

Section 7

DOES ALL MATTER CONTAIN CHARGE? WHAT ARE ELECTRONS?

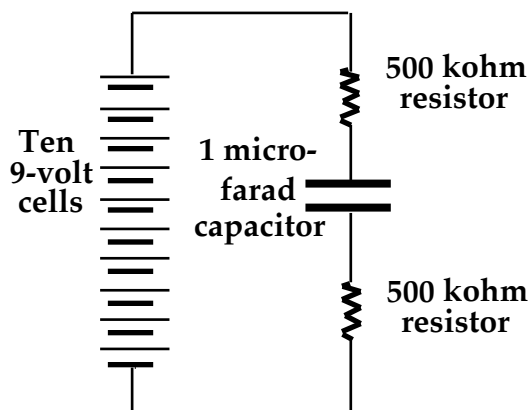
INTRODUCTION

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: A NEW BULB AND A NEW CIRCUIT

7.1 Activity: A new kind of bulb

1. Consider the following circuit (Figure 7.1a), which your teacher will assemble. This is a very familiar circuit, except that --



- the low voltage battery has been replaced by a high voltage battery (90 volts)
- the two bulbs have been replaced by resistors that will not be burned out
- the resistors have a much higher resistance than the bulbs (about 10,000 times that of a long bulb)
- the 25,000 microfarad capacitor has been replaced by a smaller 1 microfarad capacitor with a higher voltage rating

2. What will the value of the final steady voltage across the capacitor after a long time has passed.

Figure 7.1a

RESISTOR AND CAPACITOR CIRCUIT

3. Based on the relative values of the resistances and the capacitance, and comparing this circuit with your familiar circuit using two long bulbs and a 25,000 microfarad capacitor, about how long would you estimate it would take to establish this voltage?

4. Now we will modify the circuit by adding a new kind of bulb, a neon bulb, in parallel with the capacitor as in Figure 7.1b.

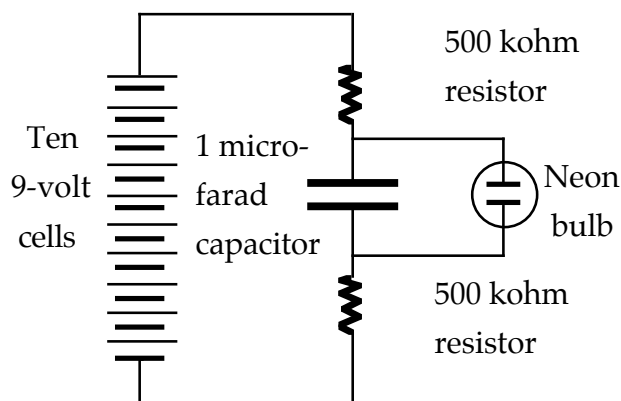


Figure 7.1b
NEON BULB ADDED TO CIRCUIT

Look closely at a neon bulb against a white background such as a piece of paper. You should see that there are two wires going into the glass bulb, and they are connected to two short metal rods with a gap between them. Inside the bulb is neon gas. This arrangement resembles a capacitor – two metal plates separated by an insulator.

Notice that this circuit is similar to the one you just analyzed. If the neon bulb behaves like an ordinary light bulb – which is a conductor – what would you expect to happen to the pressure difference across the capacitor and neon bulb after the battery is connected?

If neon behaves like a capacitor – which has an insulator between its plates – what would you expect to happen to the pressure difference across the neon bulb after the battery is connected?

Describe what you actually see happening when the battery is connected.

5. Try to predict the effect of each of the following changes.

Change #1 – Add a second identical capacitor in parallel with the existing capacitor.

Prediction:

Result:

Change #2 – To the original circuit, add a second 500 kilohm resistor in parallel with each of the original 500 kilohm resistors.

Prediction:

Result:

6. Based on the behavior of the circuit, see if you can figure out how the neon gas is behaving as the electrical pressure difference across the capacitor and neon bulb changes.

a. Is the neon gas an insulator at low pressure difference? What is your evidence?

b. Is the neon gas an insulator at high pressure difference? What is your evidence?

Try to explain the behavior of the circuit to a partner using your answers to these questions.

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

7.2 Activity: Testing neon gas at different voltages

Look again at the neon bulb. The bulb has two wires that pass through the glass – and in that respect it is like our long and round flashlight bulbs. 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 two 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 7.2.

