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 will investigate the non-battery causes of charge movement in circuits.

INVESTIGATION ONE: WHAT HAPPENS WHILE A CAPACITOR CHARGES?

4.1 Activity: Experimenting with an already-charged capacitor

Charge a 25,000 μf capacitor through two long bulbs, using a 3-cell battery as shown in Figure 4.1a. **Use a compass under one of the wires to monitor direction of flow.**

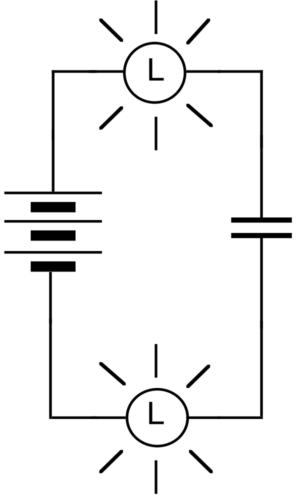


Figure 4.1a
CHARGING

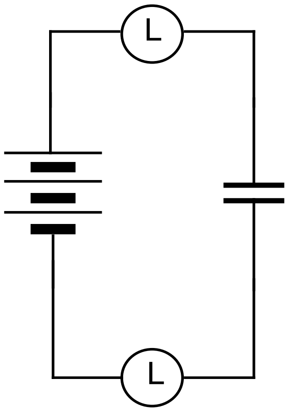


Figure 4.1b
CHARGING COMPLETED

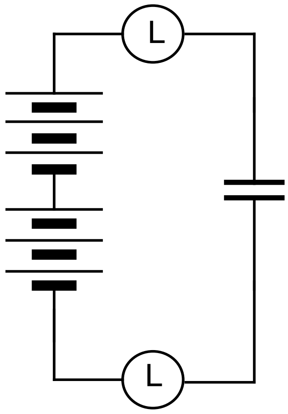


Figure 4.1c
ADDED BATTERY

1. Draw arrows on Figure 4.1a to show charge flow in all parts of the circuit while the bulbs are lit. Don't attempt to use arrowtails to show flow rate – just show directions.

2. Figure 4.1b 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 4.1c. 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 4.1c, 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 4.1c to show the direction charge was moving everywhere during the second bulb lighting.

5. Did more 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. Regarding both the bulbs and the compass, what did you observe? Explain why this happened.

Demonstration:

The teacher will now charge a capacitor with one battery pack as in Figure 4.1a, then add a second pack as in Figure 4.1c, 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?

4.2 Activity: Exploring air as an analogy

In Section 3 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 4.2a 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.

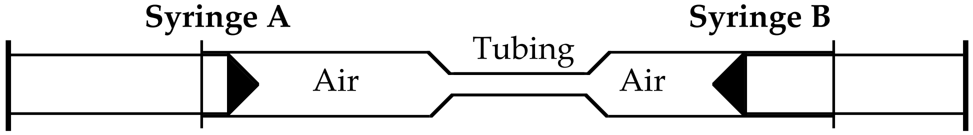


Figure 4.2a
SYRINGES CONTAINING AIR CONNECTED BY TUBING

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?

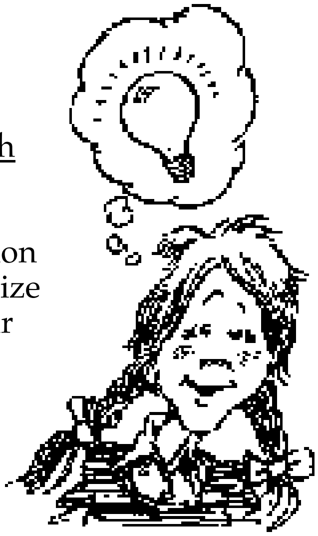
5. Let go of syringe A's plunger, and describe what happens. Then start over and let go of syringe B's plunger. Describe what occurs.

6. Using the connected syringes, air provides a model for explaining the observed electrical behavior in the circuit of Figure 4.1c. What are a) the advantages, and b) the limitations of this model?

4.3 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 trying to expand. The evidence for trying-to-expand was clear: When you released plunger A, you saw it being pushed back out by the compressed air.

Increased concentration – 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 adding more air in a given volume. You are creating the same basis for trying-to-expand. The proof is that the extra air will expand out through any hole 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 part 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 no matter how you make it more concentrated. The term "compressed air" is generally used for all trying-to-expand situations.

4.4 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.

