APPENDICES

Appendix A-1

EQUIPMENT FOR THE CORE CURRICULUM (Sections 1 – 6)

CASTLE Kits: Two options are available from PASCO Scientific (800-772-8700):
Catalog #EM-8624A: Box of circuit components frequently used by two students
Catalog #EM-8654: Economy package with parts for four kits (no container box)

Number of kits needed: The optimum way to teach the CASTLE curriculum is with two students per kit. However, teachers have worked quite successfully with as many as four students per kit. Some have started with four students per kit, and then purchased more kits in subsequent years.

Battery holder: The battery holder supplied has spaces for 4 cells, but students will usually use only 2 or 3cells. The space at the positive end next to the red dot will rarely be used. Connections will be made to the bolt near the blue dot and to the spring near the red dot. With this holder, you can easily reduce the battery voltage by removing the cell farthest from the post and changing the position of the positive lead to the newly-freed spring. Replacement holders of this type can be found at Radio Shack and electronic stores.

Batteries: Fresh batteries will help the experiments run smoothly. Therefore, it may be helpful to test used batteries. Simple battery testers are available from electronic stores, and are built into the package of some batteries. Alkaline batteries will remain fresh longer than others, and are worth the extra cost.

Bulb Sockets: Care should be taken to see that all bulbs are firmly seated to assure good electrical connections. The sockets in the CASTLE kits have been carefully selected to avoid any 'mystery'. Other types of sockets (more conventional but less desirable for teaching electricity) can be found at many electronic and hardware stores.

Light bulbs: The bulbs used in these experiments have been chosen for their high resistance and short warm-up time. They are designed to operate at 2 to 2.5 volts. Students should be cautioned not to connect single bulbs directly to the 4.5 volt battery (unless they are told to do so – and then only briefly), because this will cause early burnout.

Bulb Type	Name in Text	RESISTANCE (approximate)		Superior Feature
		Hot	Cold	
#48	"long"	40 Ω	4.5 Ω	Longer life
#14	"round"	10 Ω	1.2 Ω	Brighter

Two #14 bulbs in series with a 0.025farad capacitor and a 4.5 volt battery emit light that is bright enough to be noticed, with lighting time (about 1/2 second) short enough to avoid incomplete charging and discharging. The #48 bulbs have a longer lighting time (about 2 seconds), though with some sacrifice of brightness. In experiments that apply 4.5 volts per bulb, the #48 bulbs are preferable since they are better able to withstand the higher voltage.

Bulb burnout: It is expected that bulbs will burn out. Extra bulbs are provided with each CASTLE kit, and additional replacements can be purchased from PASCO Scientific. The #14 bulbs are sold by Radio Shack. Delta Education (800-442-5444) sells #48 bulbs in packets of 10 or boxes of 100. Mouser Electronics (800-346-6873) sells #14 and #48 in boxes of 100.

Capacitors: For hands-on instructional use, capacitors should meet two requirements:
(1) Enormous capacitance — needed to stretch the time scale of transient bulb-lighting events for purposes of human perception.
(2) Compact and non-polar — needed for devices to be user friendly for students who are just beginning the study of electricity.

These features have been made available and affordable by recent advances in capacitor technology. The exact specifications will depend upon the desired duration of bulb lighting.

Capacitor non-polarity: CASTLE capacitors are non-polar. But they are placed in cans that are made for commercial polar units -- and thus come with (+) signs that suggest polarity. These signs should be ignored. To be reassured that your CASTLE capacitors really are non-polar, look for "20VNP" printed on the 25,000 microfarad can and "10VNP" on the 100,000 microfarad can — standing for "20 Volts Not Polar" and "10Volts Not Polar".

Capacitor damage: Capacitors can be damaged permanently if they are connected to voltages greater than those printed on the capacitor (20V-dc for the blue and silver capacitors and 5V-dc for the green 1.0 farad capacitor). For testing purposes, several capacitors were connected to 120V-ac. The results produced smoke, heat, and physical damage, but nothing that would produce serious injury to the student.

Capacitor maintenance: The blue and silver capacitors have a glycol-based electrolyte that may penetrate the aluminum oxide dielectric over years of disuse, resulting in low leakage resistance. However, the dielectric can be re-formed by applying the maximum permitted voltage for a few minutes (until the leakage current drops). For preventive maintenance, it is recommended that this "forming voltage" be applied once a year for 15 minutes in each direction. Twelve D-cells in series, applied to one's entire collection of capacitors connected in parallel, should work very well for the 20 volt units described above.

Capacitor testing: If you have occasion to wonder if a capacitor is functioning properly, it can be easily checked using an ohmmeter. First, short the leads of the capacitor, then connect the leads of the ohmmeter to the capacitor. The meter should first show a low resistance and increase to infinity as the capacitor charges. The time may take one to five minutes.

Magnetic compass: The high-quality liquid-filled compass will not bind or oscillate. A compass needle should deflect about 20 degrees when used with a 4.5 volt battery and two round bulbs. If substantially less deflection is observed, there is probably a piece of magnetized iron under the table that is restraining the needle — in which case the remedy is to move the compass to another location. Since some D-cell cases can become magnetized, these should be kept as far from the compass as possible.

Appendix A - 2

EQUIPMENT FOR THE INTERMEDIATE AND ADVANCED CURRICULUM (Sections 7 - 12)

Neon bulbs: At least 70 volts is needed initiate a discharge through a neon bulb (in some up to 90 volts and once in a while even 100 volts), after which the discharge process will drop the potential difference across the bulb to about 55 to 60 volts. Standard Ne-2 neon bulbs are available in 2-bulb packs at Radio Shack, or much ore cheaply in bulk from suppliers such as Mouser Electronics (800-346-6873).

Charge flow detection: When a neon bulb lights, the glowing gas surrounds the negative electrode. Observing which electrode lights allows the direction of conventional charge flow and of the potential difference to be determined. The bulbs require very little current to show a discharge, and can be used to detect tiny charge flow rates in electrostatics experiments where a magnetic compass is useless. (See J. Layman and D. Rutledge, "Neon Lamps and Static Electricity", The Physics Teacher, p 49, vol 10, Jan 1972.)

Current-limiting resistor: A series resistor of about 200,000 ohms is used to prevent large current 'arcing' in neon bulbs. The internal resistance of the 9 volt batteries used in Section 9 is great enough to prevent arcing without the use of a current-limiting resistor, and none of the battery combinations used require such a resistor. It is nonetheless O.K. to use a large resistance in series with the bulb if you wish. But do not use it in the electrostatic discharge experiments in Sections 8 and 9.

Acrylic plastic: Acrylic plastic glazing is sold under trade names such as Plexiglass™ and Plaskolite™. Safety glazing with 3/32 inch thickness is usually available in hardware and lumber stores at about $2 per square foot. It is easily cut by scoring it heavily with a sharp knife and breaking it over the edge of a table. Thicker plastic may need cutting with a saw.

Photoelectric tube: Type 1P39 is recommended. It is routinely found in Photoelectric Effect kits, such as the one distributed by PASCO scientific. It costs approximately $60 and may be obtained from Allied Electronics (800-433-5700) or Newark Electronics (800-298-3133).

Bicolor LEDs: Red/green Bi-color Light Emitting Diodes are used to indicate conventional current direction in low voltage applications with diodes in Sections 9 and with field production in Section 12 (Radio Shack #276-012).

Field effect transistor: The IRF510 MOSFET is recommended for use in Section 10 (Radio Shack catalog #276-2072, approximately $3).

Coaxial coils with iron core: The important design consideration is that both primary and secondary coils will light a bicolor LED will light to optimal brightness when a battery is connected to the primary coil -- and when it is disconnected. The PASCO Scientific coaxial coils, catalog #SE-8653, do this very well with a battery of 2 or 3 D-cells.

Electromagnetic radiation detector: Most portable radios with an AM band will respond to an electromagnetic field coming from accelerating charge in the PASCO primary coil, out to a distance of 1 meter. Panasonic model RF-2400 is notable for light weight and easy tuning.

Appendix B

REPRODUCIBLE DIAGRAMS

These diagrams are for making transparencies for projection, or for copying and distributing in class.

In the first set of 8 diagrams, "pressure" values in the circuit are represented in shades of gray. The darkest shade represents highest "pressure" in the circuit, and the lightest shade represents lowest "pressure". In the second set of 8 diagrams, the circuit is not shaded -- so that appropriate parts of the circuit can be color-coded using colored marking pens. The third set contains pre-colored circuits to be printed on a transparency as a focus for group discussion.

Charging and Discharging a Capacitor Through Light Bulbs

Diagram 1: With no battery, all wires and capacitor plates are at normal pressure (Yellow).

Diagram 2: Adding a battery produces HIGH (Red) and LOW (Blue) pressure values in wires connected to it but the remainder of the circuit has not yet changed in this first moment (Yellow). Large pressure differences across the bulbs result in a high flow rate and therefore bright bulbs.

Diagram 3: Inflow continues to raise the pressure in the top capacitor plate (Orange), while outflow lowers the pressure in the bottom plate (Green). The reduced pressure differences across the bulbs now drive a lower flow rate, so the bulbs are dimmer.

Diagram 4: The pressure difference across the capacitor plates has increased to the same value as the pressure difference across the battery (Red/Blue). There is now no pressure difference across the bulbs, so there is no flow and the bulbs are not lit.

Diagram 5: Removing the battery leaves the final pressure values in the capacitor plates and in the wires, with no pressure difference across the bulbs and no flow.

Diagram 6: After the free ends of the wires are connected, pressure in the middle conductor equalizes to normal (Yellow). Large pressure differences across the bulbs drive large flow rate in a direction opposite from Diagram 2. The bulbs are brightly lit.