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. 100,000 ohms (100 k-Ω) will work fine.

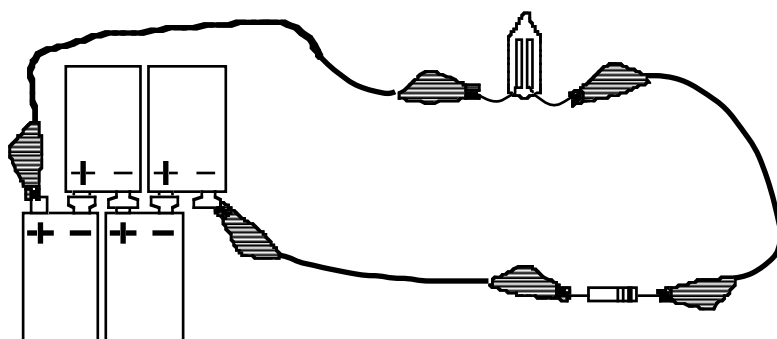
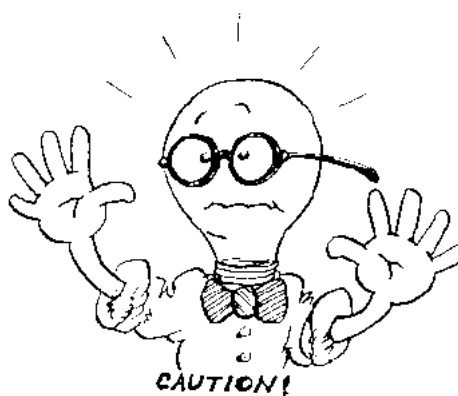


Figure 7.2
NEON BULB WITH FOUR 9-VOLT CELLS AND
A RESISTOR TO REDUCE THE FLOW RATE

1. Does the bulb glow at this pressure difference? 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?

7.3 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 electric pressure difference across it is provided by only a small number of the 9-volt cells.

But a neon bulb will glow if the electric 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 as 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 as in a metal conductor.

High voltage can make other gases glow; since different gases produce their own characteristic colors, 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 electric pressure difference in the plates will cause this insulating layer to become a conductor. The statements “MAX SURGE 25 VDC” printed on the 25,000 μf capacitor (or “MAX SURGE 12 VDC” on the 100,000 μf capacitor) tell us that the insulating layer will become a conductor if the electric 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 electric pressure difference across the insulator can break some of this charge loose from its confinement, making it able to move — just as in a conductor.

7.4 Activity: Using a neon bulb to determine the direction of flow

1. A neon bulb can be used to detect the direction of movement of charge passing through it. Refer to Figure 7.2. Note which electrode of the neon bulb glows. 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 tell the direction charge flow.



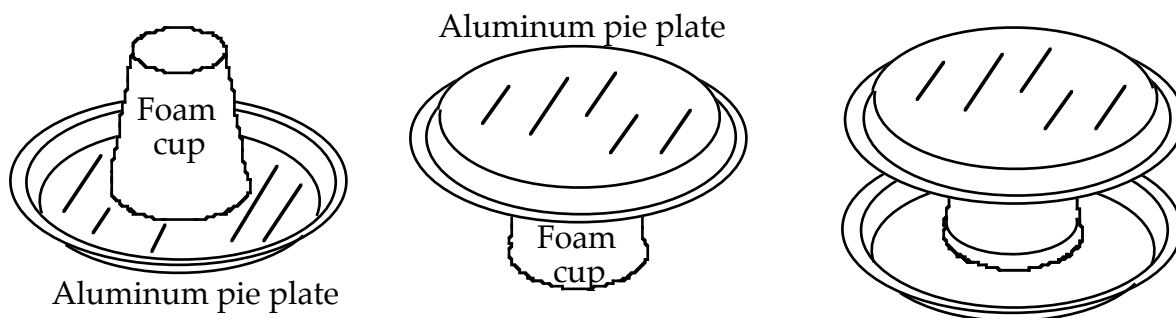
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INVESTIGATION THREE: DO SOLID INSULATORS ALSO CONTAIN CHARGE?

7.5 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 electric pressure in a capacitor plate.

Figure 7.5a 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.