4.5 Commentary: Is the air analogy really right?

Thinking about "electric pressure" in a container of charge as being like "air pressure" in a container of air helps you keep in mind that charge always tries to move from a place of higher electric pressure to a place of lower electric pressure. It reminds you that this movement continues until the pressures are equalized. The same idea that helps you understand when and where air moves will also help you predict when and where charge moves.

Nevertheless, we shouldn't expect charge to behave like air in absolutely every respect. We will use the term "pressure" to emphasize that compressed charge behaves like compressed air in important respects. But we will add the qualifier "electric" as a reminder that differences of behavior may exist in circumstances that we have not yet encountered.

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

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

Suppose a battery moves charge internally as depicted in Figure 4.6a – out of its bottom terminal and into its top terminal. The consequences of this movement are shown in Figure 4.6b – charge depletion (–) in the bottom battery terminal and charge compression (+) in the top terminal. Figure 4.6c shows the presence of below-normal LOW pressure in the bottom terminal (produced by depletion) and above-normal HIGH pressure in the top terminal (produced by compression).

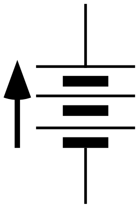


Figure 4.6a
CHARGE MOVED INTERNALLY BY THE BATTERY

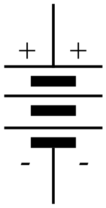


Figure 4.6b
COMPRESSION (+) IN TOP TERMINAL ALONG WITH DEPLETION (–) IN BOTTOM

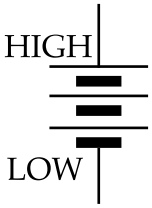


Figure 4.6c
RESULTING HIGH PRESSURE IN TOP & LOW IN BOTTOM

Figure 4.6c 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 4.6c 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.

4.7 Activity: How below-normal air pressure behaves

Figure 4.7 shows an air capacitor with both sides open to the atmosphere through a tube in each side. There is atmospheric pressure in each side, which we will call NORMAL air pressure.

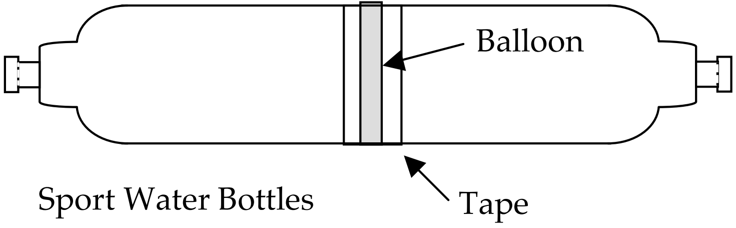


Figure 4.7
AIR CAPACITOR OPEN BEFORE INVESTIGATION

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. 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. Release both ends of the air capacitor to normal atmospheric pressure. Then place your mouth over the tube at the other side of the air capacitor and inhale; hold the depletion inside by closing the tube. Draw a new sketch of the air capacitor, and label the pressure in each side as NORMAL or HIGH or LOW. Explain why the membrane between the two sides changes shape.

4. 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?

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

Consider a battery described by the model proposed in Activity 4.6. 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 4.8.

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 4.7.

1. Set up the circuit in Figure 4.8 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?

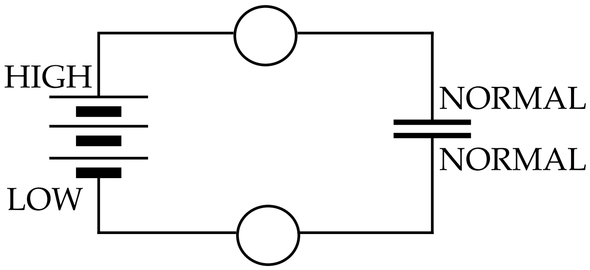


Figure 4.8
THE MOMENT CHARGING BEGINS

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 THREE: HOW CAN WE 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.

4.9 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.

4.10 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.

Whenever two or more wires touch each other, charge flow between them will equalize the pressure everywhere in the connected wires in an instantaneous transient process.

4.11 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?