Diagram 7: Outward flow reduces pressure in the top capacitor plate (Orange); likewise the flow into the lower plate increases pressure (Green). Meanwhile the reduced pressure differences across the bulbs drive a lower flow rate, so the bulbs are dimmer.

Diagram 8: The pressure difference between capacitor plates has returned to zero. With no pressure difference across either bulb, there is no flow.

CAPACITOR CHARGING SEQUENCE

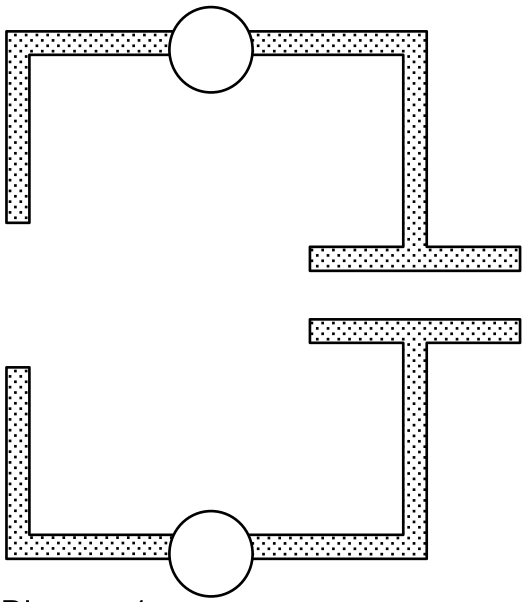


Diagram 1

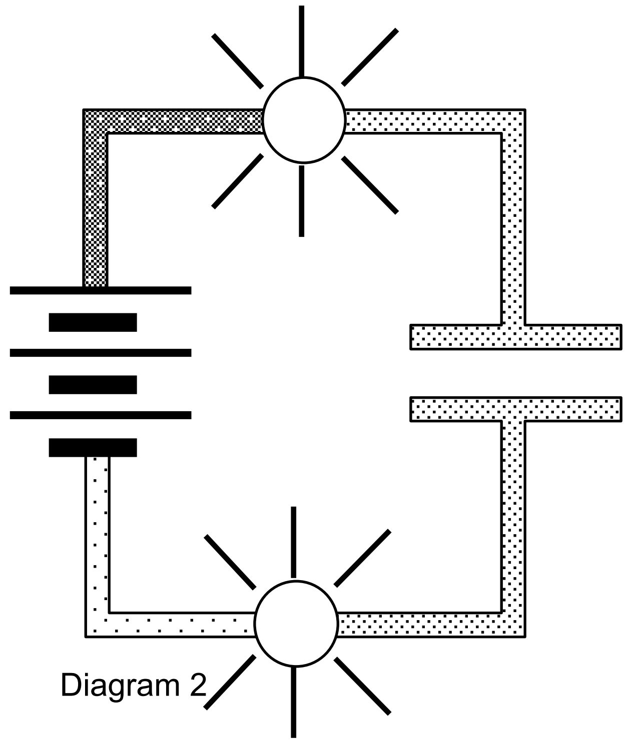


Diagram 2

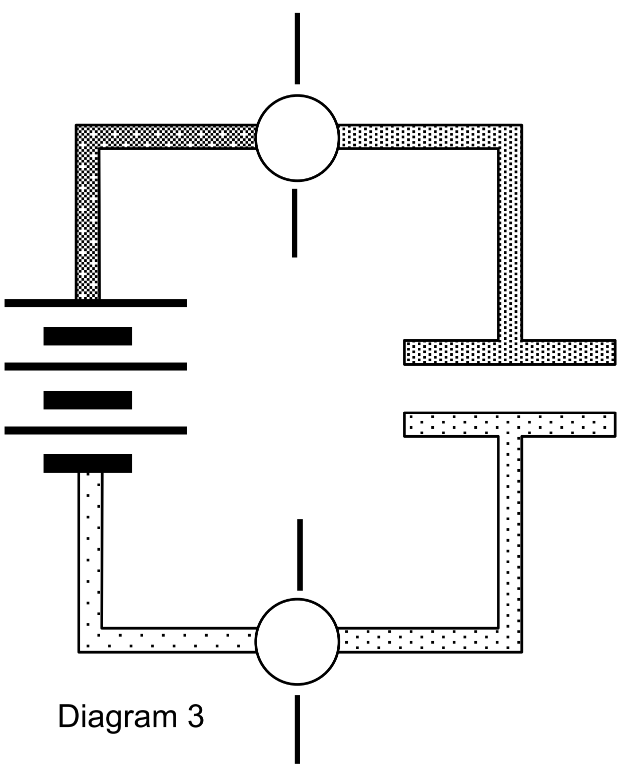


