an excessive flow rate. 10,000 ohms will work fine.

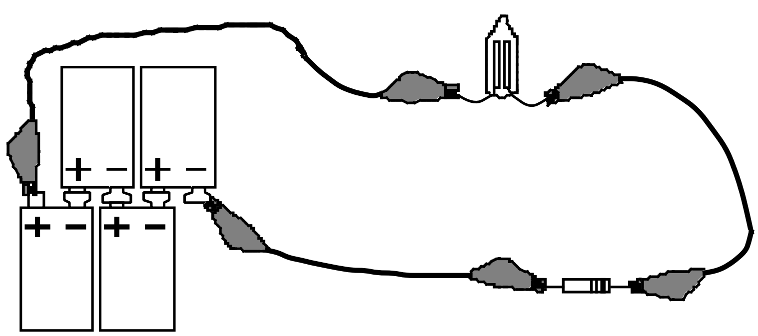
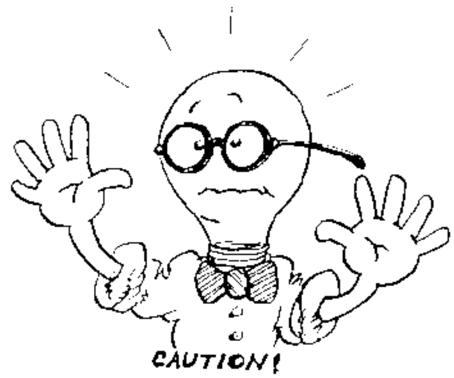


Figure 8.1
NEON BULB WITH FOUR 9-VOLT CELLS AND A RESISTOR TO REDUCE THE FLOW RATE

1. Does the bulb glow? Would you describe the neon gas inside the bulb as being a conductor or an insulator? Justify your answer.

Now snap on additional 9-volt cells — one at a time — until the bulb glows. When you add a cell, remove one clip only from the previously closed circuit. Though the pressure differences in this exercise are not high enough to be dangerous, it is possible to feel a minor electric shock if you put both hands across a string of 9-volt cells connected in series. You can avoid that if you touch only one point of the circuit at any given time.



2. Based on what you now see, would you describe the neon gas inside the bulb as being a conductor or an insulator? Justify your answer.

3. How much electric pressure difference (in Volts) is there across the bulb, when you use the smallest number of 9-volt cells that will make the bulb glow? Is this minimum number the same if you reverse the battery polarity?

8.2 Commentary: How an insulator could become a conductor

The gas in a neon bulb is normally an insulator. The evidence is that the bulb does not glow when the pressure difference across it is provided by only a small number of the 9-volt cells.

But a neon bulb will glow if the pressure difference across it is made sufficiently large -- provided by 8 or 9 or 10 cells. This much larger pressure difference does make charge flow through neon gas. So the neon gas is then a conductor.

The ability of neon gas to become a conductor is evidence that it contains charge, just like metal conductors do. The difference must be that neon gas won't let its charge move, ordinarily. The fact that a high voltage battery can make your neon bulb glow suggests that a sufficiently large pressure difference breaks charge loose in the neon gas -- allowing the charge to move just like in a metal conductor.

High voltage can also make other gases glow; since different gases each produce their own characteristic color, tubes of various gases are used for manufacturing multicolored advertising lights. Cases where an insulator is turned into a conductor by a large pressure difference are not restricted to gases. Consider the layer of solid insulator between the metal plates of our capacitors, which has prevented flow through the capacitor in every circuit we have used so far. A sufficiently large pressure difference in the plates will cause this insulating layer to become a conductor. The statements "MAX SURGE 25 VDC" printed on the blue capacitor (or "MAX SURGE 12 VDC" on the silver capacitor) tell us that the insulating layer will become a conductor if the pressure difference across the capacitor exceeds 25 volts (or 12 volts).

These statements are printed on our capacitors because the manufacturer believes three things to be true: (1) There is charge in the insulating layer. (2) This charge is normally unable to move. (3) A sufficiently large pressure difference across the insulator can break some of this charge loose from its confinement, making it able to move — just like in a conductor.

8.3 Activity: Using a neon bulb to determine the direction of flow

A neon bulb can be used to detect the direction of movement of charge passing through it.

1. Refer to Figure 8.1 above. Note which electrode of the neon bulb is glowing. Disconnect both wires from the battery. Then reconnect the bulb with the wires reversed. In each case, which electrode glows?

2. Explain how you can use the neon bulb to indicate the direction of charge flow.

INVESTIGATION TWO: DO SOLID INSULATORS ALSO CONTAIN CHARGE?

8.4 Activity: Building equipment to detect charge transfer between solid insulators

To investigate the possibility that solid insulators also contain charge, we will rub dissimilar materials against each other -- in the hope that rubbing will transfer some charge from one object to the other. If one of the rubbed materials acquires some charge, that charge should be able to change the pressure in a capacitor plate.

Figure 8.4a shows how to assemble a pie-plate capacitor to test for the pressure change. First, tape a foam cup upside down on top of one aluminum pie plate. Second, tape another cup right side up underneath another plate. Finally, nest the second cup and plate down onto the first cup as shown.

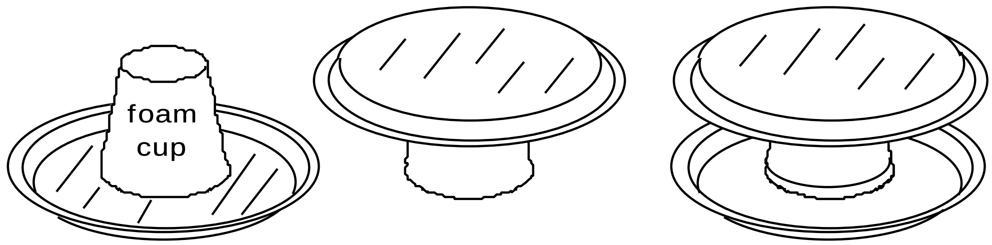


Figure 8.4a
BOTTOM PIE PLATE   TOP PIE PLATE   ASSEMBLED CAPACITOR

Our choice of solid insulators that might contain charge will be a foam picnic plate and a square of transparent acrylic. Suppose that rubbing these against each other transfers some charge from the foam to the acrylic. That would give the acrylic more than the normal amount of charge. This possibility is indicated by the (+) signs on the acrylic in Figure 8.4b.

To find out if some charge is actually transferred to the acrylic by rubbing, set the rubbed acrylic down on the top capacitor plate shown in Figure 8.4b. Use a wire to connect one neon bulb electrode to the bottom capacitor plate as shown in Figure 8.4b. Attach another wire to the other electrode in the neon bulb, but leave that wire unconnected to the top capacitor plate for the moment.

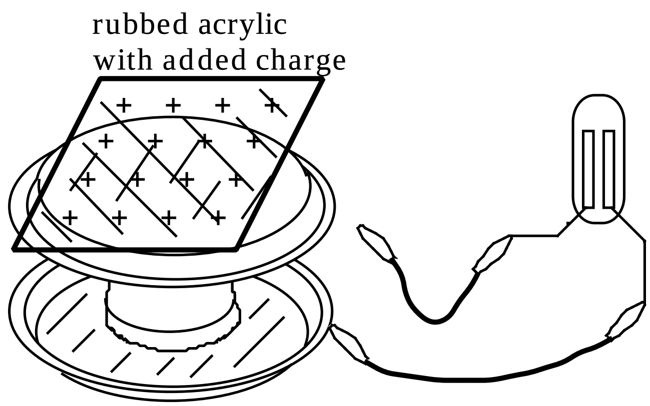


Figure 8.4b
RUBBED ACRYLIC RESTING ON THE TOP CAPACITOR PLATE   NEON BULB RESTING ON THE LAB TABLE

At the appropriate time, you will test for charge flow through the bulb by touching the free end of the second connecting wire to the top metal plate with. Light from the neon bulb will be easy to observe if you follow these two rules:

(1) The resistor used to reduce the flow rate in Activity 8.1 should not be placed in the conducting path in this case.

(2) Make the final connection to the top capacitor plate only after the acrylic sheet has been set down on that plate.

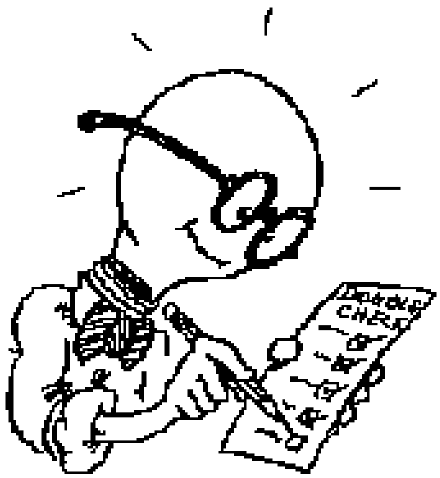
Activity 8.5: Looking for evidence of extra charge on the rubbed acrylic

Lay an acrylic sheet on your lab table, and rub the bottom of a foam plate on it.
If rubbing transfers some charge from the foam to the acrylic, the acrylic will then have added charge (+) and the foam will have a deficiency (-).

Handle these materials near their edges. Since both of them are non-conductors, they will retain any charge you give them for a relatively long time — provided you don't give the charge a way to run off through other objects that touch them. We will first test the acrylic sheet, to find out if it has acquired an excess of charge.

The complete list of steps for this experiment is:

1) Lay the rubbed acrylic down on the top plate of the capacitor.
2) Touch the free wire clip to the top plate, and observe which electrode in thebulb glows.
3) Disconnect the wire from the top metal plate. Then take the acrylic away from the top plate.
4) Touch the free wire to the top plate again, and observe which electrode in the bulbglows.



<u>If you get lost</u>: Discharge the metal plates by connecting a wire to them. Then start over.

One partner should <u>close the gap</u> between the free wire and the top capacitor plate. The other partner's job is to carefully <u>observe the electrodes</u>, to find out which one glows. Placing white paper under the bulb will improve visibility.

Repeat these steps as often as you need to confidently answer the questions below.

1. In step #1, was the electrode that glowed connected to the top or the bottom plate of the capacitor?

2. In which plate-to-plate direction did charge move through the bulb?

3. Which plate was at a HIGHER pressure -- the top one or the bottom one?

4. After the bulb lights, remove the acrylic from the top capacitor plate and <u>then</u> disconnect the top plate from the wire that leads to the bulb. Describe the locations of excess (+) and depleted (-) charge that remain in the capacitor plates.

5. When you reconnected the top capacitor plate to the bulb, was the direction of charge flow consistent with your answer to question #4? State the evidence.

8.6 Commentary: Are there two kinds of charge in insulators?

Why is the pressure in the capacitor plates changed only by charge that is added to the acrylic when it is rubbed? Why doesn't the charge that is normally present in the acrylic raise the pressure in nearby pieces of metal before the acrylic is rubbed?

A simple way to explain what we do and don't observe is to revise our model to include a pressure-lowering "negative" kind of charge as well as the pressure-raising "positive" kind that we are already familiar with:

- "Positive" charge raises the pressure in nearby conductors.
- "Negative" charge lowers the pressure in nearby conductors.

This terminology allows us to maintain continuity between the older model with one type of charge and the new model with two types of charge. Instead of letting (+) and (-) symbols denote above-normal and below-normal amounts of "charge," we can use these symbols just as before but give them different meanings:

(+) will indicate an excess of pressure-raising charge.

(-) will indicate an excess of pressure-lowering charge.

The revised model explains why we don't see normal insulators having a distant-action pressure effect: A normal insulator has equal amounts of pressure-raising and pressure-lowering charge, so their opposite effects cancel out. Only an excess of one kind over the other will cause an observable effect.

