SECTION 2

Modeling Electricity: The Electron Shuffle

Section Overview

Students participate in a kinesthetic model of a simple circuit to gain understanding of electric current and the flow of energy in a circuit. In this model, students role-play the part of a bulb and battery and simulate charges using pretzels. By forming a large circle, students pass the pretzels around, starting from the "battery," passing through the bulb, and returning to the battery. The teacher acting as a switch tells students when to start and stop. The model provides an idea of how energy and current flow through a circuit. Students then simulate what occurs in a series circuit with increasing battery voltage, more than one bulb, and bulbs requiring different amounts of energy. Based on the model, the class discusses series circuits, power, resistance, and electric potential. Students also draw diagrams of electrical circuits and apply the concepts they have modeled to describe and compare different series circuits.

Background Information

One of the attributes of metals that contribute to their high electrical conductivity is that their outermost electrons are easy to move. These outermost electrons are known as free electrons. They are bound to the metal lattice but not to any single atom. They move randomly from atom to atom due to thermal energy, hence they are also good heat conductors. However, on the average there is no net current when they are in thermal equilibrium due to the randomness of their thermal motion.

When a voltage is applied across a metal, an electric field is set up across the conductor that pushes the charge toward the positive terminal. The analogy of current flowing often leads to a misconception that electrons flow out of the negative terminal of the battery and to the positive. What occurs in the circuit is that all the electrons feel a push toward the positive terminal of the battery at the same time. Current does not begin to flow in one location of the circuit, rather it begins to flow in the entire circuit. A current is described as opposite to the flow of electrons.

A voltage is the electric potential energy per unit charge and is often called the electric potential. If there is no difference in voltage across part of a circuit, then no work is done. The difference in voltage is equal to the work done to move a charge over a distance per unit of charge. When electrons (or ions) are pushed in a circuit, work is done to move the charge. As the charges move, they lose some of their kinetic energy due to colliding with other charges in the material. This causes the circuit to warm up.

Crucial Physics

- Models can be used to study phenomena.
- Electric potential or voltage is the potential energy per unit of charge, and is measured in volts (1 V = 1 J/C).
- Current is the amount of charge per unit of time that flows past a point and is measured in amperes (1 A = 1 C/s).
- Resistors are electronic devices that resist the flow of electric charge.
- In a series circuit, the current has a single path it can follow. The sum of the voltage dropped across each resistor is equal to the total voltage supplied to the circuit (conservation of energy). The current through each resistor is the same (conservation of charge).

Learning Outcomes	Location in the Section	Evidence of Understanding
Develop a physical model for electric current and potential energy.	***Investigate*** Part A, Steps 1-9 ***Physics Essential Questions***	Students run a kinesthetic model to simulate electric current and potential in series circuits. They describe various situations using this model and consider how to improve it.
Apply this physical model to trace the flow of electric current in series circuits.	***Investigate*** Part B, Steps 1-4 ***Physics Essential Questions*** ***Physics to Go*** Question 2	Students apply the kinesthetic model to describe and compare various circuits.

Section 2 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Pretzels, bag*	1 per group	

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the students to complete the *Investigate* portion of this section.

Teacher Preparation

- Open space for the students to form the circuit is required, or the students may circulate around the outside of the desks if done in a classroom.
- Poker chips (or other tokens such as pennies) may be substituted for pretzels if school regulations require this.
- Setting up an actual circuit that duplicates what the students are acting out is desirable. After the students have completed each section of the *Investigate*, showing the electric circuit relates their motion in the *Investigate* to the circuit.

Safety Requirements

- The students should have sufficient space to walk so they are not crowded together, and the area is clear of any obstructions.
- Pretzels should not be eaten after being handled by numerous students.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Pretzels, bag*	1 per group	

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the students to complete the *Investigate* portion of this section.