Diagram 3

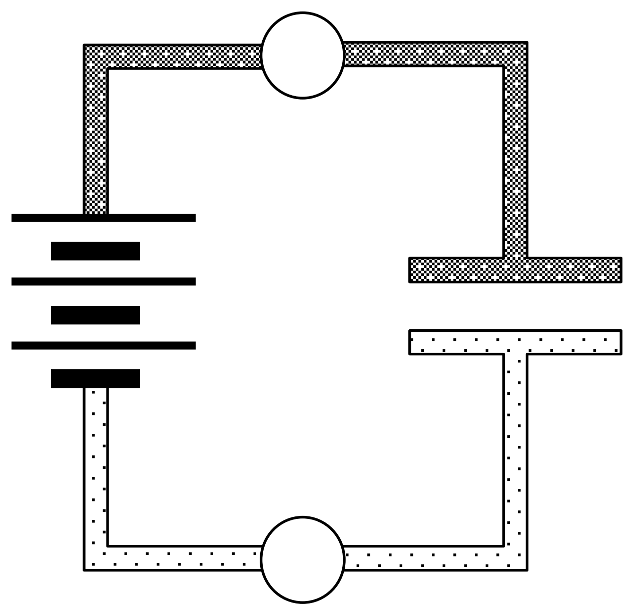


Diagram 4

CAPACITOR DISCHARGING SEQUENCE

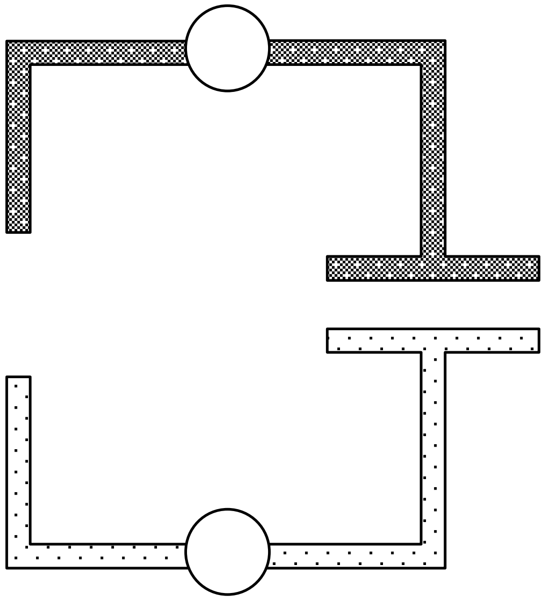


Diagram 5

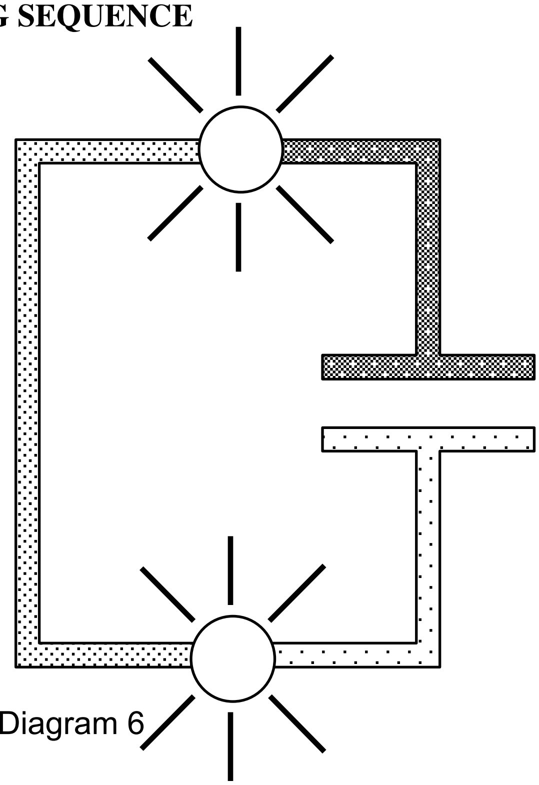


Diagram 6

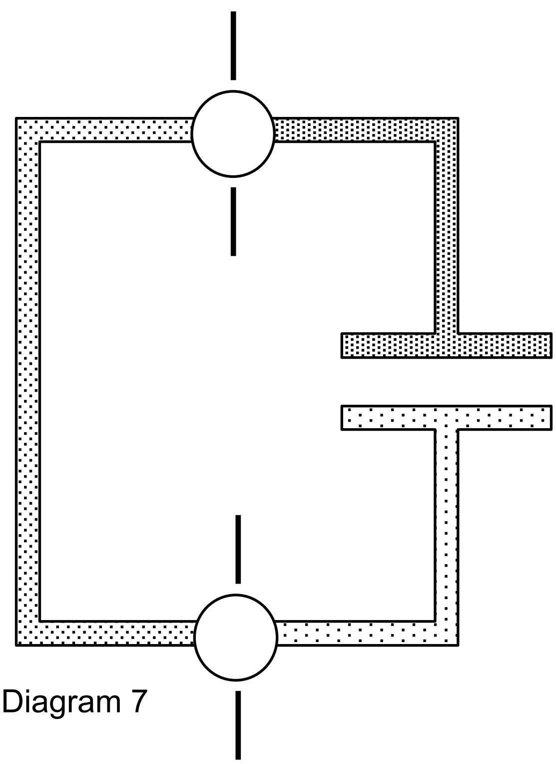


Diagram 7

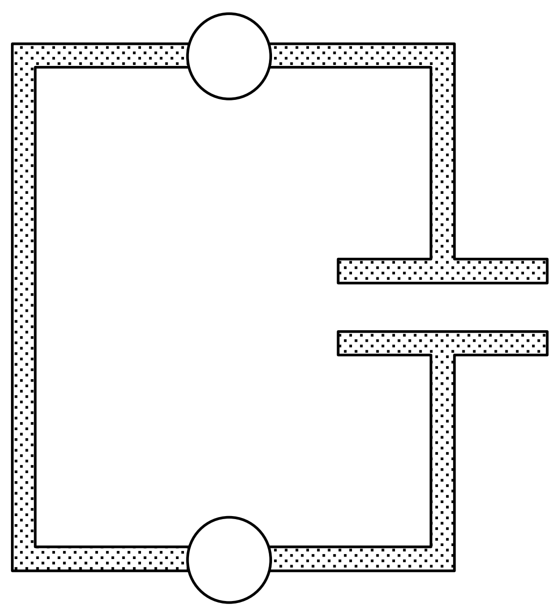


Diagram 8

CAPACITOR CHARGING SEQUENCE

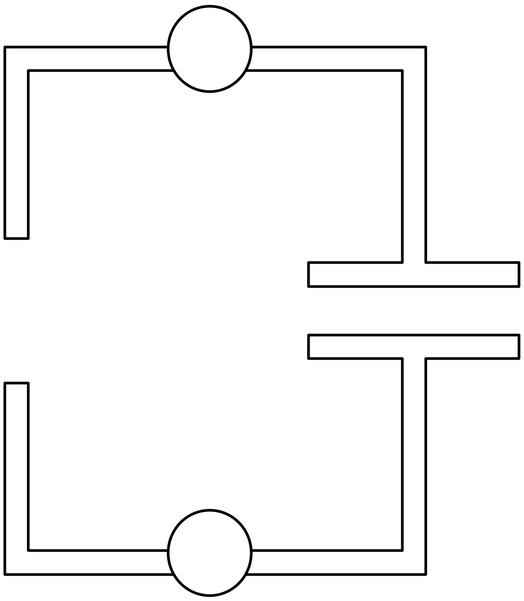


Diagram 1

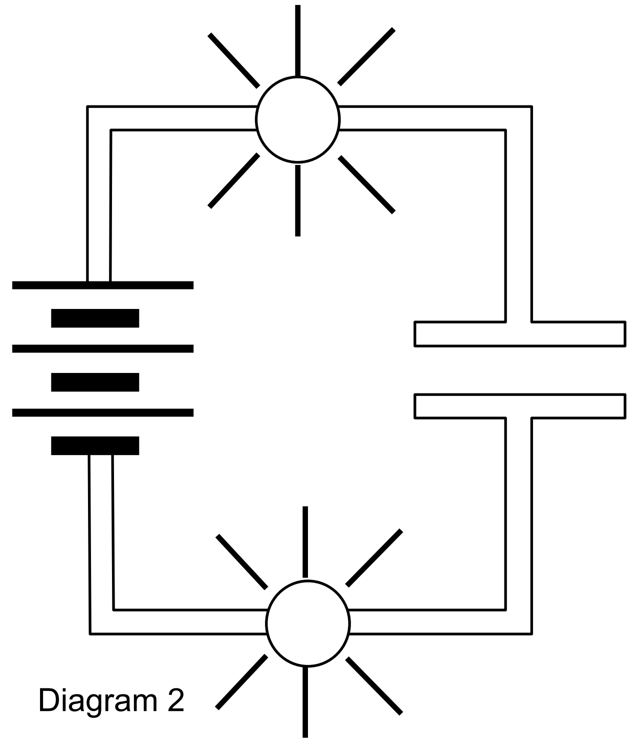
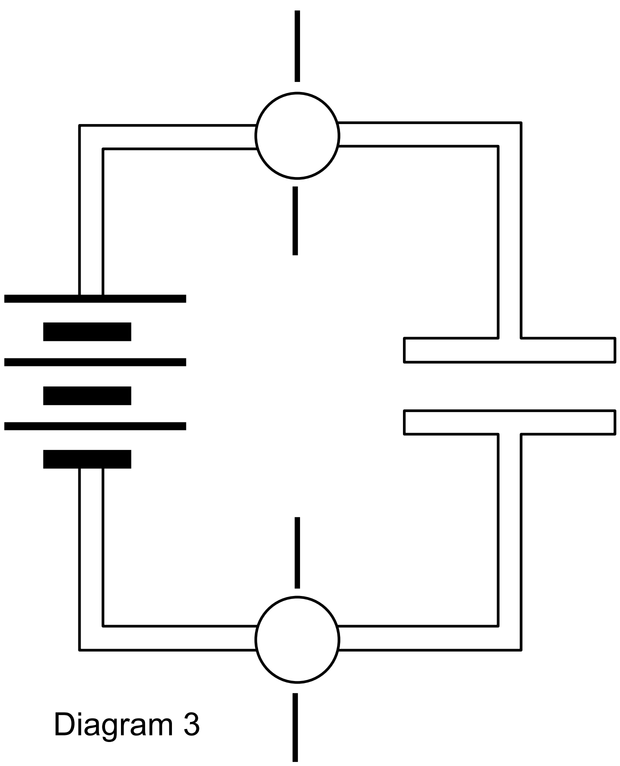


Diagram 2



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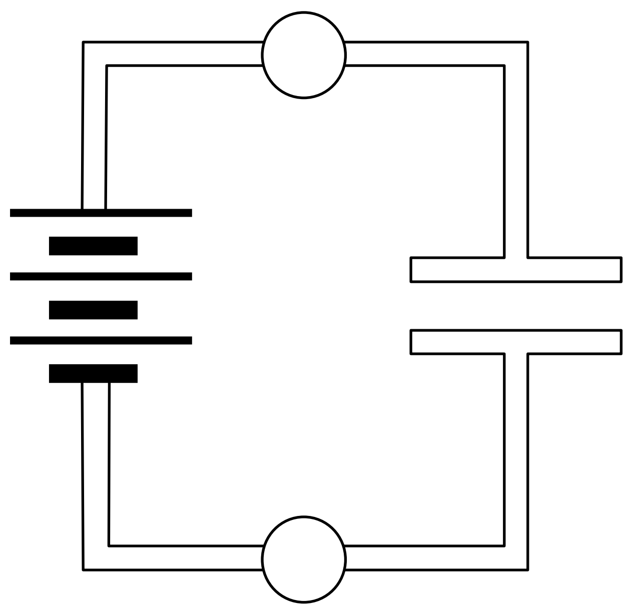