- Adding more (+) charge to the acrylic gave it excess (+) charge, which provided a basis for the observed pressure-raising effect.
- Depleting the (+) charge in the foam left excess (-) charge, which created a basis for predicting a pressure-lowering effect.

The revised model also raises another question: Which kind of charge **actually** moves in the wires in a circuit? An investigation that answers this question will be postponed until the end of the section, in order not to interrupt the flow of emerging ideas. For the present we will assume that positive charge is the kind that can move in a circuit, while negative charge is held in place and cannot move.

8.7 Activity: Looking for evidence of negative charge in the rubbed foam

Our new model of pressure effects caused by charge predicts that putting excess (-) charge on a capacitor plate will cause LOWER electric pressure in that plate. Does this actually happen? You can find out by laying the rubbed foam down on the top capacitor plate, as illustrated in Figure 8.7, and repeating the experiment that you performed earlier using the rubbed acrylic.

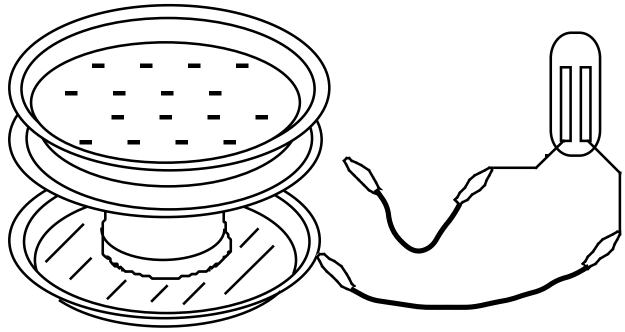


Figure 8.7

RUBBED FOAM PLATE RESTING ON THE TOP CAPACITOR PLATE — **NEON BULB RESTING ON THE LAB TABLE**

Before performing this experiment, discharge the capacitor plates by connecting them with an extra wire. Leave the wire from the neon bulb unconnected to the top capacitor plate for the moment, as shown in Figure 8.7.

1. When you connected the free wire to the top capacitor plate, in which plate-to-plate direction did charge move through the bulb? What is the evidence provided by neon bulb lighting?

2. Was the pressure in the top capacitor plate made HIGHER or LOWER by the presence of the rubbed foam? Was this effect caused by excess positive charge or by excess negative charge on the foam?

3. Describe the locations of excess (+) and (-) charge in the capacitor plates after charge has moved through the bulb, and the foam has been taken away.

4. After the bulb lights, remove the foam from the top capacitor plate and then disconnect the top plate from the wire that leads to the bulb. If you were to reconnect the bulb to the top capacitor plate again, would you expect to observe bulb lighting again? Why or why not -- and which bulb electrode would glow if lighting were to occur?

5. In the space below, describe the differences in (a) the way the neon bulb lit when you placed rubbed acrylic and rubbed foam near the top capacitor plate and in (b) the direction mobile (+) charge moved in response to pressures in the capacitor plates, and (c) the role of (+) and (-) charges on the rubbed insulators in causing those pressure differences.

INVESTIGATION THREE: DOES (+) OR (-) CHARGE MOVE IN CIRCUIT WIRES?

8.8 Activity: Which way would negative charge move in circuit wires?

In Figure 8.8a, the arrows show the direction mobile particles carrying positive (+) charge must move in order for a battery to charge a capacitor.

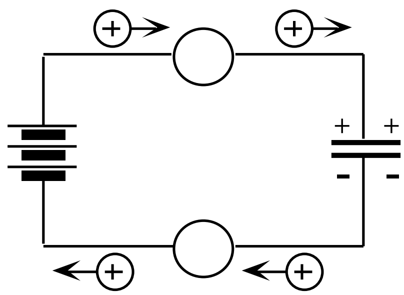


Figure 8.8a
CAPACITOR CHARGING IF (+) CHARGE MOVES

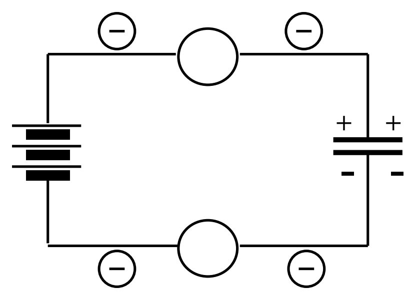


Figure 8.8b
CAPACITOR CHARGING IF (-) CHARGE MOVES

1. On Figure 8.8b, draw arrows to show the direction hypothetical mobile particles carrying negative (-) charge must move in order to discharge the capacitor (if any exist).

2. In your own words, describe the direction of negative charge flow compared to the direction of positive charge flow.

3. Describe the final state of the capacitor in each case.

8.9 Commentary: Where mobile charge comes from in the neon bulb

Normal atoms have no charge, and a pressure difference can't make them move. So how can we explain charge flow in a neon bulb -- when a sufficiently large pressure difference applied to it? The following model of charge in atoms can help make sense of neon bulb lighting:

- Neon (and other) atoms are made of <u>fragments</u> that have (+) and (-) charge.
- A large pressure difference can tear atoms apart into (+) and (-) <u>fragments</u>.

The breaking-up process is called "ionization".

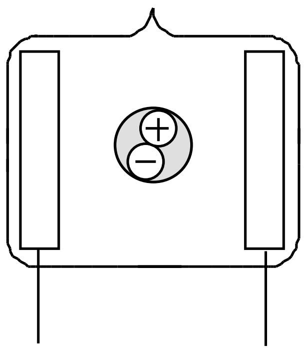


Figure 8.8a
NEON BULB BEFORE IONIZATION: WHOLE ATOM WITH NO NET CHARGE

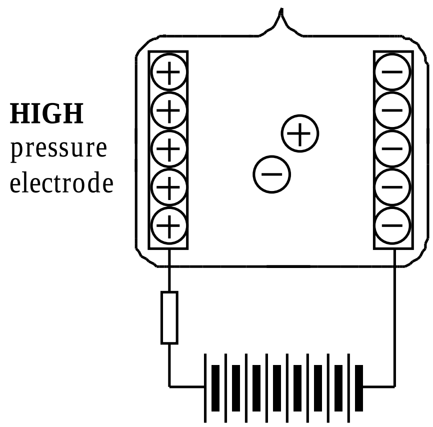


Figure 8.9b
(+) AND (-) FRAGMENTS SEPARATED BY A LARGE PRESSURE DIFFERENCE

8.10 Commentary: The process of light emission by a neon bulb

Suppose neon atoms are being ionized everywhere in the bulb. Figure 8.10 shows how a pressure difference in the electrodes will make (+) and (-) fragments move <u>in opposite directions</u>.

The big question about neon bulb lighting is:

What's happening at the electrode where light is emitted?

In order to maintain a steady glow of the neon bulb, two things must be occurring:

- There is continual <u>ionization</u> of the atoms into (+) and (-) fragments.
- There is continual <u>recombination</u> of fragments into new whole atoms.

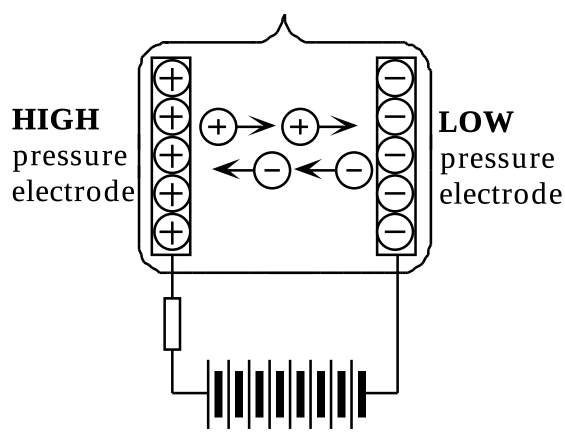


Figure 8.10
MOTION OF (+) AND (-) NEON FRAGMENTS DUE TO ELECTRODE PRESSURE DIFFERENCE

We can characterize these as opposite energy transfer processes:

- During ionization, parts of atoms are pushed apart "against their will". This makes it a process in which the battery gives energy to atoms.
- During recombination, atoms give energy back out. Where does the energy go? It is transformed to light energy and emitted.

This identifies what's happening at the electrode where light is emitted:

The place where the bulb emits light is the place where the (+) and (-) fragments recombine to form new whole atoms.

8.11 Activity: What is moving in the wires when the neon bulb is lit?

Suppose carriers of (+) charge are moving in the circuit wires as shown in Figure 8.11a. Then (-) fragments of neon moving leftward though the bulb will meet (+) charge coming out of a wire at the (+) electrode on the left. Light being emitted at the (+) electrode would be evidence that this meeting results in new whole atoms being formed inside the bulb at the (+) electrode on the left.

Suppose carriers of (-) charge are moving in the circuit wires as shown in Figure 8.11b. Then (+) fragments of neon moving rightward though the bulb will meet (-) charge coming out of a wire at the (-) electrode on the right. Light being emitted at the (-) electrode would be evidence that this meeting results in new whole atoms being formed inside the bulb at the (-) electrode on the right.

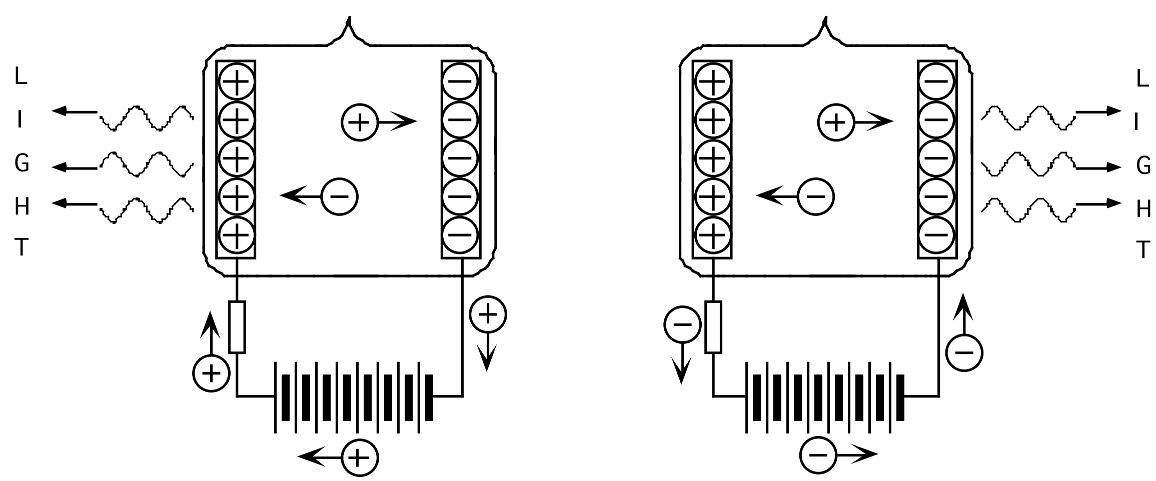
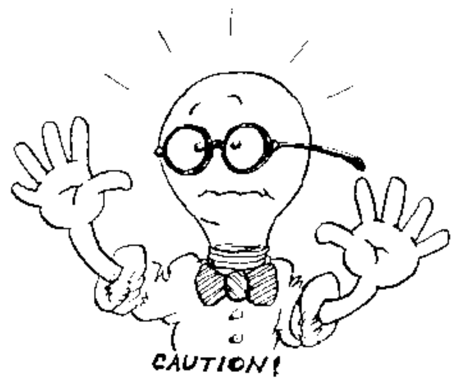


Figure 8.11a
LIGHT EMITTED AT LEFT IF (+) CHARGE IS MOVING IN WIRES

Figure 8.11b
LIGHT EMITTED AT RIGHT IF (-) CHARGE IS MOVING IN WIRES

To find out which of these two diagrams describes what is actually happening, set up circuit 8.11c with a neon bulb and enough 9-volt batteries to make the bulb light. Note the electrode where light is being emitted. (You may recall having seen this already in Activity 8.1.) Be sure to include a resistor in the circuit, to limit the flow rate through the bulb and avoid burnout.