BOTTOM PIE PLATE

Figure 7.5a
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 square in Figure 7.5b.

To find out if some charge is actually transferred to the acrylic by rubbing, set the rubbed acrylic down on the top capacitor plate as shown in Figure 7.5b. Use a wire to connect one neon bulb electrode to the bottom capacitor plate as shown in Figure 7.5b. Attach another wire to the other electrode in the neon bulb, but leave that wire unconnected to the top capacitor plate for the moment.

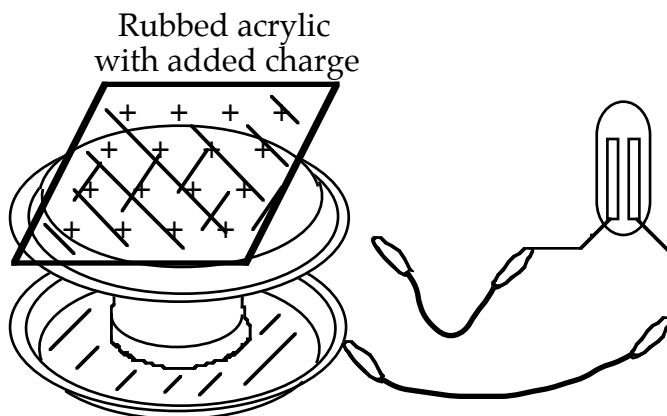


Figure 7.5b

**RUBBED ACRYLIC
RESTING ON TOP
CAPACITOR PLATE**

**NEON BULB
RESTING ON
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. 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 7.2 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.

7.6 Activity: Looking for evidence of extra charge on the rubbed acrylic

Rub the bottom of a foam plate on a piece of acrylic plastic.

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 the bulb 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 bulb glows.

If you get lost: Discharge the metal plates by connecting a wire to them. Then start over.

One partner should close the gap between the free wire and the top capacitor plate. The other partner's job is to carefully observe the electrodes, 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 then 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.

7.7 Commentary: Are there two kinds of charge in insulators?

Why is the electric 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 the opposite effects of each kind of charge 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 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.

7.8 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 7.8, and repeating the experiment that you performed earlier using the rubbed acrylic.

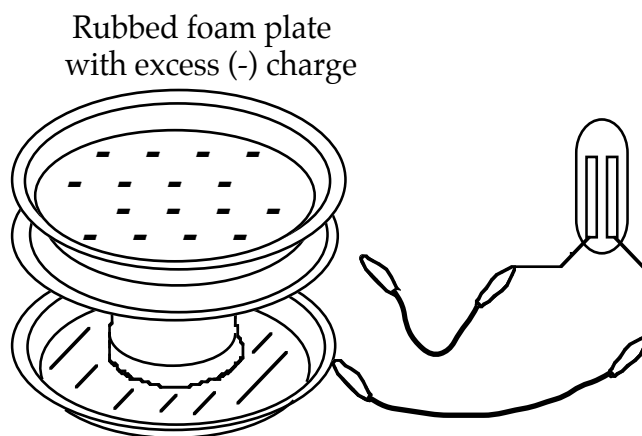


Figure 7.8

**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 7.8.

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 neon bulb lights, disconnect the top capacitor plate from the wire that leads to the bulb. Then remove the foam from the top capacitor plate. 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? Predict first, and then try it.

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 FOUR: DOES (+) OR (-) CHARGE MOVE IN CIRCUIT WIRES?

7.9 Activity: Which way would negative charge move in circuit wires?

In Figure 7.9a, the arrows show the direction mobile particles carrying positive (+) charge must move in order for a battery to charge a capacitor.

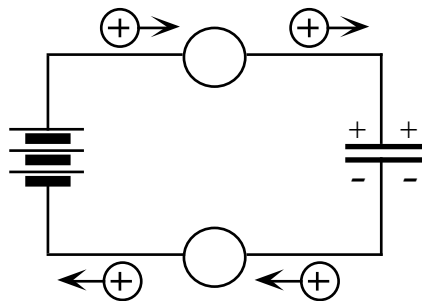


Figure 7.9a
CAPACITOR CHARGING
IF (+) CHARGE MOVES

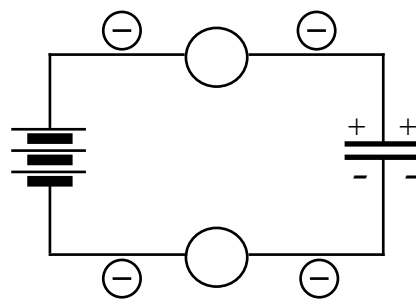


Figure 7.9b
CAPACITOR CHARGING
IF (-) CHARGE MOVES

1. On Figure 7.9b, draw arrows to show the direction hypothetical mobile particles carrying negative (-) charge must move in order to charge the capacitor (if they 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.