Diagram 4

CAPACITOR DISCHARGING SEQUENCE

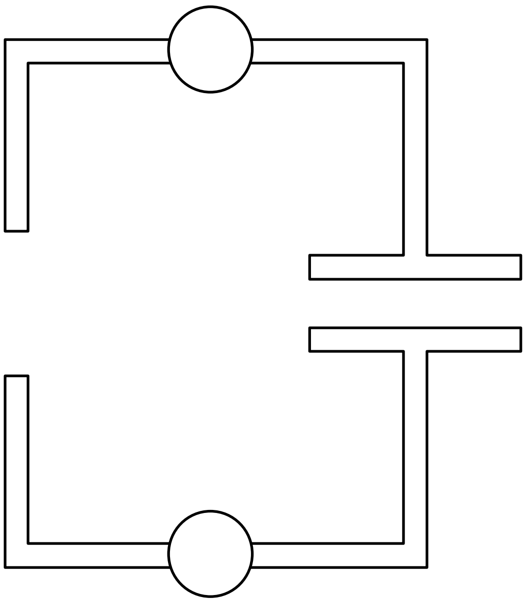


Diagram 5

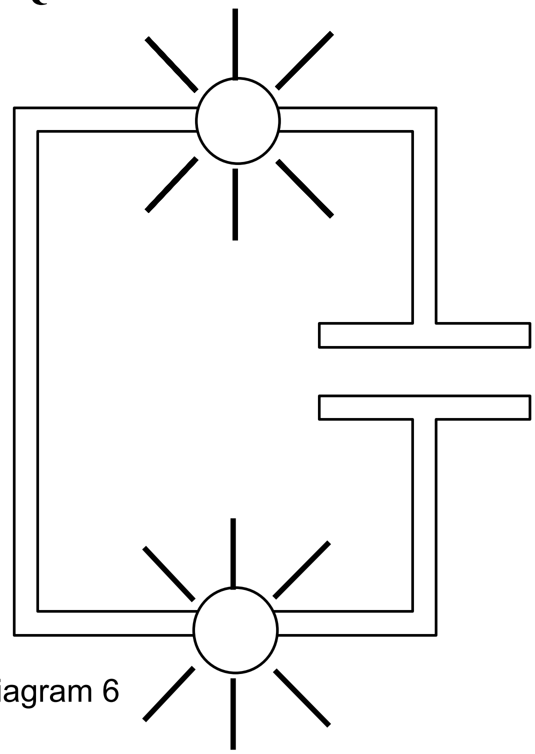


Diagram 6

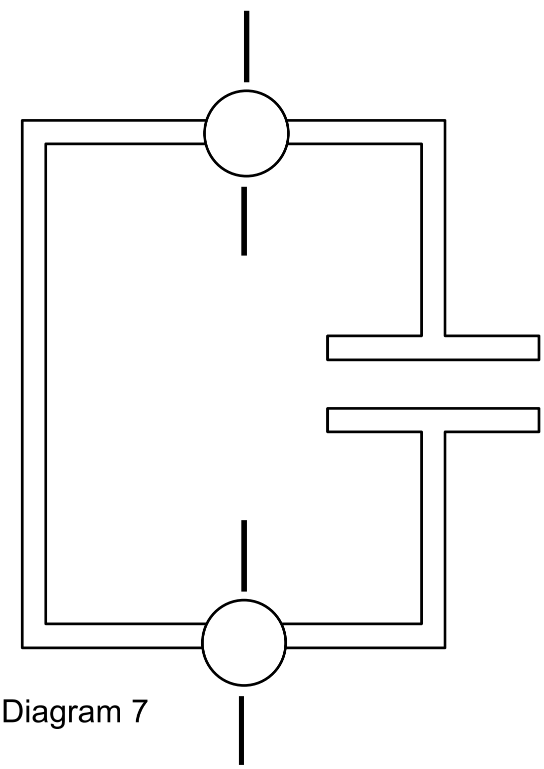


Diagram 7

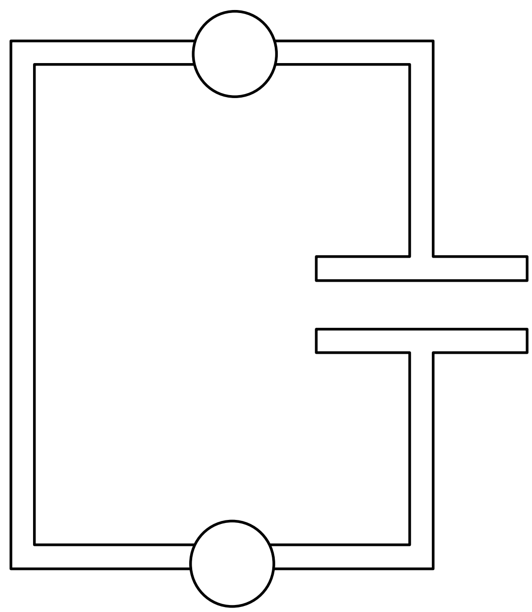


Diagram 8

CAPACITOR CHARGING SEQUENCE

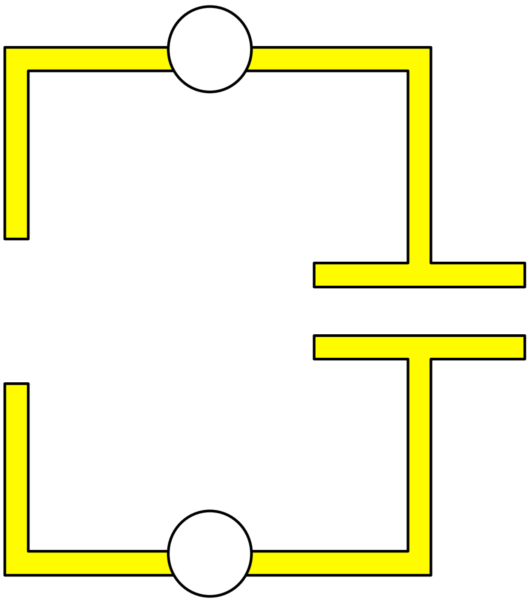


Diagram 1

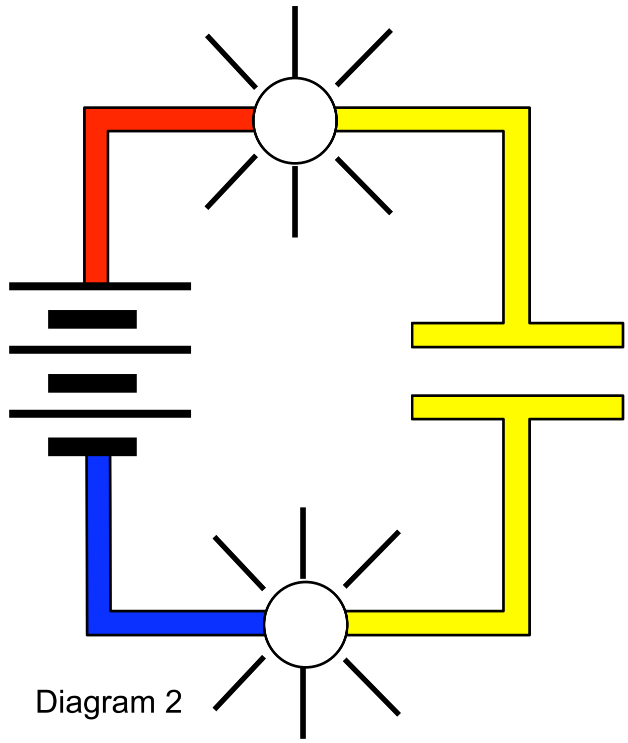


Diagram 2

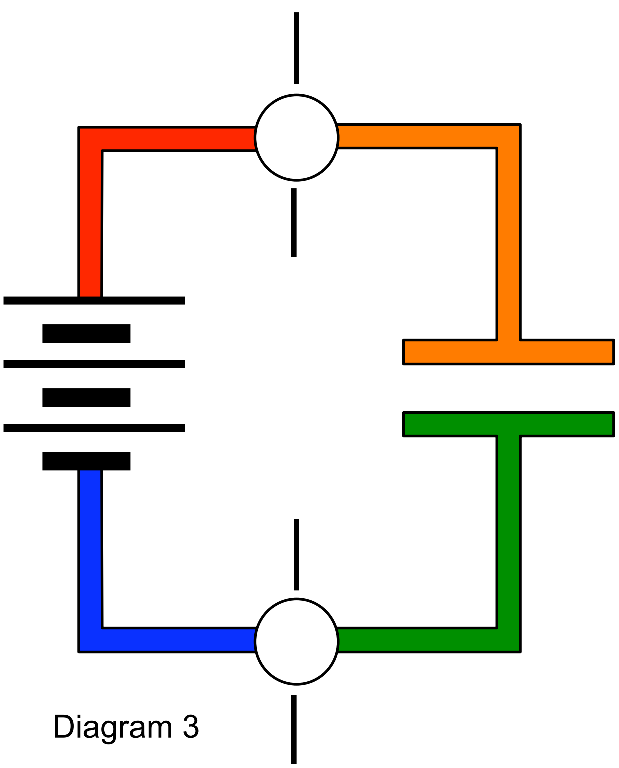


Diagram 3

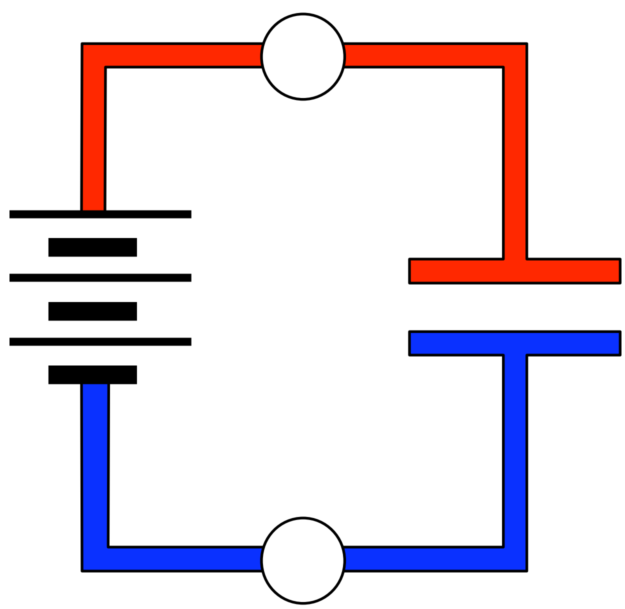


Diagram 4

CAPACITOR DISCHARGING SEQUENCE

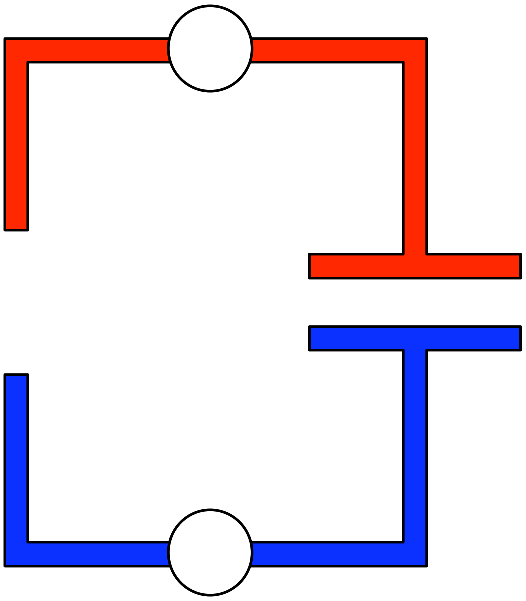


Diagram 5

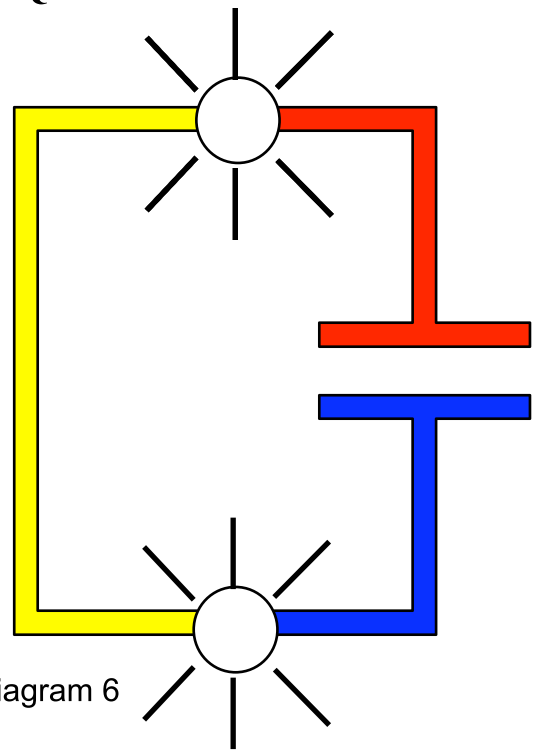


Diagram 6

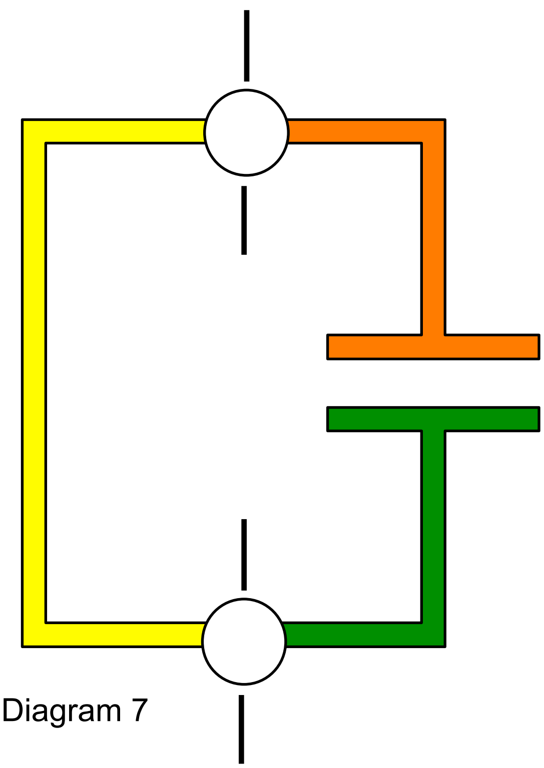


Diagram 7

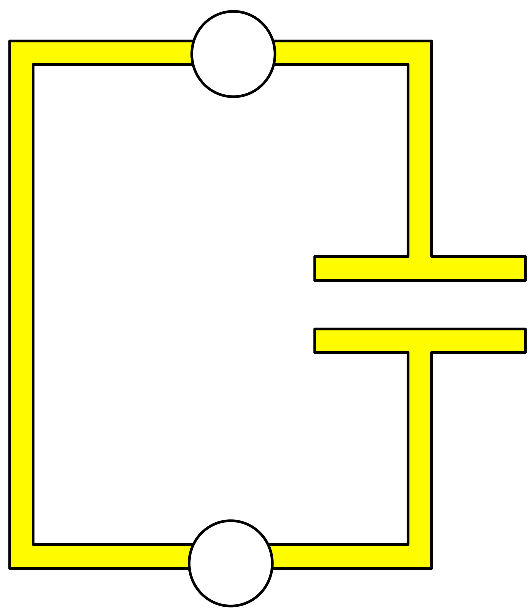


Diagram 8

Appendix C: Alternative Curriculum for Sections 7 & 8: "Short Circuit to Semiconductors"

Teacher Notes

OBJECTIVES

After completing quick tour through Section 7 and 8, each student will be able to cite evidence that:

(1) Insulators also contain charge -- but it is not mobile like the charge in conductors.
(2) Matter contains pressure-lowering (–) charge as well as pressure-raising (+) charge. Normal matter contains equal amounts of both kinds.
(3) The charge moving in circuit wires is (–). It is carried by particles that are much smaller than atoms.
(4) There are "halos" in the space around +/– charges, which act to raise/lower the electric pressure in distant matter.

OVERVIEW

Appendix C is intended for teachers who, after finishing electrical measurements in Section 6, want to move quickly to Section 9 on semiconductor devices. The broad experience with electrostatics provided by Sections 7 and 8 is set aside in order to provide rapid development of the four key ideas listed above that are needed to understand Section 9. For each of these ideas, the teacher performs demonstration experiments that create a need for the idea -- and then leads a class discussion based on what students have observed.

SUMMARY

INVESTIGATION ONE: DO INSULATORS CONTAIN CHARGE?
A large pressure difference across a neon bulb changes the neon gas from insulator to conductor, showing that insulators also contain charge. (Charge in insulators is "locked in", but can be "broken loose" by a large pressure difference.) Lighting only at one electrode of a neon bulb indicates direction of charge flow through the bulb.

INVESTIGATION TWO: ARE THERE TWO KINDS OF CHARGE?
A neon bulb connected across a pie plate capacitor glows when either of two different rubbed solid insulators is placed on the top plate. Flow directions through the bulb show there are two kinds of charge on the rubbed insulators. Materials that we have labeled +/– are now seen as containing the kind that raises/lowers pressure.