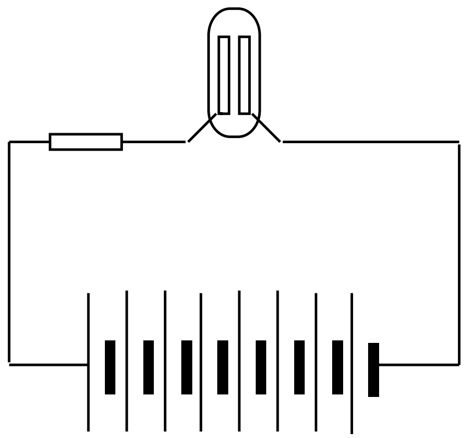


Figure 8.11c
CIRCUIT FOR OBSERVING WHERE LIGHT IS EMITTED

1. At which electrode are the (+) fragments of ionized neon atoms recombining?

2. What is the evidence for this?

3. Where is the (-) charge coming from that recombines with the (+) fragments?

4. Which kind of charge can we infer is moving in the circuit wires?

5. What happens to (-) fragments of ionized neon atoms at the other electrode?

6. What path do (+) fragments of ionized atoms take to the site of recombination?

7. What path do (-) fragments of ionized atoms take to the site of recombination?

8. Do you conclude that carriers of positive charge, or carriers of negative charge, are moving through the wires of an operating circuit?

8.12 Commentary: The discovery of electrons

Seeing a neon bulb lit at its negative electrode supports the following ideas about charge in matter:

- What's moving in a circuit carries negative charge through the wires.
- The non-moving matter in conductors contains fixed positive charge.

These ideas are part of a big, important story revealed by the circuit in Figure 8.11c.

Recall from Section 2 that charge moving in circuit wires is not moving through empty pipes, but always exists everywhere in the circuit and could have started out anywhere in the circuit. Therefore, the (-) charge carriers that move in circuits are the (-) parts of copper atoms that the wires are made of.

These (-) parts of copper atoms become the (-) parts of neon atoms as they leave the wires and recombine with the (+) parts of neon atoms at the electrode where light is emitted. Meanwhile, the (-) parts of ionized neon atoms move into the wires at the bulb's other electrode. So the (-) parts of copper atoms that move through the wires are identical to the (-) parts of neon atoms that come into the wires at a bulb's (+) electrode and go out the wires at its (-) electrode.

How can the (-) parts of neon atoms (and sodium or mercury atoms in highway lamps) be identical to the (-) parts of copper atoms (and aluminum or silver atoms in other metals that wires can be made of)? There only way to make sense of this is to conclude that the carriers of mobile charge in circuits are identical to the (-) parts of the atoms of every kind of matter.

Note that these (-) charge carriers are able to move through very dense metal wires and batteries. You can't blow atoms of air through those materials — and neither can you do it with whole atoms of neon gas. In order to pass through such dense matter, the (-) charge carriers must be extremely tiny compared to the size of any whole atom. And tiny size suggests tiny mass — much less than the mass of any whole atom.

The evidence is that identical, tiny, low-mass, carriers of (-) charge are present in atoms of every kind of matter. They are called ELECTRONS. The parts of ionized atoms with (+) charge, called IONS, are much larger in size and have much more mass. Ions from atoms of different kinds may have different amounts of mass.

8.13 Commentary: The idea of "conventional" charge flow

When a battery is lighting a bulb, charge is NOT moving out of the (+) terminal of the battery – as we assumed early in this curriculum!!!

Based on observations of a neon bulb, the "conventional current" flow is not correct! Actually, electrons are moving in the reverse direction. This conclusion should not come as a complete surprise, since we noted in Section 1 that we were making an assumption about the direction of motion — and assumptions may turn out to be incorrect. So what do we do now? Do we have to go back and change all the earlier statements we made about the direction of flow in circuits?

The pioneers of electricity research had to face this same dilemma when electrons were discovered at the end of the nineteenth century. They decided to keep using the fiction that positive charge moves out of the (+) terminals of batteries. It was a reasonable decision, because reasoning that way still leads to correct conclusions. For example, the charges that end up in the plates of a capacitor when it is charged by a battery are the same whether you say (+) charge moves in one direction or (-) charge moves in the other direction. (See Figures 8.8a and 8.8b, which describe the charging of the capacitor.)

So there is no need to change the way you have been reasoning about circuits. Just remind yourself that you're using a convenient fiction by speaking every now and then of "conventional flow," as this book has done. You are welcome to reason (as a few books do) with "electron flow" moving in the opposite direction. But it is easier to reason with conventional flow — because it is intuitive to think about positive charge being pushed through a resistor toward lower "pressure". Since thinking about negative charge being pushed toward higher "potential" (or higher anything) is not intuitive, such a relationship must be memorized. For this reason, physicists and engineers usually communicate using conventional flow.

SUMMARY EXERCISE

1. This Section concludes that insulators as well as conductors contain charge. What is the observable evidence for this conclusion?

2. In previous sections, discussions were based on an excess or depletion of one kind of charge. In this section, the hypothesis was provided that there are actually two distinct kinds of charge. What is the evidence for two kinds of charge?

3. Under certain circumstances, insulators can sometimes become conductors.

   a. Describe a case in which this occurs.

   b. Does this provide additional evidence for two kinds of charge? Explain.

4. If insulators always contain charge, why aren't they ordinarily considered to be "charged".

5. Prior to this section, current has always been analyzed on the basis of conventional charge flow. What is the evidence that current actually consists of negative charges moving through the wires?

Section 9

WHAT IS THE CAUSE OF DISTANT-ACTION EFFECTS?

INTRODUCTION

In this section our model of battery-driven flow predicts cannot happen. The model will continue to be revised and improved. Quantitative features will be added, which make the model even more powerful.

INVESTIGATION ONE: IS CHARGE CHANGING PRESSURE ACROSS GAPS?

9.1 Activity: Circuit with a conducting "island"

The circuit in Figure 9.1 contains an "island" containing wires and two bulbs between the insulations of the two capacitors (A and B). We call this part of the circuit a "conducting island," because charge cannot flow into or out of it through the insulating layers.

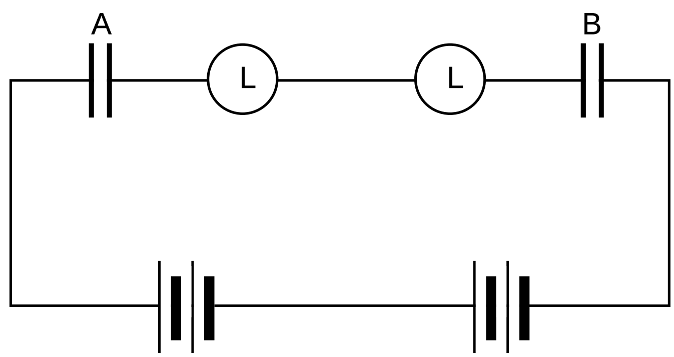


Figure 9.1
ELECTRIC CIRCUIT WITH A "CONDUCTING ISLAND"

1. Do you think the bulbs in the "island" will light when you connect the last wire? Write your prediction below, based on the compressible fluid model. Explain your reasoning.

Join with another lab group to build the circuit in Figure 9.1, with two blue capacitors (A and B) and two 2-cell batteries. First, use a wire to discharge each capacitor. Then connect the capacitors in series, with two long bulbs between the capacitors. Connect the wire between the batteries and observe the bulbs. You can repeat the experiment by reopening the circuit and discharging each capacitor with a wire.

2. Do the bulbs light? If they do light, are they brightest right after the connection is made or at some later time?

3. If the bulbs light, use a compass to compare direction and magnitude of current in the island with direction and magnitude in all the wires of the circuit. What do you observe?

4. What have you observed that cannot be explained by the model of battery driven charge flow that we have developed in our earlier work?

9.2 Commentary: Reviewing the compressible fluid model of charge flow

Up to this point we have built a conceptual model in which pressure difference in a fluid of mobile charge is the cause of charge flow through a resistor. However, there is no way for the battery to drive charge into or out of the conducting island in the circuit of Figure 9.1. So our model envisions no way for charge in the island to become compressed or depleted -- and no way to create pressure differences that could drive charge through the bulbs in the island. Therefore, the model predicts there will be no bulb lighting in the conducting island.

In Activity 9.1 we saw that this prediction of the model is false. Clearly, something is wrong with our model. But should we abandon a model that works perfectly everywhere except in conducting islands? And if we were to do that, how would we find a different explanation for all the correct predictions of the old model?

Let's try instead to revise and improve the model — in a way that will make it valid also for conducting islands. Let's start by applying the compressible fluid model to the bulb lighting that actually does occur in the "island" part of the circuit, and see if that suggests ideas about improvement:

1) Glowing bulbs indicated that charge was being driven through the island.

2) To make that happen, pressure differences were being created in the island.

3) These differences were not caused by charge entering and leaving the island.

4) The cause must have been charge accumulation and depletion in capacitor plates located outside the island.

This line of reasoning suggests we can improve the model by adding the following new feature to the model:

Charges located outside the island influence pressure inside the island.

This added feature of the model is called "distant action". The distant action of the two kinds of charge is assumed to work in the following specific manner:

Excess (+) charge makes electric pressure higher in a conductor across a gap.

Excess (-) charge makes electric pressure lower in a conductor across a gap.

This added feature of the model is at present only a proposal. It must be tested to determine **if** it can explain what happens in a variety of situations.

9.3 Activity: More work with the pie plate capacitor and neon bulb

To obtain direct experience with (+) and (-) charges raising and lowering pressure values across gaps, we will return to the rubbed insulators and neon bulb that we worked with in Section 8. Set up the capacitor made of two aluminum pie plates, and rub a foam picnic plate on a sheet of acrylic.

You will soon be asked to grip the acrylic with excess (+) charge by the edges, and hold it up in the air a little above the top capacitor plate. This situation creates a gap between the top capacitor plate and the (+) charge on the acrylic. Note also the larger gap between the bottom capacitor plate and the (+) charge on the acrylic.

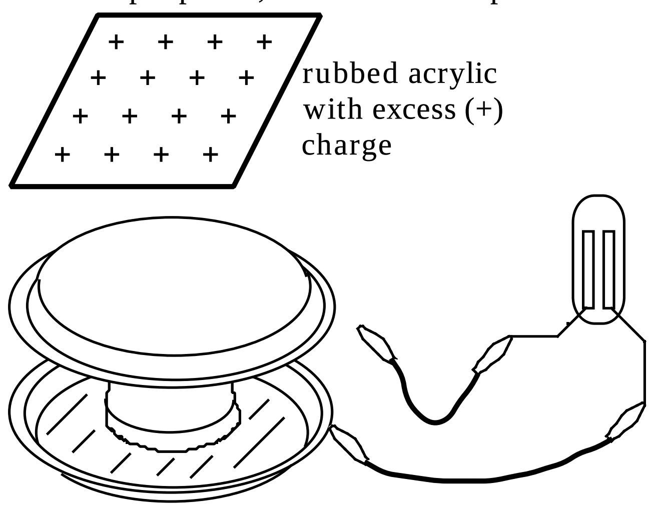


Figure 9.3a

(+) ACRYLIC HELD UP ABOVE THE TOP CAPACITOR PLATE **NEON BULB RESTING ON THE LAB TABLE**

One partner should now hold the charged acrylic up above the top capacitor plate as in Figure 9.3a. The other partner should then touch the free wire from the bulb to the top capacitor plate.