Teacher Preparation

- Open space for the students to form the circuit is required, or the students may circulate around the outside of the desks if done in a classroom.
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Safety Requirements

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NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Using short-term memory	***Investigate*** Part A, Step 6	**Augmentation** • Students who struggle to access their short-term memory may need note cards with the vocal parts written on the card to prompt the required vocal announcements. This type of repetition is very beneficial for these students to commit the concepts to their long-term memory, but they will need the note cards to assist them in the beginning.
Using academic vocabulary to explain understanding of concepts	***Investigate*** Part A, Step 9 ***Investigate*** Part B, Step 3	**Augmentation** • Students with language-based learning disabilities struggle to clearly explain their thoughts in words, especially when using new vocabulary. They often use vague words such as "thing" or "stuff." • Require students to use words such as coulomb, joule, energy, ampere, etc. in their explanations. Remind them to refer back to Step 2 to review the vocabulary. • Check in with students who report that they are struggling to use the required vocabulary. To help students use the descriptive words, model a good written response to Step 9.a), ask them to tell you how to write the answer for Step 9.b), and then ask them to independently answer Steps 9.c)-f). • Ask students to share their answers with the class. Then ask the group if they agree and disagree and to explain why. **Accommodation** • Provide statements that allow students to fill in the blanks. For example: A five-volt battery requires __________ joules of energy for each _____________ of charge.
Learning content-specific vocabulary	***Physics Words*** ***Physics to Go*** Question 1	**Augmentation** • Students do not use most content-specific vocabulary in their daily lives so it takes much longer for students to learn this type of vocabulary. Instruct students to make flashcards with a new vocabulary word on one side and the definition on the other side. • Create a word wall in the classroom. This is a strategy that many elementary teachers use. You or the students can decide which words to include and then display the words on note cards, construction paper, etc. The word wall has many uses and can be differentiated and interactive. Students who struggle with reading should be required to practice reading the challenging words and/or writing sentences with these words. Students could also be asked to sort the words to create a concept map with meaningful connections. • During this unit, encourage students to use a certain number of words from the word wall in discussions or assignments. **Accommodation** • Provide students with two-column study sheets that have the vocabulary word in one column and the definition in the other column. Teach them how to study with this type of study sheet. Require students to use the study sheet when answering assignment questions to include content vocabulary in their answers.

<table>
<tr><th>Learning Issue</th><th>Reference</th><th>Augmentation and Accommodations</th></tr>
<tr><td>Learning SI units</td><td>Physics Words</td><td>Augmentation
• Students struggle to memorize units, especially if the words are unfamiliar and the symbols are used interchangeably with the words before the words are learned.
• Ask students to create a chart that includes the quantity, variable, unit, and unit symbol.
<table><tr><th>Quantity</th><th>Variable</th><th>Unit</th><th>Symbol</th></tr><tr><td>charge</td><td>q</td><td>Coulombs</td><td>C</td></tr><tr><td>voltage</td><td>V</td><td>volt</td><td>v</td></tr><tr><td>current</td><td>I</td><td>ampere</td><td>A</td></tr><tr><td>power</td><td>P</td><td>watt</td><td>W</td></tr><tr><td>energy</td><td>E</td><td>joule</td><td>J</td></tr></table>
Accommodation
• Provide the chart for students to tape into their notebooks.</td></tr>
</table>

NOTES

CHAPTER 6

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Comprehension	***Investigate*** Part A, Steps 9.a)-f) Part B, Steps 3.a)-d)	Students will not be able to understand the questions if they do not understand the vocabulary. After students have answered the questions in their *Active Physics* log, pair ELL students with native speakers. Have each pair compare answers and come to a consensus where they disagree. Hold a class discussion to check answers and understanding of the vocabulary and concepts. You may wish to role-play any situation with which students have trouble.
Comprehension	***Investigate*** Part B, Step 4.a) ***Physics to Go*** Questions 5-6	Once students have completed each table, hold a class discussion to review their answers. Encourage ELL students to tell why they answered as they did. They will benefit from the opportunity to use their verbal language skills.
Vocabulary comprehension	***Physics to Go*** Question 1	Check the definitions in students' charts for accuracy. Have ELL students give the definitions orally. Listen for correct grammar and sentence construction, as well as proper pronunciation. Model proper usage and pronunciation as necessary.
Vocabulary Making inferences	***Investigate*** Part B, Step 2 ***Physics Words*** ***Active Physics Plus***	The word "electron" is used here, but it is not defined until the next section. Before you wrap up instruction, have students attempt a definition of "electron" in their *Active Physics* log. Revisit their ideas in the next section, when the definition is presented.
Higher order thinking	***Physics Essential Questions***	The introductory paragraph in the *Investigate* section points out that no scientific model is perfect. Now that students have role-played different versions of the circuit model and have written about the model, ask students to identify and explain some of the imperfections of the model.