INVESTIGATION THREE: DOES (+) OR (–) CHARGE MOVE IN A CIRCUIT?
Neon bulb lighting is explained by atoms with (+) and (–) parts being "broken apart", making these parts mobile. Lighting at the bulb's (–) terminal shows this is where the parts recombine. It suggests that the charge moving in circuit wires is (–), carried by "electrons" that exist in all atoms and are tiny compared to the size of the atoms.

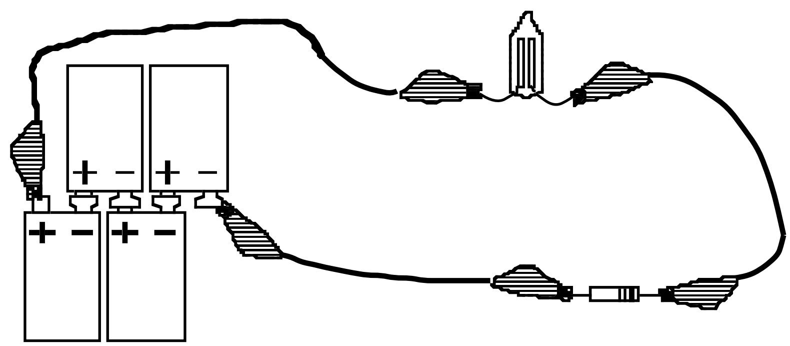
INVESTIGATION FOUR: WHAT CAUSES EFFECTS IN DISTANT MATTER?
There are invisible "halos" in the space around +/- charges, which can raise/lower the electric pressure in any conductor placed in a halo. This "halo" model of distant action is confirmed using a pie plate capacitor with a neon bulb and +/– charges on rubbed insulators that are held up above the capacitor plates and do not touch them.

Appendix C:

Alternative Curriculum for Sections 7 & 8: "Short Circuit to Semiconductors"

INVESTIGATION ONE: DO INSULATORS CONTAIN CHARGE?

1st Teacher Demonstration:



OBSERVING WHEN AND WHERE A NEON BULB LIGHTS

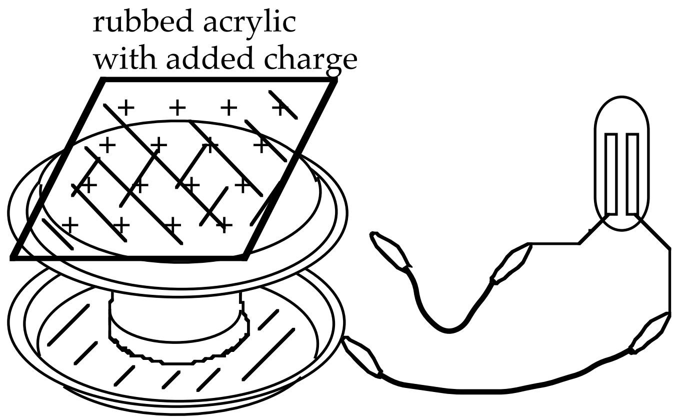
Four 9-volt batteries in series will not make a neon bulb glow. But 8 to 10 such batteries will. Note that the glow occurs at the low pressure electrode – connected to the (–) battery terminal.

Discussion should bring out that

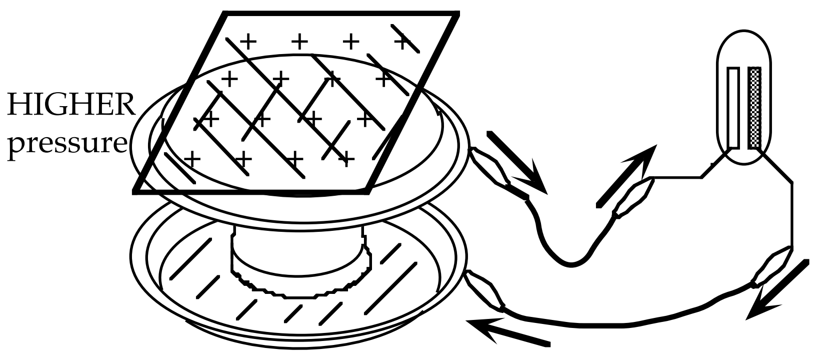
- When the neon gas glows, it has changed from being an insulator to being a conductor.
- This means neon contains charge, even though it's an insulator in normal circumstances.

Target Concepts -- to be generated in class discussion
Charge is present in neon atoms but can't move until a large pressure difference breaks atoms into (+) and (–) parts. Neon is then a conductor, so pressure difference <u>can</u> drive charge flow.

2nd Teacher Demonstration:



READY TO TEST FOR PRESSURE CHANGE IN THE TOP PLATE



OBSERVE BULB LIGHTING AND INFER CHARGE FLOW

Discussion should bring out that

- Bulb lighting at the electrode on the right indicates the flow pattern shown. The electrode that glows is attached to the low-pressure plate glows.
- This flow pattern is evidence of HIGH pressure in the pie plate the acrylic is resting on.
- The pressure there means foam contains charge, some of which rubbed off on the acrylic.

Target Concepts -- to be generated in class discussion

Charge is present in all insulators. Rubbing two types of insulators on each other can transfer some charge off type #1 and onto type #2, so that #2 then has more than the normal amount of charge (+).