1. Was the pressure in the top capacitor plate higher than, lower than, or the same as the pressure in the bottom plate? What is the evidence?

Use a wire to discharge the capacitor, and then repeat this experiment. Do this as many times as you need, in order to be certain about the observed result.

One partner should now hold the negatively charged foam up above the top capacitor plate as in Figure 9.3b. The other partner should then touch the free wire from the bulb to the top capacitor plate.

2. Was the pressure in the top capacitor plate higher than, lower than, or the same as the pressure in the bottom plate?

What is the evidence?

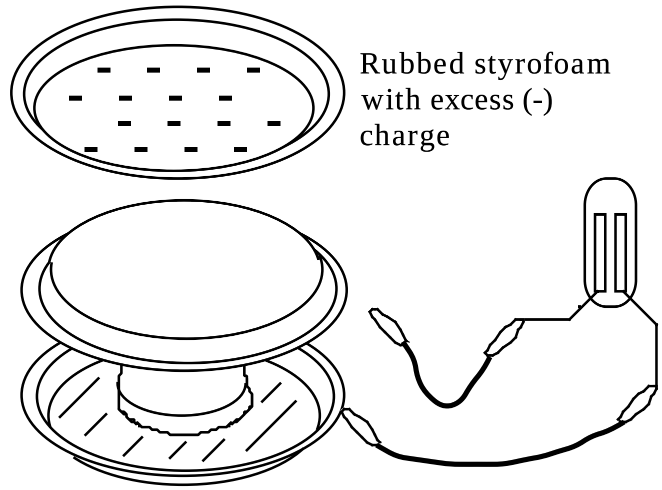


Figure 9.3b

(-) STYROFOAM HELD UP ABOVE THE TOP CAPACITOR PLATE

NEON BULB RESTING ON THE LAB TABLE

3. Do accumulations of excess (+) and (-) <u>cause a change</u> in the electric pressure in nearby conductors <u>across gaps</u> -- YES or NO? What is the evidence?

4. Does it matter how wide the gap is -- YES or NO? Explain in detail.

This decreasing strength of the effect with increasing distance from the cause tells us that the idea of a distant pressure-raising effect is making sense. That is the way the world works in all the cases that we know about. <u>Example</u>: A flame that raises the temperature in your nearby hand will raise the temperature less when your hand is farther away from the flame.

INVESTIGATION TWO: WHAT'S BRIDGING THE GAPS TO CAUSE CHANGE?

9.4 Commentary: The "pressure halo" idea

What enables charge located outside the island to cause pressure changes inside the island, without actually entering the island and being compressed there? Are there some kind of invisible structures attached to charges outside the island, that bridge the gaps and cause pressure changes inside the island? There is a possibly useful analogy in the external influence of flames and ice:

- A candle flame is surrounded by a zone of higher-than-normal temperature.

  Your finger placed in this zone is made hotter without the flame touching it.
  The temperature decreases toward normal at a large distance from the flame.

- A chunk of ice is surrounded by a zone of lower-than-normal temperature.

  Your finger placed in this zone is made colder without the ice touching it.
  The temperature increases toward normal at a large distance from the ice.

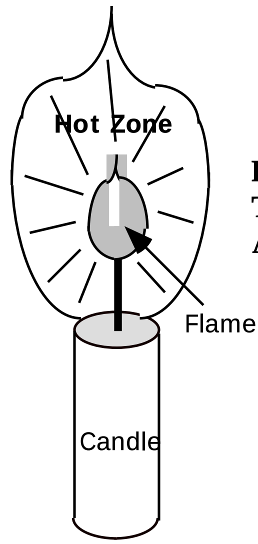


Figure 9.4
TEMPERATURE HALO AROUND A CANDLE FLAME

We'll use the name "halo" for external zones of influence. We will say that there is a "temperature halo" in the space around a candle flame or a chunk of ice. The temperature halo in the space around a candle flame is illustrated in Figure 9.4.

By analogy, we will assume there are "pressure halos" in the space around charges. These halos influence the electric pressure in any conductor that is placed in them.

- Excess (+) charge has a pressure halo that raises electric pressure in conductors.
  A conductor in this halo has its pressure raised without the charge touching it.
  The pressure is less and less above normal at greater distances from the charge.

- Excess (-) charge has a pressure halo that lowers electric pressure in conductors.
  A conductor in this halo has its pressure lowered without the charge touching it.
  The pressure is less and less below normal at greater distances from the charge.

9.5 Activity: Visualizing pressure halos around (+) and (-) charges

Figure 9.5a shows the distribution of a pressure-causing capability in a halo around an object with excess (+) charge. Points where the halo has equal pressure-raising capability are connected by a dashed line. The dashed lines are like atmospheric pressure contours or equal-temperature contours on a weather map. The numbers compare the pressure-raising capability of different parts of the halo.

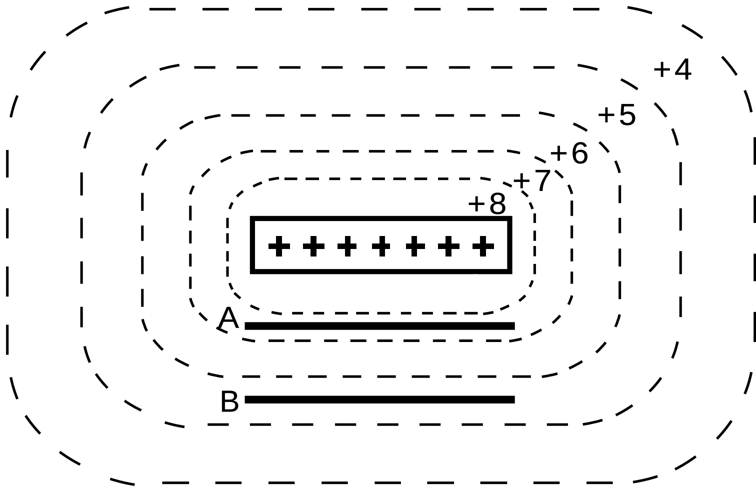


Figure 9.5a
PRESSURE HALO AROUND AN OBJECT WITH EXCESS (+) CHARGE

Figure 9.5a also shows two uncharged metal plates labeled A and B, which are placed at different distances from the charged object.

1. Which metal plate (A or B) is predicted to be at higher pressure?

2. If a neon bulb is connected to the plates, will charge move through the bulb in the A-to-B direction or in the B-to-A direction? Which bulb electrode will glow?

3. Refer to Activity 9.3a. Do your results agree with this hypothesis?

Figure 9.5b shows the distribution of pressure-causing capability in a halo around an object with excess (-) charge. Negative numbers by the dashed lines compare the pressure-lowering capability of different parts of the halo. In the numerical scheme used in Figures 9.5a and 9.5b, normal pressure is represented by zero.

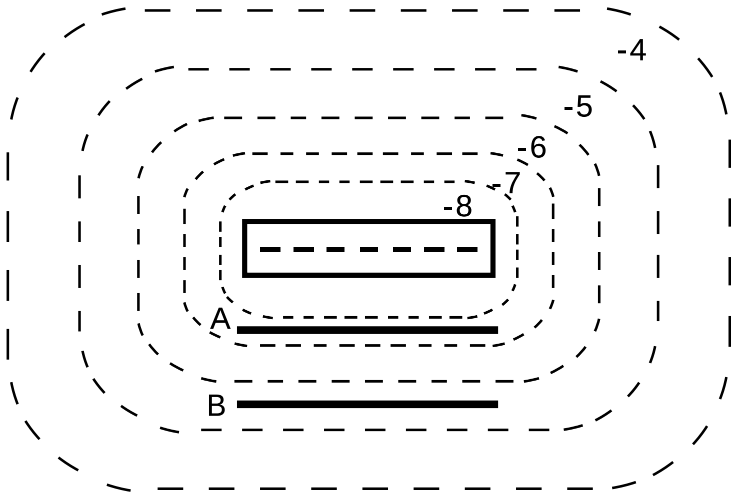


Figure 9.5b
PRESSURE HALO AROUND AN OBJECT WITH NEGATIVE CHARGE

4. Which metal plate (A or B) is predicted to be at higher pressure?

5. If a neon bulb is connected to the plates, will charge move through the bulb in the A-to-B direction or in the B-to-A direction? Which bulb electrode will glow?

6. Refer to Activity 9.3b. Do your results agree with this hypothesis?

7. Suppose the neon bulb is removed after the experiments in questions 2 and 5, and <u>then</u> the object with excess (+) or (-) charge is taken away. Describe the type of excess charge that will remain on each of the metal capacitor plates.

8. Suppose the plates are again connected through the neon bulb. Is the direction of charge flow from A to B or from B to A? Why? Which electrode will glow?

To be confident that you understand what these diagrams represent, you may want to re-do Activity 9.3 while referring to these figures.

9.6 Activity: More work with the island circuit

Pressure halos have been hypothesized as the mechanism of distant action. Let’s find out how much this mechanism can explain about the island circuit in Activity 9.1. Set up the circuit without the wire between the bulbs, as in Figure 9.6.

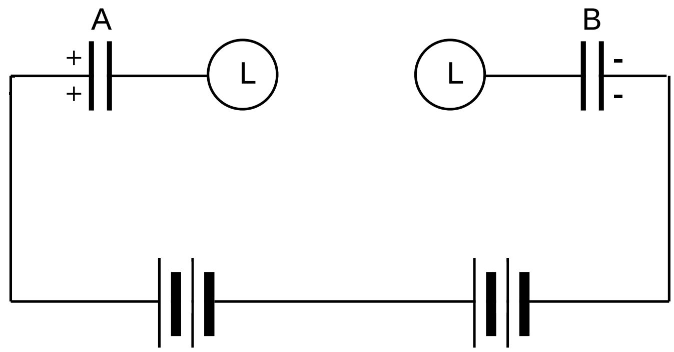


Figure 9.6a
INCOMPLETE "CONDUCTING ISLAND" CIRCUIT

Assume the battery drives transient flow that leaves excess (+) charge on the left plate of capacitor A and excess (-) charge on the right plate of capacitor B as shown.

1. Use a high resistance (digital) voltmeter to measure the pressure difference across each capacitor, across each bulb, and between the unconnected bulb socket clips. Record your measurement here.

2. How does the pressure difference between the unconnected bulb socket clips compare with the pressure difference across the battery?

3. Color code this circuit.

4. Use the pressure halo idea to explain the distribution of pressure values.

Now connect the missing wire in the conducting island, and watch the bulbs light.

5. Draw starbursts on Figures 9.6b, 9.6c and 9.6d to describe the bulb lighting you observe. Color code these Figures to explain the causes of the bulb lighting.