4. Suppose that BOTH positive and negative charge carriers can move. Describe the directions of flow of each kind of charge in this case while a capacitor is charging.



7.10 Commentary: Where mobile charge comes from in the neon bulb

How can we explain charge flow in a neon bulb in which neon is an insulator – but apparently becomes a conductor when a sufficiently large pressure difference is applied to it? The following simple model of charge in atoms can help make sense of neon bulb lighting:

- Neon (and other) atoms are made of fragments that have (+) and (-) charge.
- A large pressure difference can tear atoms apart into (+) and (-) fragments.

This tearing-apart or breaking-up process is called “ionization”.

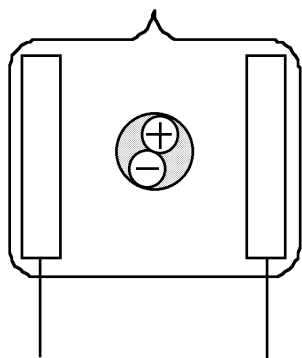


Figure 7.10a
NEON BULB
BEFORE IONIZATION:
WHOLE ATOM WITH
NO NET CHARGE

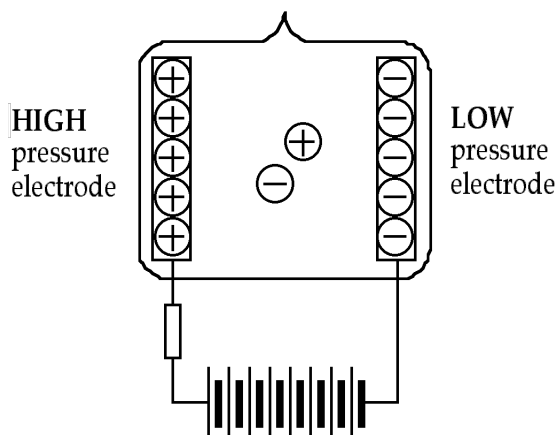


Figure 7.10b
(+) AND (-) FRAGMENTS
SEPARATED BY A LARGE
PRESSURE DIFFERENCE

7.11 Commentary: The process of light emission by a neon bulb

Suppose neon atoms are being ionized everywhere in the bulb. Figure 8.11 shows how a pressure difference in the electrodes will make (+) and (-) fragments move in opposite directions.

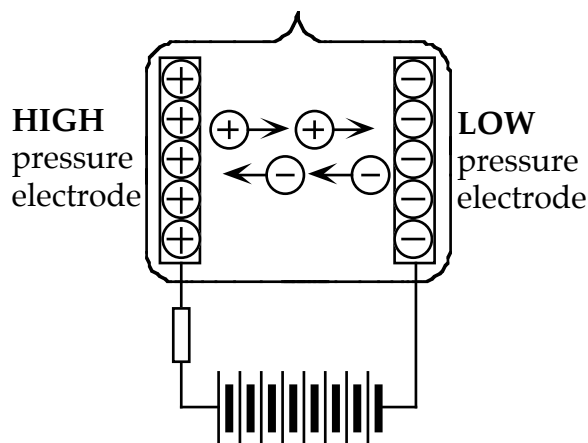


Figure 7.11
MOTION OF (+) AND (-) NEON FRAGMENTS
DUE TO ELECTRODE PRESSURE DIFFERENCE

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:

- Continual ionization of the atoms into (+) and (-) fragments.
- Continual recombination of fragments into new whole atoms.

We can characterize these as opposite energy transfer processes:

- During ionization, parts of atoms are pushed apart "against their will", 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.

7.12 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 7.12a. Then (-) fragments of neon moving leftward inside 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 7.12b. Then (+) fragments of neon moving rightward across 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.