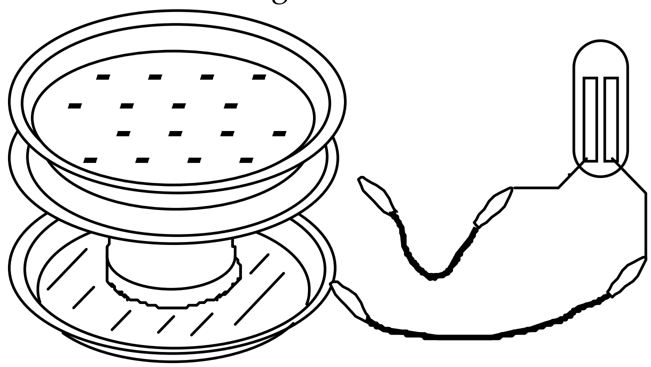
Materials vary in their ability to hold onto charge, or to let it be rubbed off.

Setting #2 down on the top capacitor plate should then increase the pressure in the top plate.

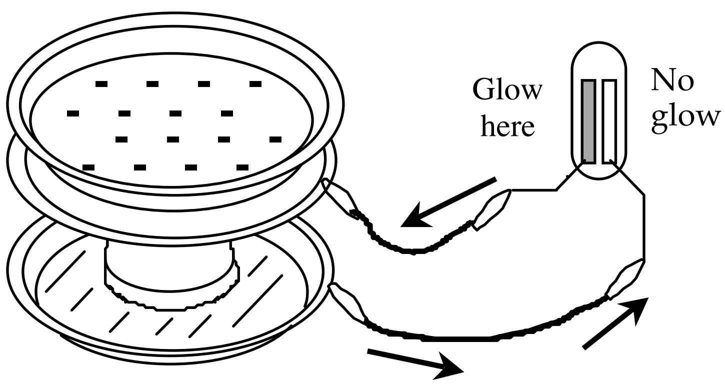
INVESTIGATION TWO: ARE THERE TWO KINDS OF CHARGE?

Rubbing some charge off the foam plate and onto the acrylic leaves the foam with less than the normal amount of charge (–). Can the neon bulb detect this depletion of charge in the foam?

Teacher demonstration:



READY TO TEST FOR PRESSURE CHANGE IN THE TOP PLATE



OBSERVE BULB LIGHTING – INFER CHARGE FLOW

Discussion should bring out that

- Bulb lighting at the left electrode shows LOW pressure in the pie plate the foam rests on.
- This pressure lowering is caused by what's left in foam after some charge is scraped off.
- "What's left" is something <u>active</u>. It does the <u>opposite</u> of what we've seen charge doing.

Target Concepts -- to be generated in class discussion

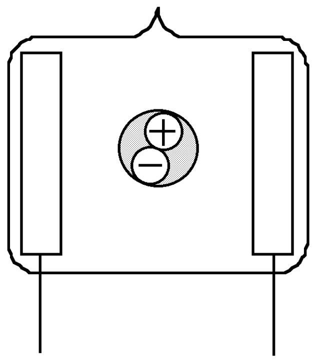
Matter also contains a <u>second kind</u> of charge, which acts to <u>lower</u> electric pressure in matter. In normal matter, the pressure-raising and pressure-lowering effects of the two kinds cancel out. From now on, (+) will stand for pressure-raising charge and (–) for pressure-lowering charge.

INVESTIGATION THREE: DOES (+) OR (–) CHARGE MOVE IN A CIRCUIT?

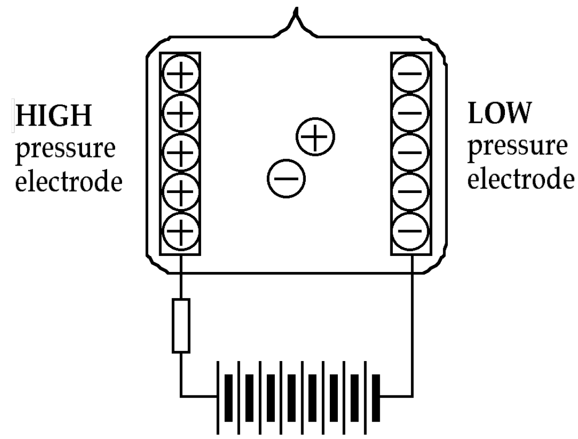
Since there are two kinds of charge, the question arises: Which type is moving in a circuit?

(+) charge would move from HIGH-to-LOW pressure.
(–) charge would move from LOW-to-HIGH pressure.

Teacher shows 1st diagrams:



BEFORE IONIZATION: WHOLE ATOM WITH NO NET CHARGE



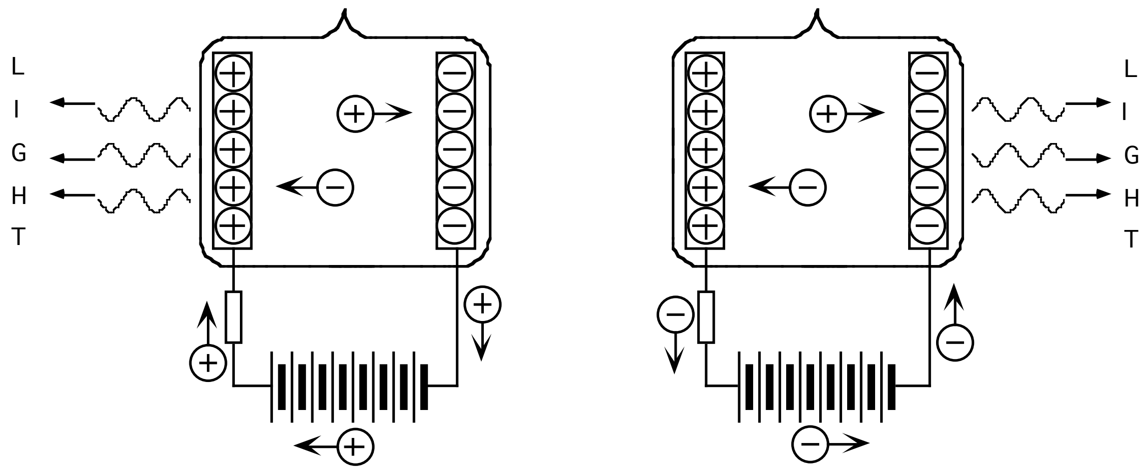
(+) AND (-) FRAGMENTS ARE DRIVEN APART BY PRESSURE DIFFERENCE

Discussion should bring out that

- Neon gas is not being used up. So pieces of broken-up atoms are recombining somewhere.
- Atoms must be given energy to break up –- and will give it back when the parts recombine.
- Energy is given out at the electrode that glows -- so that is where the recombination occurs.

Target Concepts – to be generated in class discussion
Breakup and recombination keep going in a continual process that does not destroy any matter. For this to happen, pieces of neon atoms must (a) go into the circuit at one electrode, (b) go through the wires and the battery and into the other electrode, and (c) recombine there with other pieces to form whole new neon atoms. Glow is observed where recombination occurs.

Teacher shows 2nd diagrams: Ask which diagram correctly shows where light is given off.



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

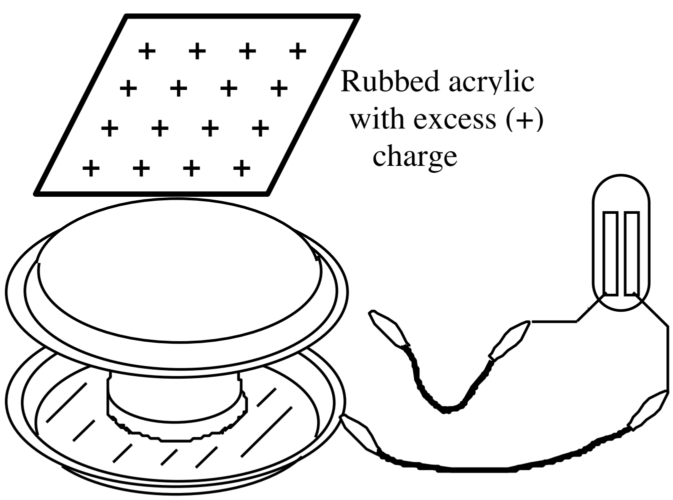
LIGHT EMITTED AT RIGHT IF (-) CHARGE IS MOVING IN WIRES

Target Concepts -- to be generated in class discussion:
The fact that glow occurs at the LOW-pressure terminal is evidence that particles with (-) charge are moving through the wires. These negative particles are normal parts of the copper (or gold, silver, aluminum, etc.) atoms in the wires – and must be tiny compared to these atoms in order to move through them without resistance. They also combine with the (+) parts of neon ions to form whole new neon atoms – and thus are also normal parts of neon atoms.

Infer that the tiny negative particles are present in atoms of all elements. Call these particles "electrons".