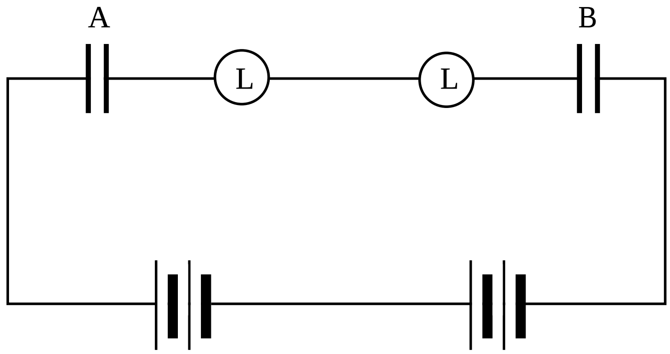


Figure 9.6b
COMPLETED CIRCUIT AT INSTANT OF CONNECTION

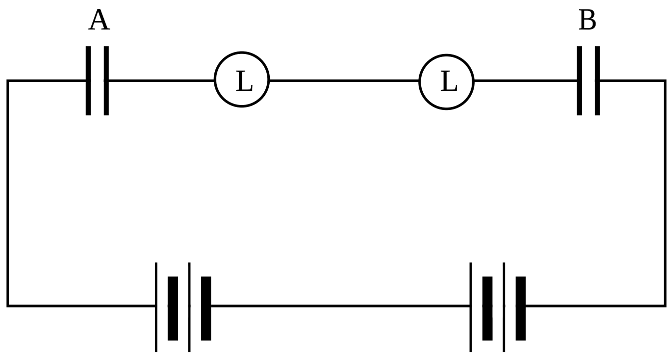


Figure 9.6c
SOME TIME LATER WHILE BULBS ARE STILL LIT

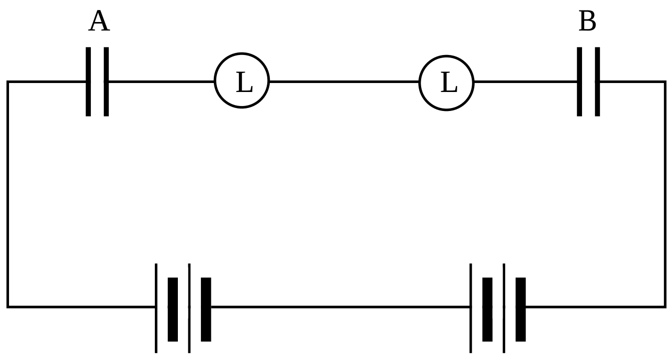


Figure 9.6d
AFTER A LONG TIME HAS ELAPSED

6. Describe how halos of charges in the extreme left and extreme right capacitor plates are acting across the gaps in the capacitors to cause the pressure changes in the island which cause the bulb lighting over time that you have observed.

INVESTIGATION THREE: HOW TO QUANTIFY THE HALO OF A CAPACITOR

9.7 Commentary: From "electric pressure" to "electric potential"

We have shown that a model in which charge flow is driven by pressure halos around (+) and (-) charges can successfully predict the behavior of even the very complex island circuit. Note that adding the pressure halo feature -- like adding a second kind of charge -- does not require that we abandon the compressible fluid model. The new model is simply the old one with added features that make it usable in a greater variety of situations. For most circuits, we can simply use the original model without even having to think about the new features.

Nevertheless, the fact that charge can influence electric pressure across gaps means that electric pressure is very different from air pressure. A pressure halo in empty space around charge is not a region where actual electric pressure exists — because there is no matter for pressure to exist in. Instead, a pressure halo has a property with the potential to do what electric pressure does. This property behaves exactly like actual electric pressure in any conducting body that is placed in the halo.

The term "potential electric pressure" can capture the idea of a condition in space that acts like actual electric pressure in matter. For historical reasons, however, the term "electric potential" has become standard usage among scientists. This is often shortened to "potential " -- like "electric pressure" is shortened to "pressure." Also, "potential difference" sometimes seems overly long and is called "voltage".

Though the term "halo" is not used by professionals, we will continue to use it in this manual. We will do this because no professional term adequately captures the idea of a non-material "thing" in the space around a charge accumulation. From now on we will use the term "potential halos" rather than "pressure halos".

9.8 Commentary: Quantifying the halo of an "ideal" capacitor

How is the halo of a charged capacitor related to the halos of each of the individual plates? Think about the simplest possible case -- a capacitor with plates that are very large, very thin, and perfectly flat -- which is called an "ideal" capacitor. When this capacitor is charged, there will be large uniform parallel sheets of (+) and (-) charge.

It is useful to develop a quantitative description of the halo. To achieve this, we will need to add two quantitative features to our model of charge flow in circuits:

Principle #1 -- a description of the halos of individual (+) and (-) charge sheets

Principle #2 -- a rule for combining these to form the halo of a whole capacitor

The long history of electricity research has discovered the specific forms of these features that are needed to solve the problem. Later on, you can verify that these forms enable the model to make correct predictions. The quantitative principles are:

1) The potential varies with distance from a sheet in direct proportion to distance.

2) The potential at each point is the sum of potentials due to the (+) and (-) sheets.

Figures 9.8a and 9.8b below demonstrate Principle #1. They show the potential varying by one volt for each one-centimeter increase of distance from a sheet of charge. The halo in Figure 9.8a has HIGH electric potential -- becoming less and less high at greater and greater distance from the individual sheet of (+) charge. The halo in Figure 9.8b has LOW electric potential -- becoming less and less low at greater and greater distance from the individual sheet of (-) charge.

Figure 9.8c demonstrates Principles #1 and #2. It shows the potential at each point -- on a line perpendicular to the plates -- as the numerical sum of the potentials at that point due to the presence of both (+) and (-) charge sheets.

As you can verify by looking at Figure 9.8c, there are potential differences between every pair of points in the s pace between the capacitor plates. But note that there are no potential differences in the external space. This is quantitative proof that the forms of quantitative Principles #1 and #2 that were proposed above are correct. The following exercise will help you look more closely at this issue.

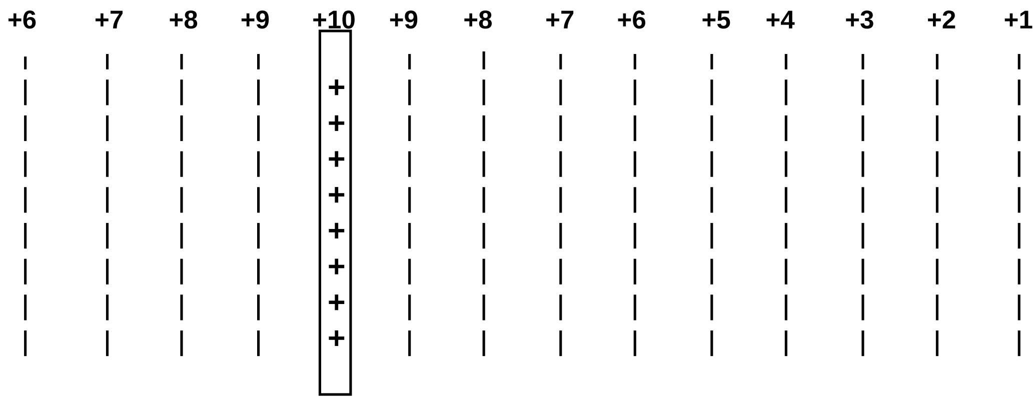


Figure 9.8a
ELECTRIC POTENTIAL NEAR A LARGE SHEET OF (+) CHARGE

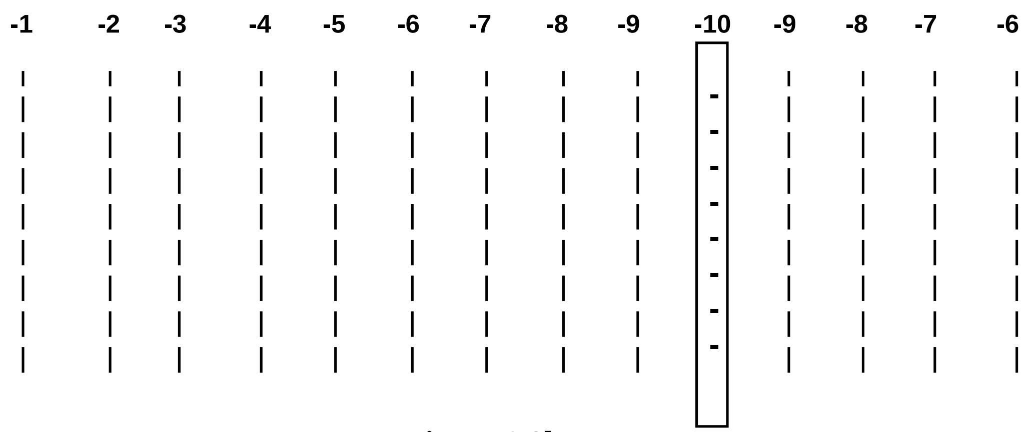


Figure 9.8b
ELECTRIC POTENTIAL NEAR A LARGE SHEET OF (-) CHARGE

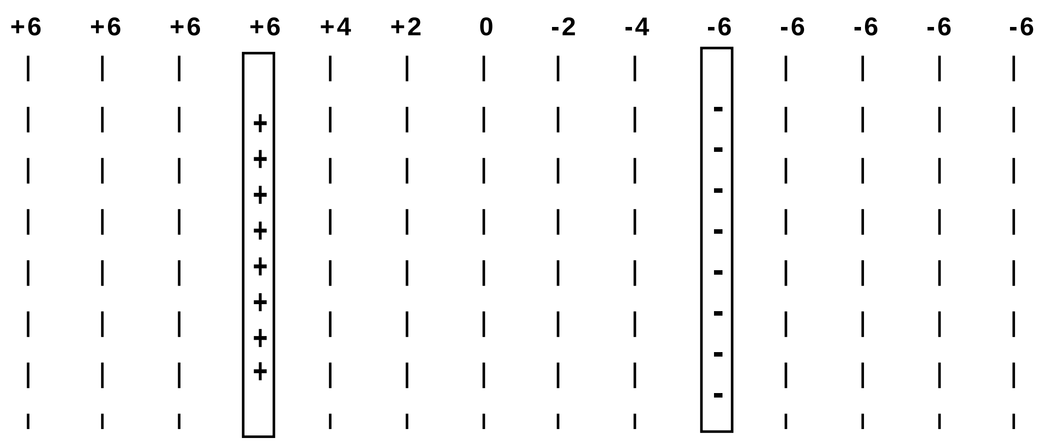


Figure 9.8c
ELECTRIC POTENTIAL OF A CAPACITOR WITH THIN PLATES

9.9 Exercise: Adding electric potentials

For each of the following questions, look at the values for the electric potential due to the arrangement of charged plates in Figure 9.8c.

1. When both plates are present, explain why the value of the electric potential is:

    a) positive on the far left and negative on the far right.

    b) the same at all points to the left of both plates; the same at all points to the right of both plates

2. Explain why the value of the electric potential in Figure 9.8c:

    a) changes from position to position in the region between the plates.

    b) changes at double the rate compared to when only the positive plate is present.

3. What is the potential difference between any two points along a wire that is:

    a) led in from the left and connected to the positive plate?

    b) led in from the right and connected to the negative plate?

4. In question 3, what would be the value of the electric potential in the wire connected to:

    a) the positive plate?

    b) the negative plate?

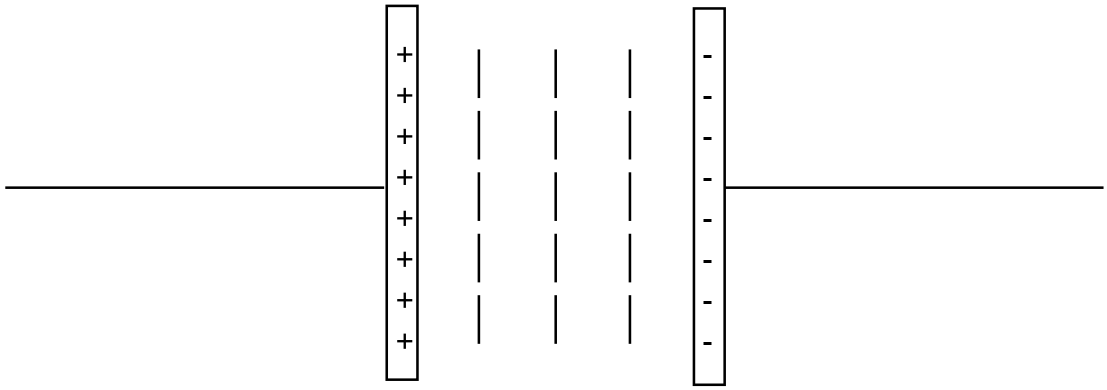
5. In question 3, would charge flow, or would there be no flow, in:

    a) the wire connected to left hand plate? Explain why.

    b) the wire connected to right hand plate? Explain why.