Two important aspects of learning a new language are speaking and writing in that language. Some ELL students will be self-conscious and shy about speaking in front of their peers, while others will be less reluctant to try. Be sure to encourage all ELL students to speak in class, and give them opportunities to write on the board from time to time. Experience will broaden their comfort level. Over time, the shy students will get increasingly less self-conscious about speaking in front of their classmates.

With that in mind, hold a class discussion to review *Section 2*. Call on ELL students to answer or address the bulleted items below.

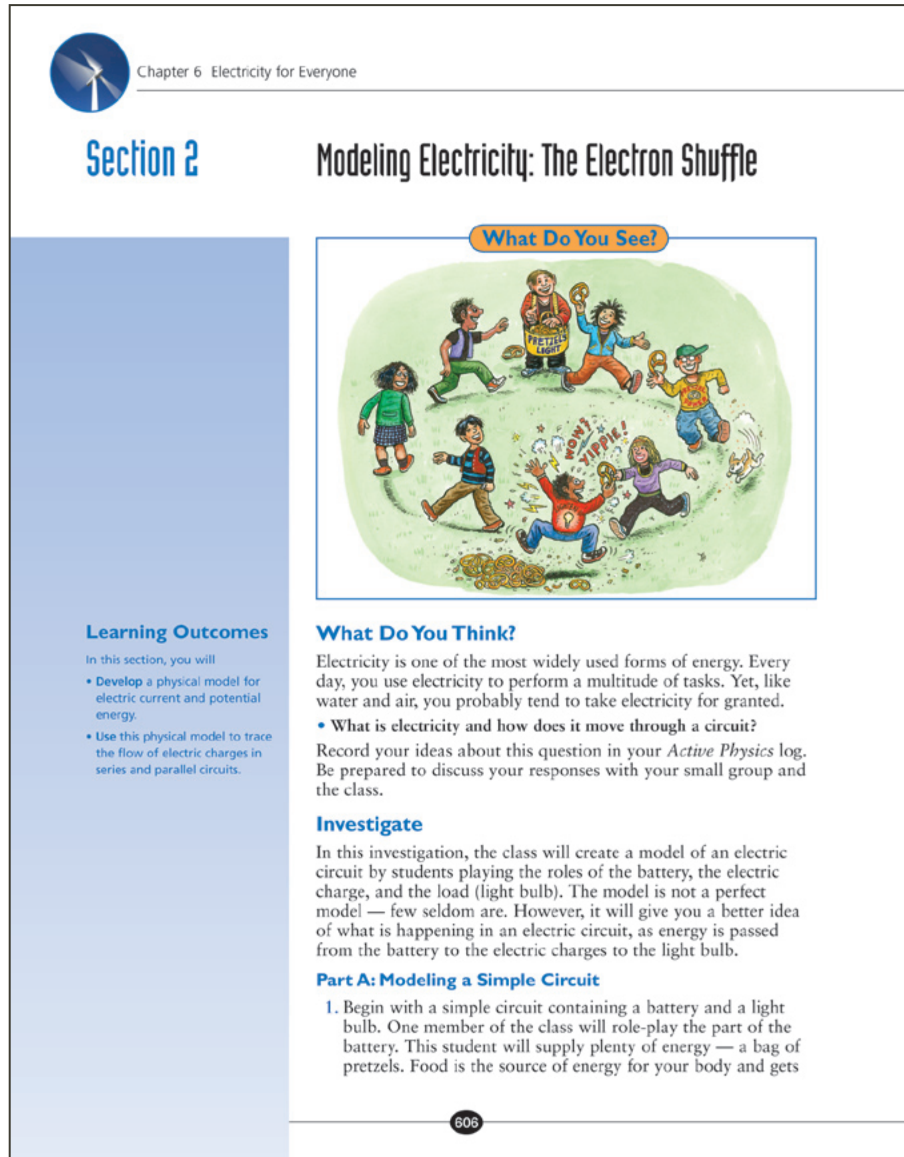
- In a schematic diagram, what represents a light bulb? (*A loop in the center of a circle.*) What does a zigzag line represent? (*A resistor.*) Write the definition of resistor on the board. (*An electronic device that opposes electric current.*)
- Current can be defined as the rate of flow of electric charge. How else can current be defined? (*The number of coulombs passing a point in one second.*) What is the SI unit of current? (*The ampere.*)
- Write the equation for voltage on the board. (1 V = 1 J/C) What does it mean, in words? (*One volt equals one joule per coulomb.*)
- How much electric power is represented by 60 joules per second? (*60 watts.*)
- In the Electron Shuffle, what did the student receiving the pretzels represent? (*The light bulb.*) What represented the current? (*The number of students passing a point every second.*) What did each moving student represent? (*A coulomb.*)