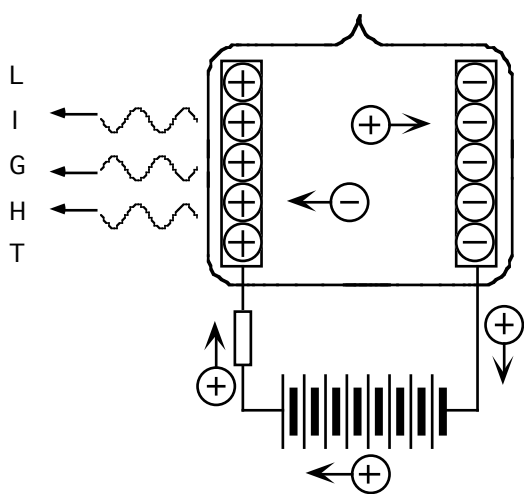


Figure 7.12a
LIGHT EMITTED AT LEFT IF (+)
CHARGE IS MOVING IN WIRES

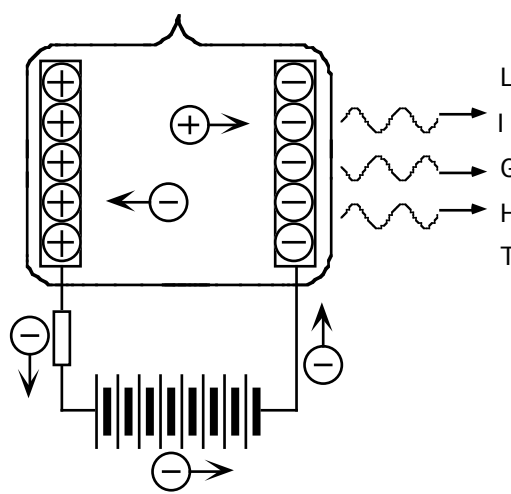


Figure 7.12b
LIGHT EMITTED AT RIGHT IF (-)
CHARGE IS MOVING IN WIRES

To find out which of these two diagrams describes what is actually happening, set up circuit 7.12c 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 7.2.) Be sure to include a resistor in the circuit, to limit the flow rate through the bulb and avoid burnout.

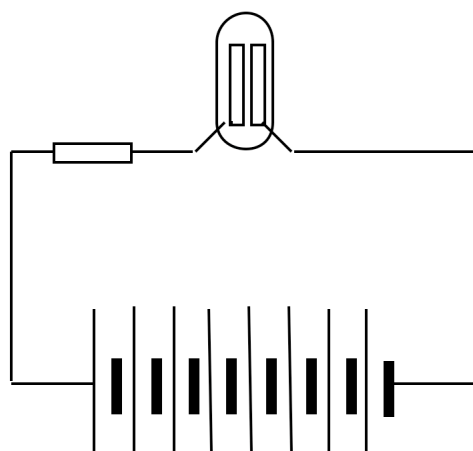
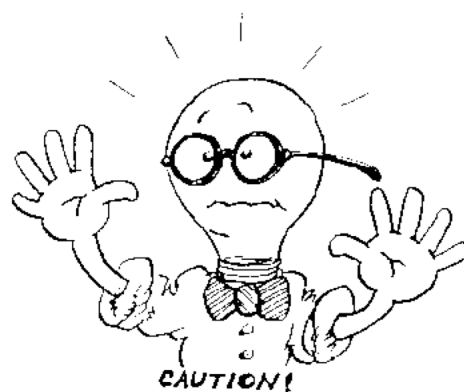


Figure 7.12c
CIRCUIT FOR OBSERVING WHERE LIGHT IS EMITTED

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?

7.13 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 7.12c.



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)? The 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.

7.14 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 8.9a and 8.9b, 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 “pressure” (or higher anything) is not intuitive, such a relationship must be memorized. For this reason, physicists and engineers usually communicate using conventional flow.

A review of the theories of charge flow developed so far in this curriculum:

Ben Franklin’s Model: Charge is neither positive nor negative; accumulation or ‘excess’ charge was labeled as positive; a deficiency of charge was labeled as negative.

Conventional Charge Flow Model: Positive charges flow through circuits from regions of high electric pressure toward low electric pressure.

Electron Flow Model: Negative charges flow through circuits in the opposite direction as conventional flow, from low pressure to high pressure.