9.10 Activity: Verifying the quantitative features of the model

1. Use the same coloring scheme for electric potential that we have been using for electric pressure -- to color code the capacitor plates and wires in Figure 9.10.



2. Color the dashed lines -- representing planes of uniform potential -- in the space between the plates.

3. Does the coloring you have done describe what you already knew to be true about a charged capacitor and wires connected to it? Explain.

4. Refer to the two quantitative features suggested in Commentary 9.8. Are they supported by evidence from prior investigations?

INVESTIGATION FOUR: HOW DO HALOS MAKE POINT PARTICLES MOVE?

9.11 Commentary: Electrical pushing and pulling

1. Your teacher will provide materials to be used in investigating how insulators with excess (+) and (-) charge push on each other. Describe how you were able to make some materials attract and / or repel each other.

2. On the diagrams in Figures 9.11a and 9.11b, draw arrows to show the directions that the (+) and (-) particles (small circles) are being pushed by the charged capacitor plates.

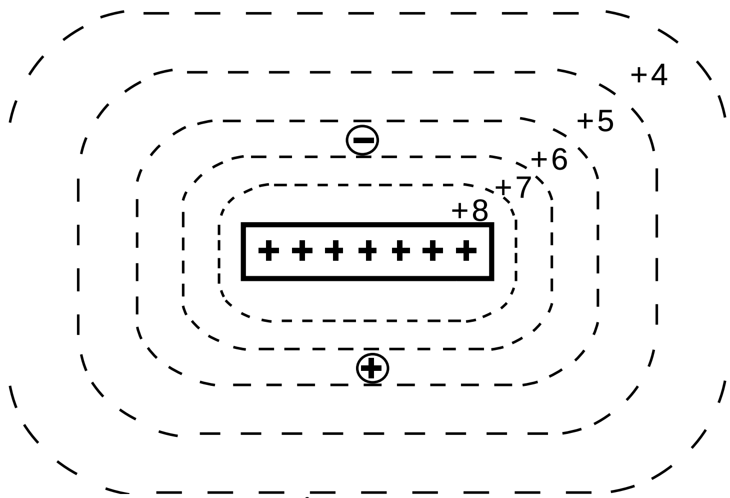


Figure 9.11a
(+) and (-) particles in the halo of a (+) capacitor plate

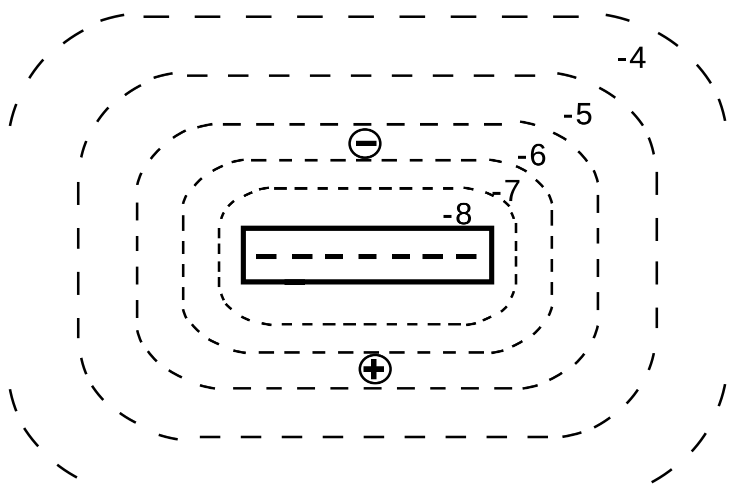


Figure 9.11b
(+) and (-) particles in the halo of a (-) capacitor plate

3. Is the above description of how charges act on each other equivalent to pressure halos pushing (+) particles from HIGH to LOW potential and pushing (-) particles from LOW to HIGH potential? Explain.

Two ways to describe electrical pushing

The arrows you placed in the halos in Figures 9.11a and 9.11b show that repulsion of like charges and attraction of unlike charges provide a different description of halos pushing (+) charge HIGH—>LOW and pushing (-) charge LOW—>HIGH.

These two descriptions are completely equivalent, but sometimes one is more useful than the other. The only criterion for which one you should use is usefulness.

9.12 Activity: Electrical pushing and "polarization"

To test the idea of electrical pushing, set up the components of Figure 9.12. A metal pie plate is supported on a foam cup to insulate it electrically from the table. Individual pieces of tinsel are taped in contact with the metal pie plate.

Predict what you will observe when you bring a charged acrylic plate near the pie plan on the opposite side from the tinsel.

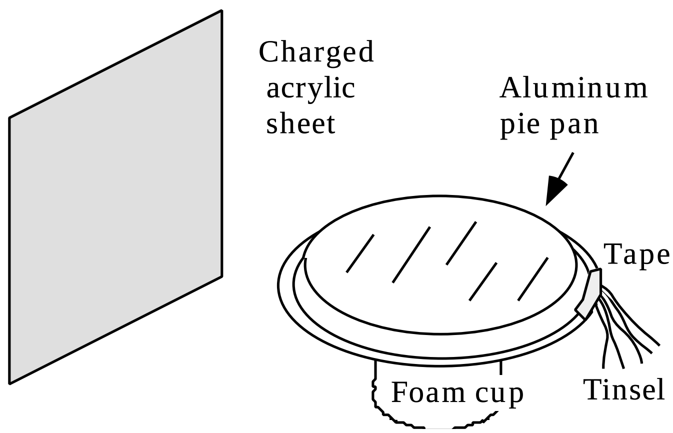


Figure 9.12
TINSEL ATTACHED TO PIE PLATE

Prediction:

1. Charge the acrylic sheet by rubbing it with a foam pie plate. Bring the acrylic sheet near the aluminum pie pan. What do you observe?

2. Explain your observations in terms of
   a) attraction and repulsion of charges:

   b) pushing as a result of an electric pressure halo:

3. Generally, the tinsel will spread out and stand away from the metal pie pan. Why does this occur?

4. On Figure 9.12, draw the concentrations of (+) and (-) charge.

Cutting each strip of tinsel into narrower strips would show that the smaller amounts of charge on these also repel each other. This suggests that the effects we have just observed exist even for extremely small amounts of charge in bits of matter too small to see. So it seems reasonable to assume that all carriers of like charge repel each other — even particles as tiny as those in atoms.

Do all carriers of unlike charge also attract each other — even the tiny particles in atoms? Evidence for the answer “Yes” is provided by the fact that matter does not fly apart due to repulsions by the like-charged particles in it. Evidently, attractive forces by unlike charges are able to hold the positive and negative charge together. The result is complete cancellation of powerful repulsions and attractions — with matter under normal circumstances showing no net electrical effects at all.

5. The noun “polarization” is used to describe a condition in matter where there is a spatial separation of (+) and (-) charges. The verb “to polarize” is used to describe an action that causes polarization. Is there polarization in the pie plate in Figure 9.12? Does the excess (+) charge on the acrylic polarize the pie plate? Explain.

9.13 Activity: Experiments with a versorium

A simple device known historically as a versorium can provide insight into the interaction between an uncharged and a charged object.

To make your own versorium, cut a rectangular piece of aluminum foil about 2 cm by 8 cm. Fold the rectangle in half along its long axis, and again along its short axis. Then open it into a "tent" shape, as shown at the top of Figure 9.13.

Take a foam cup, stick a sharp pencil outward through its bottom, and set the cup down on its rim with the pencil point up in the air. Balance the creased foil tent on the pencil point, as shown in Figure 9.13 .

1. You will bring a charged plate near the versorium. Predict what you will observe.

Prediction:

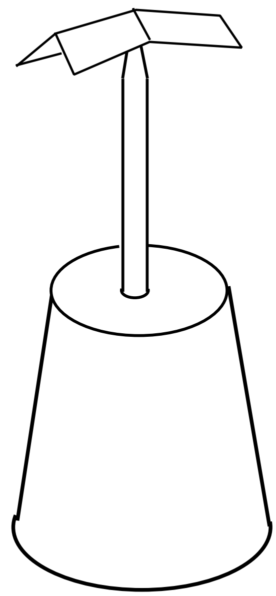


Figure 9.13
THE VERSORIUM

1. Rub an acrylic plate with a foam plate, and bring the acrylic plate near the foil level with the top of the versorium. Then move the acrylic in a horizontal arc around the foil. What do you observe?

2. An uncharged object with its (+) and (-) charges separated is said to be polarized. Does the aluminum foil become polarized? Explain.

3. Predict how the movement of the aluminum foil will be similar or different if you bring the foam plate near the versorium, instead of the acrylic plate. Then try it.

Prediction:

4. Is the piece of aluminum again polarized when you bring the foam plate near the versorium? Is there be any difference in the polarization? Explain.

5. Next, replace the metal foil “tent” with a paper “tent” resting on the pencil point. Predict what you think will happen when you bring the charged acrylic near the “tent”.

Prediction:

6. Observe what happens when you bring the (+) acrylic plate, and then the (-) foam plate near the “tent”. Why does this occur? Write a hypothesis consistent with your observations.

9.14 Commentary: Polarization of atoms

In the experiment you have just done, you may have been surprised to observe the rectangle of paper (an insulator) rotate and “point” toward the charged acrylic or foam, just like the rectangle of conducting foil did. What is going on in the paper – which is supposed to prevent charge from moving?

Certainly, charge can’t be pushed all the way through the paper to collect at one end or another. But what if an atom is a system with a (+) ion and (-) electrons that are held together by the attraction of opposite charges? What if the halos around acrylic and foam can polarize the atoms in the paper? You would then have electrons being pushed to one side of an atom -- a much shorter distance than through a piece of paper.

If atoms in the paper rectangle become polarized, then attractions and repulsions of the (+) and (-) parts of the atoms could be what’s causing the paper rectangle to rotate and “point”. The forces causing rotation may be weaker for each atom than for the metal rectangle that you used earlier in the versorium – but there are a lot of polarized atoms in the paper, compared to only one polarized metal rectangle.

The versorium experiment with the paper rectangle provides evidence that atoms are not rigid structures. The evidence is that electrons are able to move around in atoms – providing a basis for external influences being able to polarize the atoms.

SUMMARY EXERCISE

1. Using the circuit in Activity 9.1, explain why the idea that electric pressure behaves exactly like air pressure fails to correctly predict what happens in these circuits.

2. What are the essential features of the “pressure halo” or “electric potential halo” idea?

3. Describe the evidence in this section which can be cited to support the existence of two kinds of charge.

4. Explain why this section might be titled “Distant Action”?

5. Use the versorium activity to describe similarities and differences between conductors and insulators.

Section 10

HOW DO SEMICONDUCTORS WORK?
WHAT IS AC?

INTRODUCTION

In this section you will investigate the properties of semiconductor devices called "diodes". You will then learn about alternating current (AC), and how to use a diode and a capacitor to convert it to direct current (DC). Finally, you will use a semiconductor device called a "transistor" as an electronic switch that permits potential differences in the space surrounding charged objects to turn light bulbs on and off.

10.1 Commentary: What are semiconductors?

To be a conductor or not to be a conductor — that is the question!