NOTES

SECTION 2
Teaching Suggestions and Sample Answers

What Do You See?

What does electricity have to do with pretzels? This question should immediately hook your students' attention to the concepts introduced in this section. The excitement depicted serves to focus students' descriptions of the illustration. Consider using the overhead of the *What Do You See*? illustration for discussion. Students will most likely comment on what they think the people are doing. Tell that the artist had a purpose in mind and that each image provides a clue to the physics concepts they will be investigating. Continue to encourage students to elicit their responses, and remind them that they will have other



Chapter 6 Electricity for Everyone

Section 2 Modeling Electricity: The Electron Shuffle

What Do You See?

Learning Outcomes

In this section, you will

- **Develop** a physical model for electric current and potential energy.
- **Use** this physical model to trace the flow of electric charges in series and parallel circuits.

What Do You Think?

Electricity is one of the most widely used forms of energy. Every day, you use electricity to perform a multitude of tasks. Yet, like water and air, you probably tend to take electricity for granted.

- What is electricity and how does it move through a circuit?

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

In this investigation, the class will create a model of an electric circuit by students playing the roles of the battery, the electric charge, and the load (light bulb). The model is not a perfect model — few seldom are. However, it will give you a better idea of what is happening in an electric circuit, as energy is passed from the battery to the electric charges to the light bulb.

Part A: Modeling a Simple Circuit

1. Begin with a simple circuit containing a battery and a light bulb. One member of the class will role-play the part of the battery. This student will supply plenty of energy — a bag of pretzels. Food is the source of energy for your body and gets

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Students' Prior Conceptions

It may come as a surprise to some that many students are timid about using generators and bare wires in inquiry investigations, given the current technological devices available to many students. However, it is vital that teachers discuss the safety of using the bulbs, batteries, generators, power supplies, and wires with bare ends for students to know that they are working in a safe learning environment. Students may also harbor misconceptions about some of the "jargon" existing around the study of electricity, such as open circuits, closed circuits, short circuits, etc. You need to listen to conversations and intervene if a student seems fearful or unsafe and needs the confidence to explore and confront the misconceptions about what is safe and what is unsafe.

In the *Investigate* of this section, students are provided with the opportunity to model electric charge and create a physical model for the flow of electric current and the passage of energy from the battery through the atoms and electrons of the wires to the elements of the bulbs and then through the circuit back to the battery. Be cautious that this physical model does not reinforce misconceptions:

1. **Students tend to think of what happens in a circuit sequentially, rather than holistically as a system; they think that a change in one place only effects components further along in the circuit, rather than affecting the entire circuit.** During the Electron Shuffle investigations, ask students to note the behavior of the students in front and behind them. Have them keep a constant distance between themselves and ask them to observe what occurs when one part of the line slows down or speeds up (analogous to a higher or lower resistance). The slowing down of one

opportunities to revisit this illustration so that they can understand the relevance of each image and how it contributes to a deeper understanding of electricity. Accept all answers and record some of them on the board for students to retain a visual reference of their initial impressions to realize how their learning evolves.

What Do You Think?