4.12 Exercise: Color coding the circuit for capacitor charging

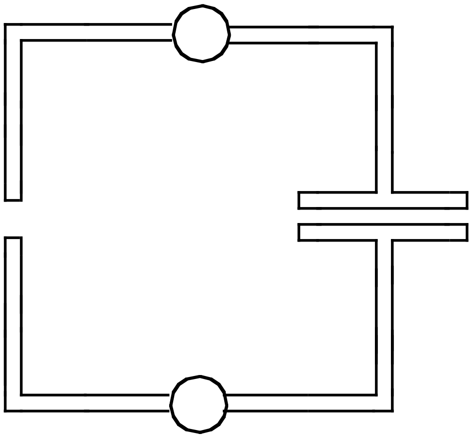


Figure 4.12a
NO BATTERY

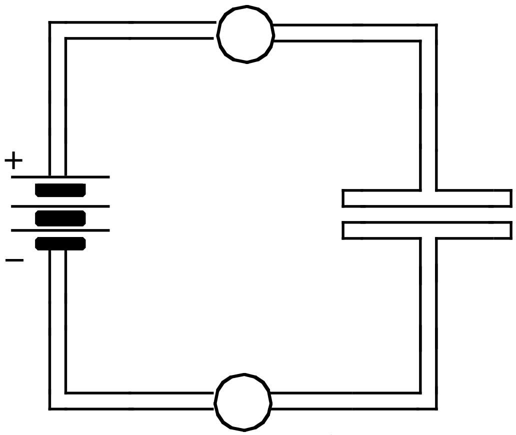


Figure 4.12b
CHARGING BEGINS

Color the battery terminals, the wires, and the capacitor plates in the diagrams in Figures 4.12a and 4.12b as you read the explanations that follow. Figure 4.12a 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; therefore the wires and plates are all colored YELLOW.

In Figure 4.12b, 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 resists 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 resists 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 drives charge through the bulb. 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 pressure difference in the wires is what drives the flow that makes the bulb lighting happen.

Figure 4.12c 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.

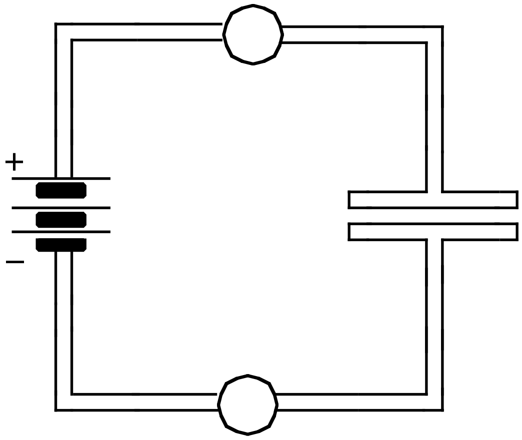


Figure 4.12c
CHARGING CONTINUES

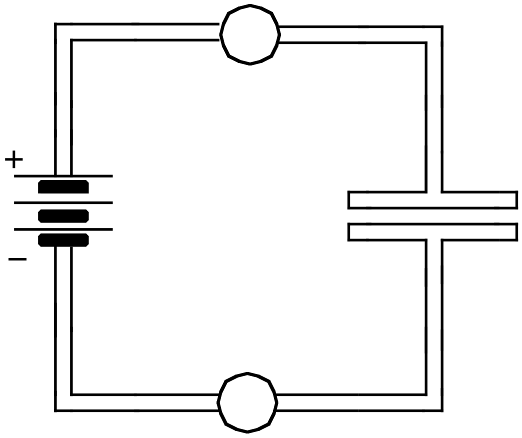


Figure 4.12d
CHARGING COMPLETED

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 4.12d, 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 <u>resist</u> flow, there is no further charge flow through the bulbs. The bulbs are not lit, and the process of capacitor charging has stopped.

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

UPPER:

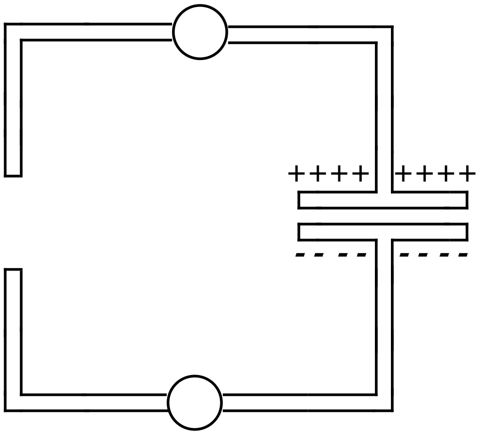
LOWER:

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

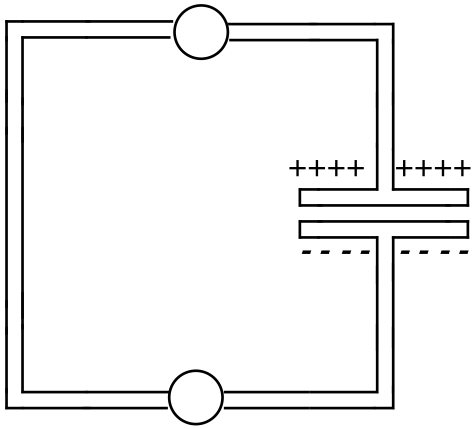
4.13 Activity: Color coding the circuit for capacitor discharging

Figures 4.13a, 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.