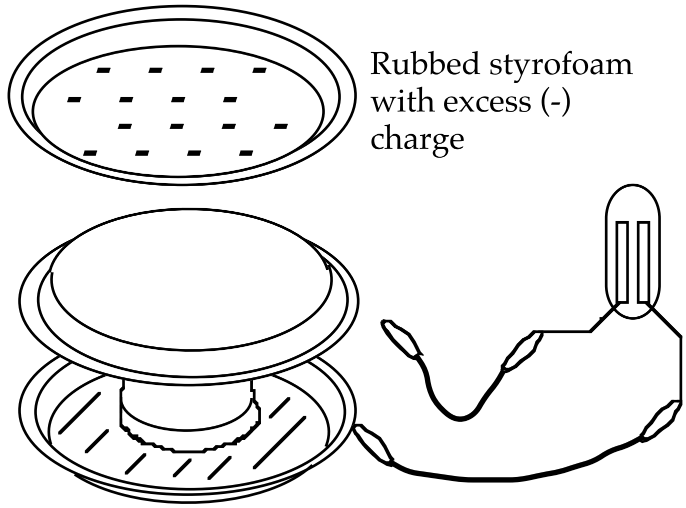
<u>INVESTIGATION FOUR: WHAT CAUSES EFFECTS IN DISTANT MATTER?</u>

Teacher demonstration #1:



READY TO TEST FOR PRESSURE CHANGE IN THE TOP PLATE WITH A (+) ACRYLIC PLATE BROUGHT NEAR

Teacher demonstration #2:



READY TO TEST FOR PRESSURE CHANGE IN THE TOP PLATE WITH A (-) STYROFOAM PLATE BROUGHT NEAR

Discussion should bring out that

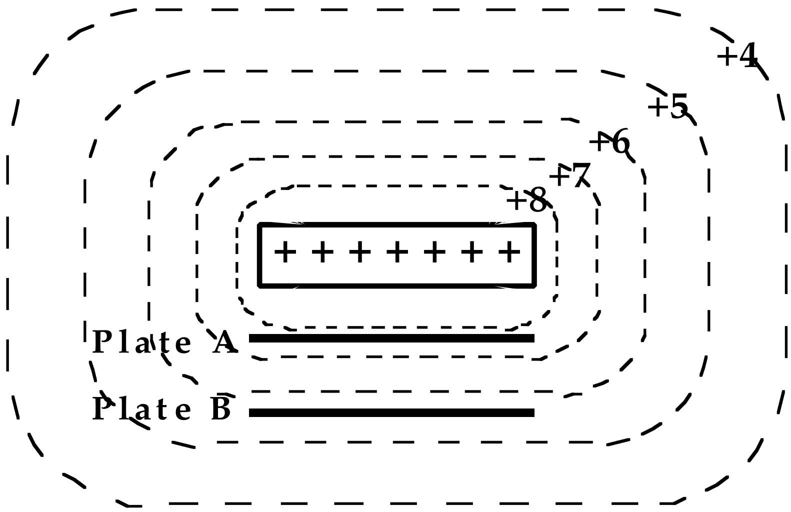
- These are repeats of earlier experiments – except that the charged objects are up in the air.
- The (+)/(–) object raises/lowers pressure in the top pie plate without touching that plate.
- It's a problem to imagine what bridges the gap between (+)/(–) charges and the top plate.

Target Concepts -- to be generated in class discussion

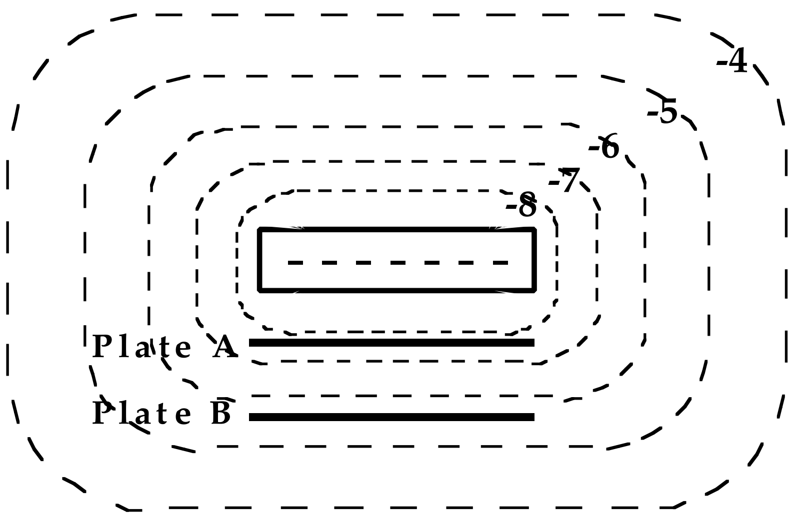
Useful analogies: The hot region around a flame can heat up one's skin without the flame touching the skin. The cold region around a piece of ice can chill one's skin without the ice touching the skin.

These images can be thought of as "temperature halos", and adapted to visualizing a "pressure halo" in the space around any accumulation of charge. The halo around positive/negative charge will raise/lower the pressure in any conductor that's placed in this pressure halo – like the halo around flame/ice will raise/lower the temperature in any matter that's placed in this temperature halo.

Teacher demonstration #3:



PRESSURE HALO AROUND AN OBJECT WITH A POSITIVE CHARGE



PRESSURE HALO AROUND AN OBJECT WITH A NEGATIVE CHARGE

Discussion should bring out that

- These halos correctly predict a <u>difference</u> of pressure values between plates A and B as a result of their distance from a positively or negatively charged object.

Target Concepts -- to be generated in class discussion

Any conductor that's brought into a halo would be polarized. The teacher might make a *versorium* and use it as a basis for visualizing the consequences of polarizing a conductor.

A versorium with a <u>paper</u> pointer could show that insulators can be polarized too – and provoke discussion leading to insight that polarization is occurring in individual <u>atoms</u> of the paper.

Appendix D

STUDENT MISCONCEPTIONS IN ELECTRICITY

Introduction

Students enter physics courses with many already-formed ideas about the physical world, which they use to explain observations or situations they encounter. These preconceptions are presumably the results of prior experiences and/or "common sense." The persistence of students' initial beliefs can range from weak lingering suspicions to strongly held ideas.

Some preconceptions are valuable assets for anchoring model based reasoning. One of these is the strongly held belief that something is moving in the wires connecting a battery to lit bulbs. Another is that lit bulbs are getting energy from an energy source.

Preconceptions that hinder learning the physicist's view of the physical world are called "misconceptions". Some misconceptions are so strongly held that traditional methods of instruction do not enable most students to alter their initial beliefs in any consistent manner. Their explanations of events not directly encountered in class are still formulated in terms of these ideas after instruction.

Language is important in the battle against misconceptions. Both technical words and common usage can hinder understanding by suggesting inappropriate images. Students often explain observations of electrical phenomena using "physics words" such as energy, charge, current, and "electricity" interchangeably, making it difficult to learn appropriate uses of these terms. Therefore, it is important that students not use any technical term prior to developing a clear meaning grounded in investigation of phenomena. Choosing common-usage words for describing explanatory models of electrical phenomena is also important. When developing an understanding of resistance and its effect on charge flow, the word "obstacle" or "gate" may suggest shutting off the flow to many students and the word "filter" may suggest filtering out to some. The word "hindrance" or the phrase "hard place to get through" usually suggests a clearer picture of how resistance works.

Common student misconceptions

A number of strongly held misconceptions are nearly universal. The list below describes those reported in the research literature:

BATTERY ORIGIN — Students usually believe batteries are the only sources of whatever is moving in a circuit. Lit bulbs and a compass are used to infer origin in all conducting parts of a circuit containing a capacitor. An air capacitor is used to reinforce this conclusion.

BATTERY AGENCY — Students usually believe batteries are the only causal agents that are able to drive movement through the circuit wires. Discharging a capacitor through bulbs, with no battery in the circuit, is used to attack this idea and create a need for an alternative.

CHARGE CONSUMPTION — Students often believe that what's moving through wires is "used up" in lit bulbs. Monitoring flow with an under-wire compass can provide evidence for conservation, not consumption. Bulbs lit by cranking a Genecon shows what's used up can come from muscle and doesn't move through wires – so it's "energy", not "charge".

SEQUENTIAL REASONING — Students usually believe that a circuit component can have an influence on what happens downstream, but not upstream. This idea is occasionally reinforced by observing bulbs in series with slightly different brightness (due to variations in resistance). Interchanging bulbs will help alleviate this erroneous idea. Also, changing bulb types or using shorting wires can reveal downstream as well as upstream effects.

LOCAL REASONING — Students may believe that flow into a junction must split equally to all branches – a special case of sequential reasoning. For these students, understanding parallel circuits becomes difficult.

MORE BULBS MEANS MORE RESISTANCE — A common student belief is that adding a bulb in a circuit adds to the overall resistance of the circuit. This belief is true for adding a bulb in series, but false for adding a bulb in parallel. The misconception can be confronted empirically by noting greater flow rate through the battery if bulbs are added in parallel, and conceptually by noting that parallel paths connect the same regions of electric pressure.

To attack misconceptions, teachers need to listen carefully to conversations during student investigations, note points where misconceptions seem to be arising and incorporate those issues into class discussions. Gains in student understanding will occur if we strive to:

- Help students develop the need and skill to carefully explain ideas to others in discussion and in exams.
- Cycle back whenever possible to concepts that students had earlier found difficult to comprehend.
- Require that students routinely give evidence to support their conclusions.

The table below identifies activities in the CASTLE curriculum that help students confront these misconceptions, and the sections in which those activities are found:

Strongly Held Misconceptions	Activities that Attack the Misconception	Location in Electricity Visualized
Battery Origin	A bulb placed downstream from a charging capacitor is observed to light.	Section 3
Battery Agency	A discharging capacitor drives charge flow and lights bulbs without any battery in the circuit.	Sections 3, 4
Charge Consumption	Identical bulbs in series are of equal brightness. Compass deflection is the same for all series wires.	Sections 1, 2
Sequential Reasoning	A downstream capacitor or bulbs can affect the brightness of upstream bulbs.	Sections 5, 6
Local Reasoning	Observing the independence of bulbs in parallel circuits	Sections 2, 5, 6
More Bulbs Means More Resistance	Observing greater flow through a battery when bulbs are added in parallel.	Section 5

Appendix E

HISTORY OF THE ELECTRIC POTENTIAL CONCEPT

Historical invention of "electric pressure"

The conception of electric potential employed by professionals today is the product of a research effort which began in the mid-eighteenth century, with the development of increasingly sensitive electrometers. When connected to conductors of different size that have been given equal amounts of charge, these instruments deflect more for small objects than for large ones. They were evidently measuring something that depends on the concentration of charge in a conductor — but what was it?