Let students know that electricity is the most widely used form of energy by humans. Ask them some of the tasks where they use electrical energy. Have students record their ideas to the *What Do You Think?* question in their logs and encourage them to draw diagrams depicting their ideas. After students discuss their ideas with their group, have a whole-class discussion. Focus on the responses that provide an opportunity for you to get the students engaged in the physics concepts presented in this chapter. Emphasize that there are no "right" answers and that all answers are acceptable. The purpose of the question is to elicit students' prior knowledge. Record students' misconceptions so that they can be addressed at appropriate times during the section. Ask students to refer to their answers while they are being introduced to new physics concepts. Point out that when they are aware of what they think, they will be able to increase what they know.

Students' Prior Conceptions *(continued)*

part of the line slows the entire line, and thus reduces the current. Point out that whatever occurs in one part of the circuit affects the entire circuit.

2. **Students believe that electrons flow from one source, such as a battery through the circuit, to the bulb to light it.** In this section, students need to develop more sophisticated ideas that demonstrate how energy flows and how electrical circuits are either simple loops of conductors or charge carriers. You should emphasize that electric current is not a continuous flow of electrons. The charge that flows through a circuit originates in the electrons of the atoms that are the charge carriers.

- **Electrical energy is carried by individual electrons***.* In an electric circuit, the drift speed of electrons is less than 1 cm/sec, but the energy carried by the electron movement travels as a wave at the speed of light in that material. Thus, when you close a switch to turn on a light bulb, it is not necessary for the electrons to flow from the switch to the bulb, but rather simply the energy is passed from electron to electron along the wire until it reaches those electrons in the bulb to cause it glow.
- **A battery is seen as a store of electrical energy that provides a constant amount of current to the circuit, regardless of what devices are in the circuit**. This naïve preconception hinders student understanding of the flow of current in a simple DC circuit.
- **Voltage is seen as a property of current, rather than as a cause (precondition) for current and batteries are seen**

CHAPTER 6

What Do You Think?

A Physicist's Response

Electricity is energy due to electric charges. It can be static (charges don't move) or dynamic (charges move). When electric charges move, a current can be described. Current is the amount of charge that goes past a point or surface in a second. The moving charges carry energy that can be transported to devices such as light bulbs, toasters, and radios. In order to make an electric charge move from where it normally would be, it has to experience a force – a push or a pull. This can easily be supplied by nearby charges. Charges can push and pull on each other without touching because like charges repel each other and opposites attract.

A battery has a positive and negative side. When these sides are connected a chemical reaction inside the battery takes place that produces electrons. The electrons collect on the negative terminal of the battery. The loosely bonded electrons in the entire circuit begin to move toward the positive terminal because of the force they feel (they are pushed away from the negative side by the electrons there that are leaving). The current in the circuit is the amount of these charges that pass a given point at each second. The electrons are pushed in a direction opposite to the electric field, so that they move from low potential to high potential. However, you define current to be the flow of positive charge, or the opposite flow of negative charges. So the current flows from high potential to low, even though the moving negative charges comprising the current move in the opposite direction. The electrons in a metal are special because they are not bound to any specific metal atom but to the collection of metal atoms. This special property of metals is why they conduct electricity so well.

The chemical reaction in a battery does not take place unless the battery is hooked up in a closed circuit. In common alkaline batteries, one electrode or terminal is made of zinc and the other is made of manganese-oxide with an alkaline electrolyte (a chemical) to make the reaction work.

Investigate

Part A

Teaching Tip

For very large classes (30 or more), you may choose to do the first part of the activity with one-half the class, while the other half observes and takes notes for their group. The participants and observers can then switch for other parts of the *Investigate*.

Teaching Tip

You may choose to have the students use a different type of "token" rather than pretzels. To maintain hygiene, students should not be allowed to eat the pretzels after they are handled by various people.

1.

The student who plays the light bulb would ideally be a very energetic student, perhaps one who has difficulty sitting still in class. The student should be told to act only mildly energetic during this first phase. In the following rounds, the light bulb will be much more energized.

Students' Prior Conceptions *(continued)*

as a constant source of current. You should encourage students to understand that batteries push on the mobile charges in the circuit conductors. It is the potential difference across the positive and negative poles of a battery that pushes a charge.