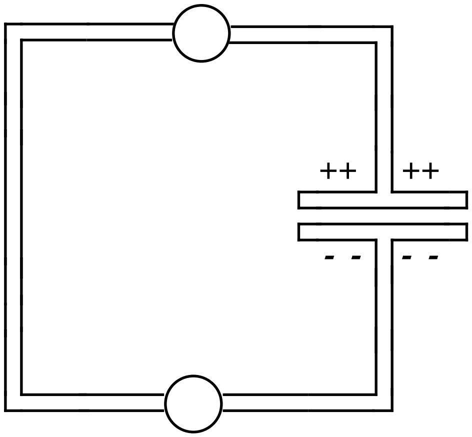
1. Draw starbursts on Figures 4.13a, b, c, d to show bulb brightnesses, and arrows to show the flow rates that cause bulb lighting. Show the distribution of pressures that make charge move by coloring capacitor plates and wires.



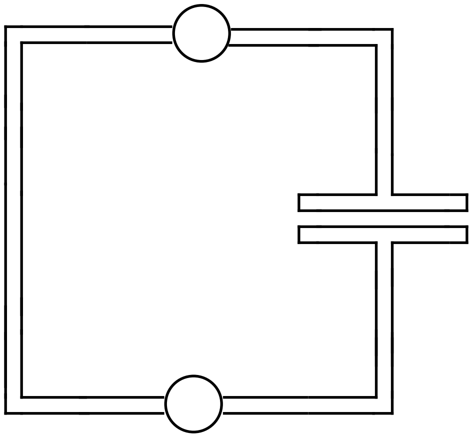
BATTERY REMOVED
Figure 4.13a



DISCHARGING BEGINS
Figure 4.13b



DISCHARGING CONTINUES
Figure 4.13c



DISCHARGING COMPLETED
Figure 4.13d

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?

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

Color each of the following circuit diagrams (Figures 4.14a through 4.14e). 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.

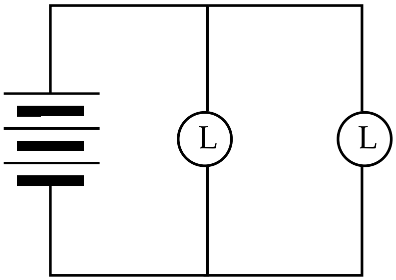


Figure 4.14a

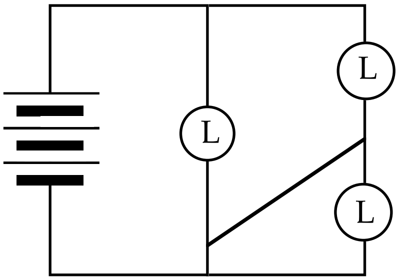


Figure 4.14b

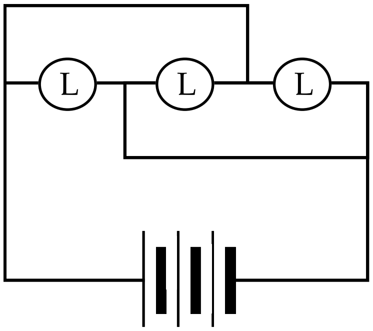


Figure 4.14c

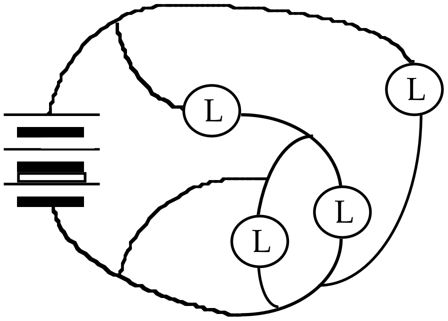


Figure 4.14d

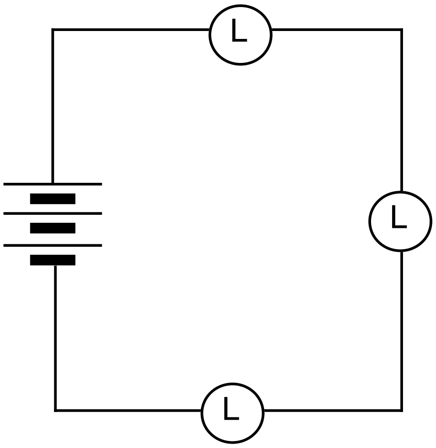


Figure 4.14e

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?