In semiconductors the presence or absence of mobile charge carriers is <u>controllable.</u> In addition, devices made of semiconducting materials behave like <u>valves</u> that can turn the flow of mobile charge on and off. Most of these devices are made of silicon. Pure silicon is an insulator, but with the addition of small and carefully controlled amounts of impurities it becomes a semiconductor.

<u>INVESTIGATION ONE: HOW ARE DIODES USED IN CIRCUITS?</u>

10.2 Activity: Investigating diodes

1. Test a diode using the circuit below to find its conduction properties. Write your observations.

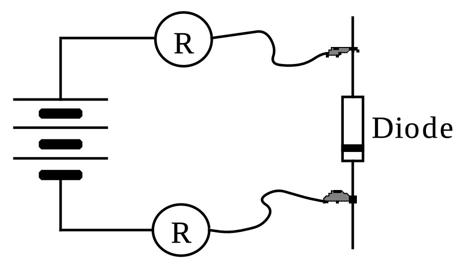


Figure 10.1
DIODE TESTING

2. Notice that one end of the diode is marked with a painted band. Is the diode a conductor when it is connected so that the band is placed

a) away from the positive terminal of the battery? __________

b) toward the positive terminal of the battery? __________

3. Sketch a picture of the diode, showing the band. Use an arrow to show the direction in which the diode will allow conventional charge flow.

10.3 Commentary: The diode symbol

The symbol used to represent a diode in a circuit diagram is shown below. The arrow points in the direction of conventional charge flow. The single vertical line represents the end with the band.

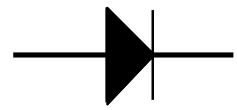


Figure 10.2
DIODE SYMBOL

10.4 Commentary: How does a diode work?

Let's now try to understand why a diode is a conductor in only one direction — a one-way valve. Pure crystals of silicon are insulators because the charge in them is not mobile. Mobile charge is due to impurities; it can be either positive or negative, depending upon the specific kind of impurity added to the silicon. Semiconductors are named by the type of mobile charge present:

"P-type" semiconductors have positive mobile charge.
"N-type" semiconductors have negative mobile charge.

The negative charge carriers are "electrons" and the positive mobile charge carriers are called "holes". A diode is formed when a "P" region and an "N" region are joined together in the same silicon crystal.

Figure 10.4 shows such a diode in two different circumstances. In both situations the metal electrodes that are bonded to the ends of the silicon are connected through light bulbs to a battery. The two situations differ only in the orientation of the battery, but the consequences are drastically different.

In the situation labeled "forward bias", the pressure difference established in the metal electrodes by battery action pushes the (+) mobile carriers to the right through the boundary and pulls the (-) mobile carriers to the left through the boundary. So both types of charge carrier are flowing through the diode.

In the situation labeled "reverse bias", the (+) carriers in the P-type material are pulled to the left and the (-) carriers in the N-type material are pulled to the right — leaving a zone in the middle of the diode that has been substantially emptied of the charge carriers that are required for conduction. This zone is shown in white in the right hand diagram. The absence of charge carriers makes the zone an insulator which prevents flow in a reverse biased diode.

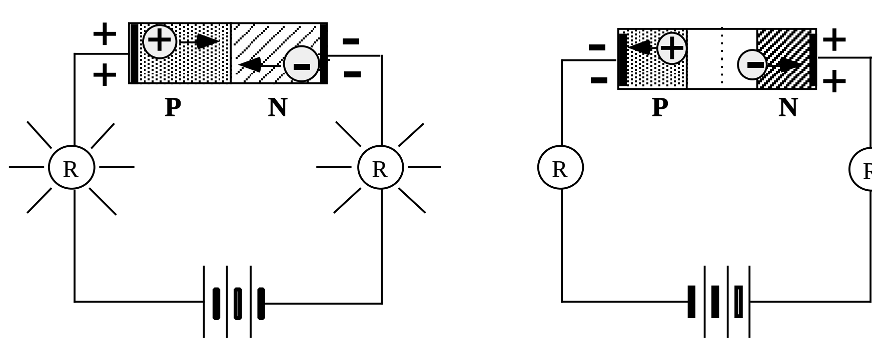


Figure 10.4
DIODE WITH FORWARD BIAS **DIODE WITH REVERSE BIAS**

10.5 Activity: Charging the capacitor through diodes and bulbs

A good way to investigate diodes in action is to use two of them in the charging and discharging of a capacitor. What do you think will happen when the circuit below is used for charging and discharging the capacitor? In assembling this circuit, make sure the diodes are connected so that one of them has the painted band at the end near its bulb and the other has the painted band at the end away from its bulb.

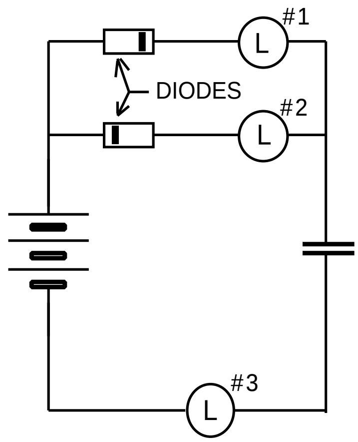


Figure 10.5a
CHARGING THE CAPACITOR

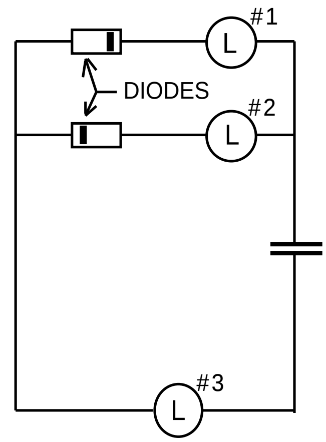


Figure 10.5b
DISCHARGING THE CAPACITOR

Charge the blue capacitor using the circuit in Figure 10.5a, and then discharge by removing the battery and connecting the free ends of the wires as in Figure 10.5b. Watch carefully how the bulbs light.

1. What happened? Which bulbs lit during each process?

2. How do you think the diodes are affecting the flow of charge in the circuit?

3. A diode sometimes acts as a conductor and sometimes as an insulator. What do you think determines when the diode conducts and when it does not?

4. What does the painted band indicate about charge flow ?

10.6 Activity: How diodes are used to convert AC to DC

Batteries produce a constant pressure difference which causes charge to flow in one direction. We call this flow **DIRECT CURRENT** — or often just **DC**. Power companies have found that it is easier and cheaper to generate and transmit **ALTERNATING CURRENT** — often just called **AC**. The direction of charge flow in an AC circuit is continually reversing — caused by a continually reversing potential difference at the terminals of the AC generator. North America uses "60 cycle" AC generators, which means that the flow is driven forward 60 times and backward 60 times each second. A Genecon can be used to drive alternating current, but at a much lower frequency.

Connect the two-color light emitting diode (LED) to the Genecon as shown in Figure 10.6a below. Turn the handle back and forth about 90° once each second. Be gentle so that you do not damage the plastic gears.

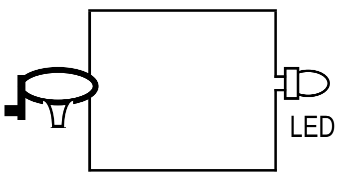


Figure 10.6a
GENECON WITH LED

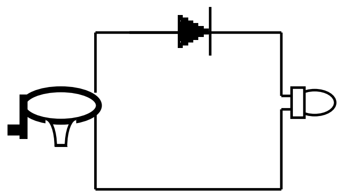


Figure 10.6b
WITH DIODE ADDED

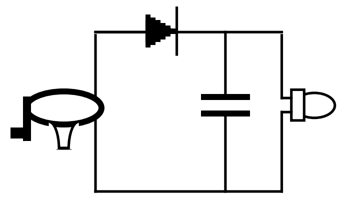


Figure 10.6c
WITH CAPACITOR ADDED

1. Observe the LED as the handle is turned back and forth. Record your observations.

2. Add the diode as shown in Figure 10.6b, and observe the LED as the handle moves in both directions.

3. Connect the blue capacitor as shown in Figure 10.6c and record your observations.

10.7 Exercise: Graphing AC line voltage

Figure 10.7a below shows how the voltage supplied by the power company's AC generator varies with time, reversing direction (forward and backward) to produce 60 complete cycles or waves each second.

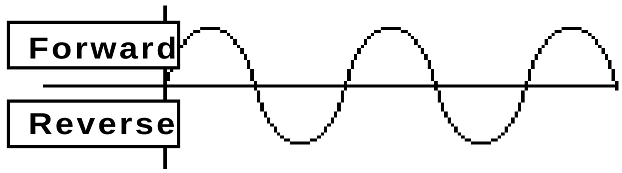


Figure 10.7a
AC LINE VOLTAGE

1. In Figure 10.7b, sketch over the dotted lines for AC line voltage to describe the voltage across the LED for a rectifier circuit like that shown in Figure 10.6b with one diode and no capacitor.

2. In Figure 10.7c, sketch the voltage across the LED for a rectifier circuit like that shown in Figure 10.6c with a diode and a capacitor added to "fill in the gaps".

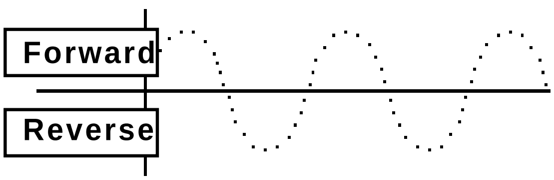


Figure 10.7b

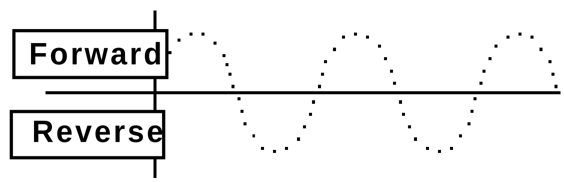


Figure 10.7c

Many types of electronic equipment – from radios to computers – require direct current to operate correctly. With 60 cycle current the gaps are very short, and the charging and discharging of the capacitor can fill the gaps to give very smooth DC current — which allows the equipment to be run from the AC power. This avoids the need for expensive batteries as a DC source.

INVESTIGATION TWO: HOW ARE TRANSISTORS USED IN CIRCUITS?

10.8 Commentary: What are transistors?

In the world of electricity where wires act like pipes, batteries are pumps and capacitors are tanks, semiconductors act like a valve. A diode is a one-way valve that allows charge to flow one way but not the other; in effect it is either 'on' or 'off'. A more complicated semiconductor device called a "transistor" is a valve that can be controlled gradually like a kitchen faucet. It is this faucet-valve action that makes semiconductors so important to electronic devices.

Transistors are semiconductor devices that have three terminals. Two of the terminals are just entrance and exit ports for a stream of charge carriers moving in an electric circuit. The third terminal is like the faucet handle that turns the stream on / off by means of HIGH / LOW electric pressure due to some kind of activity in a separate circuit. The terminal that brings conventional charge flow into a field effect transistor is called the DRAIN. The outflow terminal is called the SOURCE. (If it seems like the names DRAIN and SOURCE are backwards, you are right! They were named in reference to electron flow. Remember that any circuit can be analyzed in terms of either conventional flow or electron flow, but the results will be the same in either case.

10.9 Activity: The metal-oxide-semiconductor field effect transistor (MOSFET)

WARNING!!! A field effect transistor (FET) of the metal-oxide-semiconductor (MOS) variety used in this activity is easily damaged by static electricity. It is packed with a piece of conducting foam placed over the leads to protect the device by keeping all three terminals at the same electric pressure. A few extra precautions will help protect the device during this activity:

1. Do not touch the Gate unless you are also touching some other part of the circuit.

2. Connect the Gate to the Source when it is not in use. (Use a wire to do this.)

3. Place the conducting foam back over the leads after the activity is finished.

Connect the circuit as shown in Figure 10.9. Check the diagram on the package to be sure that the wires are connected to the correct terminals of the transistor.