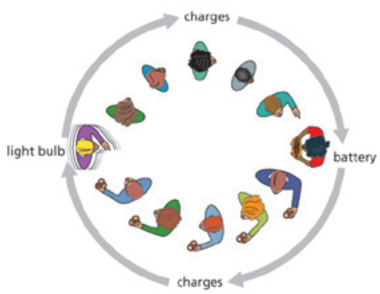
- **Students believe that bulbs use up the current in a circuit.** You need to emphasize that bulbs control the rate at which charge flows in the simple circuit but not the total amount of charge that flows.
- **Students often do not differentiate between electrical energy, current, voltage and electricity: all these share properties of movement, storability and consumption**.

Allow students to use their own words to describe their physical model and then to compare their words with the physics concepts as described in *Physics Talk* and scientific terminology. Language can be both a hindrance and a way to confront and overcome misconceptions when discussing physical models of current, batteries, and circuits.

These naïve conceptions exhibited by students can be revisited throughout the first six sections of this chapter and are not necessarily only relegated to one section. You should continue to intervene throughout the chapter to align student understanding with scientific concepts.

used up as you play. A second student will play the part of the light bulb. For example, this person will have to shake, jump, dance, or move in some way. Other students will play the parts of the electric charges in the circuit.

2. Form a large circle of the electric charges as if you were all waiting in line for something. You should be facing the back of the charge in front of you.



3. Have the battery stand at one side of the circle ready to give out the energy, the particles sent out by the batteries to carry energy to the light bulb (a pretzel to each charge). Have the light bulb stand at the opposite side of the circle ready to receive and be energized by the charges as they come past (takes the pretzel). Each unit of charge, called a *coulomb*, will pick up one *joule* of energy (represented by one pretzel).

4. The teacher will act as the switch and tell you when to begin and when to stop. On a signal from the teacher (closing and opening the switch), the charges will begin and stop moving in a clockwise circle.

5. When the energized charge passes by the light bulb, it gives its energy to the light bulb by dropping the energy into the hand of the light bulb. The light bulb needs to show that it has become energized by getting "excited" (a little dance will do). The charge now must continue on its path back to the battery to pick up more energy, and repeat the cycle. Notice that only the energy gets used up, not the charges themselves. The charges continue on their path through the circuit.

You have now completed round 1 of the "Electron Shuffle." In round 1, the battery (source of pretzels) gave each packet of charge (a student) a certain amount of energy (one pretzel). The charge then gave that energy to the light bulb (a student) who converted that electrical energy into light (a dance). The charges continue to the battery to get more energy and repeat the process.

6. In round 2 of the Electron Shuffle, the moves are the same. However, in round 2, there is a vocal part added. The person representing the battery announces once, "the battery voltage is one *volt* which equals one joule of energy for each coulomb of charge." The student receiving the pretzel then responds "one coulomb of charge receiving one joule of energy." The battery then distributes the pretzels to the students as they file through. The battery announces periodically, "Please move along, one coulomb per second is one *ampere* (often shortened to amp) of current." When the light bulb dances, he or she must occasionally say, "I just received one joule of energy from that coulomb of charge."

a) What are the variables that could change in the Electron Shuffle?

2.

Students should form a closed circle as directed.

3.

One large bag of pretzels will be more than sufficient for a class. For reasons of hygiene and possible dietary considerations, the student acting as the light bulb is not asked to eat the pretzels that have been handled by others.

4.

Let students know what signal you will give to indicate a closed and an open switch. When you give the "closed" signal, students should begin to move in a circle. Students should walk slowly during this part. A faster walk will be required in round 3 (*Step 7*). When the circuit is "open," everyone should stop.

5.

Students "energize" the light bulb by depositing their pretzel in a basket by the light bulb. The "light bulb" should appear to eat the pretzels "using them up." The pretzels may be collected at the end, and reused for the next class.

6.

Students repeat the process, by adding vocalizations.

6.a)

Students may suggest that variables would be the number of pretzels given out by the battery, and the speed at which they walk.

7.

Students repeat the Electron Shuffle using three pretzels for each student (yielding a very energized student light bulb) for round 3. Students simulating electrons provide one pretzel to the light per second.

8.

Students receive one pretzel from the battery and walk two times faster for round 4.