In 1778 Alessandro Volta began to visualize electrified conductors as containers of a compressible fluid — like air — and an electrometer as measuring a pressure-like property whose value depends on the degree of compression. His earlier research on gases is thought to have played a key role in stimulating him to adopt an air-like model. Volta gave the name "electric tension" to the pressure-like property. In his words:

> The energy which I call *electric tension* is the effort [of the fluid] to push itself out [of the conductor which contains it].

Henry Cavendish had already made explicit use of the compressed air analogy in 1771, when he invented a concept much like Volta's. His work did not achieve the notoriety of Volta's — perhaps because he gave his idea the unfortunate name "electrification" and was not as communicative as Volta.

The fact that both of these pioneers of electricity found their way to a model based on the analogy with air compression suggests the usefulness of the compressed-air analogy as an intuitive foundation for understanding the electrostatics of conductors. The CASTLE project's experience suggests that contemporary students also find this analogy useful. Students visualize the same effort to push itself out by excess charge that has been compressed into a capacitor plate. They prefer to call this pushing ability "electric pressure", but their "pressure" and Volta's "tension" appear to connote the same idea — just as "high blood pressure" and "hypertension" are essentially synonymous.

Volta's "electric tension" — or students' "electric pressure" — is a causal agent with some important equivalences to electric potential in conducting bodies: (1) The potential is uniform in a conductor when there is no charge flow, and in a resistanceless conductor also when there is flow. (2) The value of the potential is higher/lower when there is more/less excess positive charge. (3) Charge is pushed through resistors in the high-to-low direction. By showing how to measure "electric tension", Volta made it a successful and widely accepted working concept. It influenced the development of ideas about force fields through Faraday's concept of "tension" along the lines of force. Nevertheless, the concept fell out of favor with physicists after about 1850. It survives today to some extent among engineers, who occasionally speak of "high tension wires."

Including electrostatic distant action

A major difficulty of Volta's model was that "electric tension" is defined only in the interior of a conducting body. The concept is not defined in the exterior space, where there is nothing to compress. The model was therefore unable to account for electrostatic distant action. Volta tried to modify his model in a way that would enable it to explain electrical effects in distant conductors. Late in 1778, in an attempt to explain how a charged disk A might influence the compressible fluid's "effort to push itself out" of a distant conducting disk B, he suggested the following possibility for modifying the compressed-air model:

> The electric fluid in B increases as much in expansive force as air does in a container of normal density when it is heated.

Of course, this thermal analogy did not lead anywhere. The field ideas that might have enabled Volta to revise his model to include distant action in an adequate manner did not become available until after his death in 1827. The CASTLE curriculum has recently accomplished the desired model revision using field ideas. Historically, however, "electric tension"gave way to "electric potential" after about 1850.

Potential functions are mathematical artifacts that Laplace used in translating Newton's theory of gravity into the language of the calculus. Laplace's work inspired Poisson to formalize the theory of static electricity using potential functions in 1811. The term "potential" was introduced in 1828 by Green, who made additional contributions to potential theory. The decisive development that led researchers to favor the approach of Poisson and Green came in 1849, when Kirchhoff pointed out that uniform "potential" in a conductor according to their mathematical model corresponds to uniform "tension" according to Volta's compression model — and that the mathematical model <u>also accounted for distant action</u> by means of a variable potential function in the exterior space. The potential function also predicted the Newtonian force acting on a charged test particle, whereas Volta's largely qualitative model provided no clear link to mechanics. Science historian John Heilbron summarizes the situation:

> Poisson's [potential function] V is the analytic form of Cavendish's "electrification" and Volta's "tension". It is more supple than either, for it permits statement of the classic problems of electrostatics ... in full generality.

All this made potential theory extremely useful for the nineteenth-century research agenda, and it led to the rapid triumph of an approach based on formal mathematically models over an older tradition that emphasized intuitive foundations. Heilbron has this to say about the shift to mathematical instrumentalism:

The work of Volta, Cavendish and Coulomb brought electrostatics to the point that it could suffer its definitive quantification at the hands of the mathematical physicists of the Ecole Polytechnique. The step permanently removed higher electrical theories from the reach of the Gilberts, Franklins and Voltas who had prepared it.

<u>The problem of abstract definitions</u>

The triumph in research of mathematical over intuitive approaches to understanding electricity has also shaped electricity instruction. A major direction appears to have been set in 1849 by Kirchhoff's association of electric potential with electrical energy. Rather than inventing a causal-agent conception of electric potential — like "potential electric pressure" in the CASTLE curriculum — that could be linked to an intuitive foundation, textbooks have been led to employ an energy-related conception descended from Kirchhoff. Textbooks typically provide the following definitions of potential difference between points A and B:

> Definition 1 — Work done per unit charge moved from A to B.

> Definition 2 — Line integral of the electric field from A to B.

These abstract definitions are very useful in research, since they relate quantitative values of potential difference to the values of other variables in a concise manner that makes for efficient calculations. They are problematic for students, however, because they define potential by means of abstract constraint relationships which connect it only to other incompletely assimilated concepts. They fail to provide the intuitive <u>connection to the familiar</u> needed by beginners in any field.

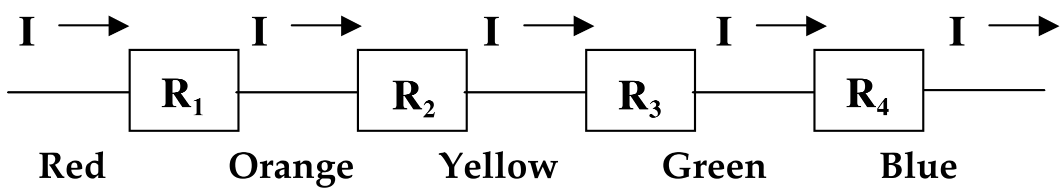
Instruction can sometimes make good use of models that have become obsolete in research, by retaining them as intuitive foundations for the formal abstractions employed in professional work. Bohr's electron orbit model is an extremely useful example in the teaching of atomic physics. A case can be made that science education lost something equally useful when the leaders of research failed to retain Volta's compressible fluid model as an intuitive foundation in the teaching of electricity. The CASTLE curriculum remedies this situation by revitalizing Volta's compression model to make the "electric pressure" concept available to beginning students. "Electric potential" is a more powerful concept than "electric pressure" in research because it is more inclusive. But "electric pressure" is more useful <u>for the beginning of</u> <u>instruction</u> because it provides an intuitive causal agent based on concrete experiences with compressed air.

Appendix F

NET RESISTANCE OF SERIES & PARALLEL RESISTORS

VISUALIZE SERIES CONNECTIONS

- Series resistors are connected end-to-end, which forms a single flow path.
- Imagine the 2 free end wires being given red and blue pressures by a battery.
- That will provide the same flow rate through each individual resistor:



CALCULATE NET SERIES RESISTANCE

The net (overall) pressure difference is the sum of the individual resistor differences:

$$\Delta V_{net} = \Delta V_1 + \Delta V_2 + \Delta V_3 + \Delta V_4$$

Use Ohm's Law with the same current **I** through each resistor to convert this to:

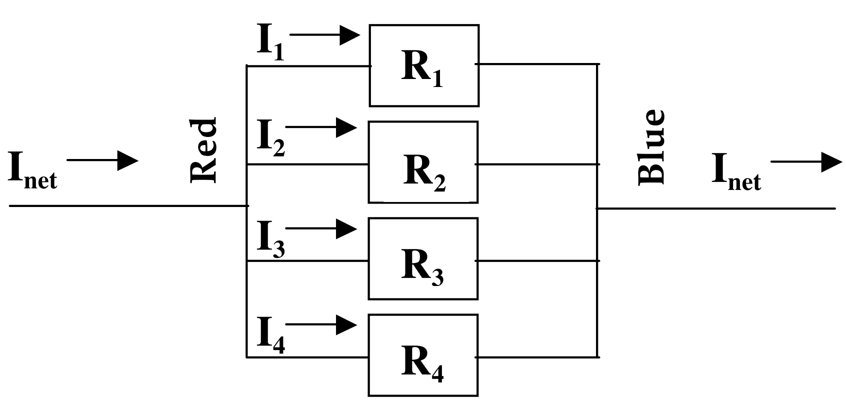
$$IR_{net} = IR_1 + IR_2 + IR_3 + IR_4$$

Dividing by **I** shows how individual resistance values determine net resistance:

$$R_{net} = R_1 + R_2 + R_3 + R_4$$

VISUALIZE PARALLEL CONNECTIONS

- Parallel resistors are separate side-by-side flow paths between 2 conductors.
- Imagine these 2 conductors being given red and blue pressure by a battery.
- That will provide the same pressure difference across each individual resistor:



CALCULATE NET PARALLEL RESISTANCE

The net flow rate out of the red conductor and into the blue conductor is

$$\mathbf{I_{net} = I_1 + I_2 + I_3 + I_4}$$

Use Ohm's Law with same voltage $\mathbf{\Delta V}$ across each resistor to convert this to:

$$\Delta V/R_{net} = \Delta V/R_1 + \Delta V/R_2 + \Delta V/R_3 + \Delta V/R_4$$

Dividing by $\mathbf{\Delta V}$ shows how individual resistances determine the net resistance:

$$1/R_{net} = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4$$

ANOTHER PERSPECTIVE

There is a simple way to think about this somewhat strange looking equation:

Since **R** measures ability to hold back or resist charge flow, **1/R** would be a measure of ability to let through, or conduct. So the equation is telling us that:

Total ability to let through	=	Channel #1 ability to let through	+	Channel #2 ability to let through	+	Channel #3 ability to let through	+	Channel #4 ability to let through

or another perspective might be:

Net conductance	=	Conductance through channel #1	+	Conductance through channel #2	+	Conductance through channel #3	+	Conductance through channel #4