Remember to keep the Gate connected to the Source until the entire circuit is wired.

Remove the protective connecting wire only when you are ready to experiment. At the moment you remove this wire, the electric pressure in the Gate will be the same as in the Source.

The light bulbs should be off, showing that the transistor is preventing flow from the Drain to the Source. Now let's see if we can turn the flow on. With one hand holding the +9 volt point on the second battery, touch a finger of your other hand to the Gate terminal of the transistor. A 9 volt pressure difference will then drive a small amount of extra charge through your body and into the Gate. (You have become part of the separate circuit controlling the Gate.) Somehow, the presence of this extra charge in the Gate turns on the flow from the Drain to the Source.

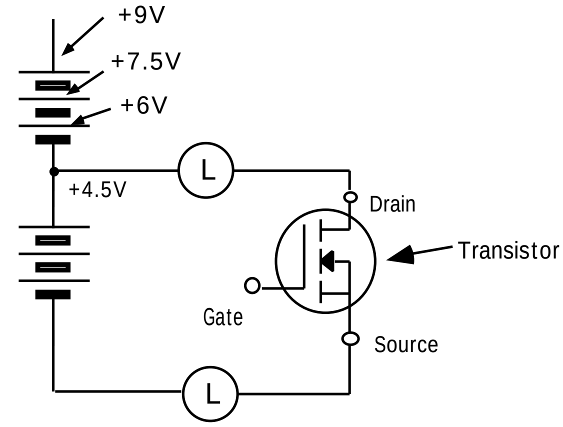


Figure 10.9
TRANSISTOR CIRCUIT

1. What is the evidence that flow is now taking place from the Drain to the Source?

2. What is the evidence that extra charge in the Gate made this happen?

3. Does the extra charge stay in the Gate when you remove your finger? What's the evidence?

4. Can you devise a way to turn the bulbs off? Why do you think this works?

5. A faucet can be opened part way. Can the transistor Gate turn the Drain-to-Source flow part-way on? Try doing this by connecting the Gate to the 4.5-volt point, then the 6.0 and then the 7.5-volt points in the second battery and observing the brightness of the light bulbs. A paper clip can be used as a probe to reach into the contact points in the second battery holder; hold the paper clip in one hand and touch the Gate with the other. What do you observe?

6. Does the experiment you have just performed reveal a limit to how bright the lamps can become as the Gate is raised to higher electric pressure relative to the Source? What is the evidence? Explain your result.

10.10 Commentary: What is going on inside the MOSFET?

How does the presence of extra charge in the transistor Gate make Drain-to-Source flow possible? To find the answer, we must know something about the architecture of the transistor.

The use of metal-oxide-semiconductor (MOS) technology to make a field effect transistor (FET) begins with a small slab of P-type silicon. As illustrated in the diagram in Figure 10.10b, two puddles of N-type material are diffused onto the left side of the slab to form the "Drain" and "Source" terminals. A very thin insulating layer of silicon dioxide (shown in white) is formed over these terminals, and a conducting layer (shown in black) is added by layering aluminum over the silicon dioxide. The aluminum layer is the "Gate" that turns the flow from Drain to Source on and off.

Remember from our investigation of diodes that charge cannot flow from N-type into P-type material. So there is no flow from the Drain to the Source as long as the N-type Drain and Source areas are separated by the P-type slab.

Flow will occur, however, if the extra charge in the Gate creates an N-type channel through the P-type slab — a channel that extends from the Drain to the Source as shown in Figure 10.10c. That is exactly what happens if there is sufficient positive charge on the Gate to give it a HIGH electric pressure.

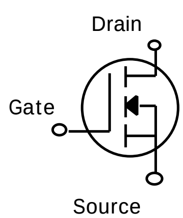


Figure 10.10a
MOSFET SYMBOL

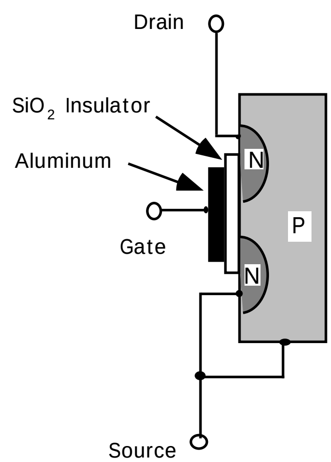


Figure 10.10b
NONCONDUCTING

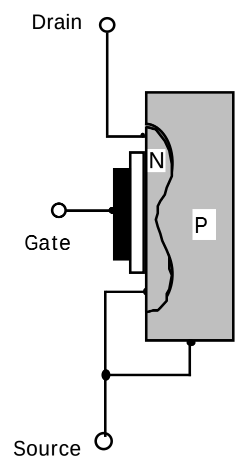


Figure 10.10c
CONDUCTING

When extra positive charge is present in the aluminum layer that forms the Gate, that layer will be surrounded by a halo of high electric pressure (electric potential). This halo will increase the actual pressure in the portion of the P-type slab situated just the other side of the insulating layer — because that part of the slab now finds itself inside the potential halo. The positive charge carriers that normally inhabit the P-region will then be pushed away from the Gate, and negative carriers will be pulled in from the two N-regions. These shifts of mobile charge will expand the two N-regions and make their edges move closer to each other.

When the edges meet, a thin channel of N-type material is opened next to the insulating layer of silicon dioxide as shown in Figure 10.10c. Charge can now flow through this channel from the Drain to the Source without crossing a boundary between N-type and P-type material. Just as the handle of a kitchen faucet controls the rate of flow of water by changing the size of the channel through which the water flows, so the potential halo surrounding the transistor Gate controls the rate of flow of charge by changing the size of the N-type channel through which the charge flows.

Since the Gate is insulated from the rest of the transistor, no current flows from the Gate lead once it is charged. MOSFET functioning depends crucially on this insulating layer being very thin, so that the potential pressure halo around the Gate can strongly influence the semiconductor on the other side of the insulator. But that makes the insulating layer easily damaged by the static electricity which creates very large potential differences as a person walks across a rug or slides on a plastic chair. When you touch the Gate lead without grounding yourself you may cause a spark to jump through this layer and form a conducting path through it. In electronics factories, workers who handle MOSFETs are required to wear a grounding strap on their wrist.

10.11 Exercise: Analyzing the MOSFET

1. Look at Figures 10.10b and 10.10c. Based on these illustrations, why does extra charge sent into the Gate stay there until something is done from the outside to get it out?

2. Again, study Figures 10.10b and 10.10c. Does the extra charge in the Gate influence the Drain-to-Source region directly or indirectly?

10.12 Activity: The magic wand

Your “magic wand” in this Activity will be an acrylic plate that has been charged (+) by rubbing it on a foam plate. You can turn the light bulbs on or off by waving this wand toward or away from the metal “detector” to which the Gate will be connected. You can make the performance more dramatic by saying a few magic words like “VOLTS! COULOMBS! AMPERES!” as you wave the wand.

Connect a large piece of metal to the Gate of your FET circuit — a soft drink can or a weight-hanger — to serve as a reservoir of mobile charge that can be driven into the Gate. Remember to discharge any static electricity from the reservoir before connecting it to the Gate of the transistor. This reservoir will be the detector (antenna) when you wave the wand. It must be carefully insulated from the rest of the circuit. A good way to do that is to place it on a glass beaker. Figure 10.12 shows a weight-hanger detector on top of an inverted glass beaker. (If you use a soda can as the detector/antenna, clip the lead from the Gate to the pop-top.)

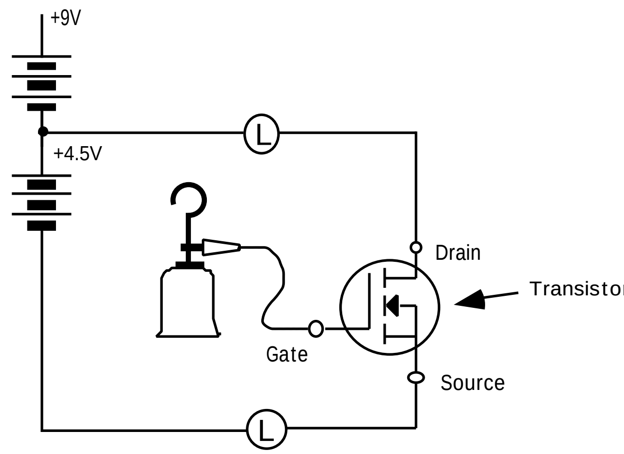


Figure 10.12
MAGIC WAND CIRCUIT AND DETECTOR

Check that the light bulbs can still be turned on by touching the 9-volt terminal of the second battery pack with one hand and touching the weight hanger with the other; and that it can be turned off by contacting the 4.5-volt terminal or the Source.

1. Turn the light bulbs on. What do you know about the charge on the gate and the condition of the internal P-type and N-type semiconductors?

If an object with negative charge is brought near the weight hanger, it will attract the positive charge away from the Gate, reducing the electric potential halo around the Gate, and the lights will go out. We found in Section 9 that rubbing an acrylic plate on a foam plate leaves the acrylic with excess positive charge and the foam with excess negative charge.

2. Rub an acrylic plate and foam plate together vigorously. What is the effect on the light bulbs as you move the foam plate toward the detector?

3. Note that the electric pressure in the antenna is lowered just because there is a negative charge in the nearby space. This is occurring <u>without touching</u>. How far away can you make this action-at-a-distance work?

4. Try other charged 'magic wands'. Rub other substances together to charge them, such as silk, acrylic, glass, plastic wrap, and overhead transparency. Or comb your hair vigorously to charge the comb. Then use the magic wand circuit to determine what charge is on each object.

Once you have demonstrated that negatively charged objects can be used to turn the light bulbs off, you should experiment with positively charged objects to turn them on. First turn the bulbs off by touching the 4.5-volt terminal and the weight-hanger detector at the same time. (Be careful that all charged objects are a long way away.) Now any nearby object that is positively charged will increase the electric pressure in the weight hanger and drive positive charge into the gate of the transistor. The potential halo of the extra charge in the gate will then open a conducting channel from the Drain to the Source — and turn the lamps on.

10.13 Activity: The potential halo of two objects

1. Touch the 4.5-volt point and the Gate to turn the bulbs off. Rub the foam and acrylic plates to charge them. Bring the positive acrylic close to the detector until the lamps are nearly full brightness. Speculate what will happen if you hold the acrylic in place and bring the foam plate up from the other side of the circuit — so that its LOW potential halo is added to the HIGH potential halo of the acrylic? What do the bulbs do when you try this?

2. Hold the charged foam and acrylic plates about 40 cm apart and parallel to each other — like the plates of a large charged capacitor — with the detector between them. Move them left and right, together as a unit, and observe how the potential varies in the space between the plates according to how the bulbs change brightness. Based on your observations, which plate is positive?

SUMMARY EXERCISE

1. How does a diode control charge flow in a circuit?

2. Explain these useful applications of diodes:
   a) How can diodes be used to convert AC to DC?

   b) How can a capacitor be used to smooth pulsating DC from the diode in an AC circuit?

3. Consider the role of electric potential in the operation of a field effect transistor:
   a) Explain the operation of an N-channel FET in terms of the electric potential caused by charge on the Gate terminal.

   b) How would a P-channel FET work?

4. How may a MOSFET be used to detect potential differences in the space outside charged objects?

5. A diode only allows current to flow through in one direction.
   a. In a diode, does charge flow as conventional current, as electron flow, or some other current? Explain carefully.

   b. Why can't current flow through in the opposite direction in a diode?