9.

Consider having the class simulate some or all of these situations to emphasize the amount of energy delivered to the bulb.

9.a)

Students walk at their original rate with five pretzels.

9.b)

Students walk three times faster with their pretzels.

9.c)

Students walk around the circle with two pretzels each at the original speed.

9.d)

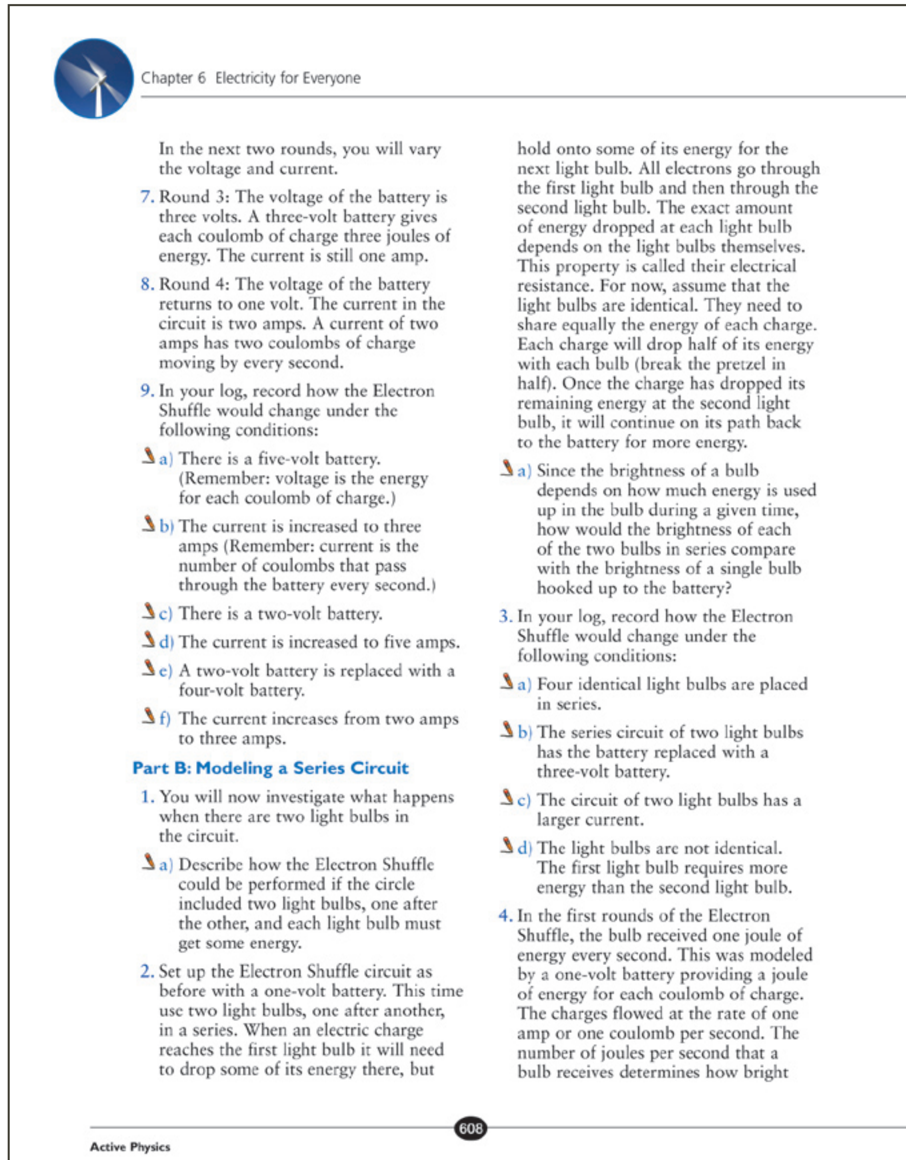
Students keep the same number of pretzels, but walk at five times their original speed.

9.e)

Students walk around the circle at their original speed with four pretzels.

9.f)

Students walk around the circle with their pretzels at three times the original speed.



Chapter 6 Electricity for Everyone

In the next two rounds, you will vary the voltage and current.

7. Round 3: The voltage of the battery is three volts. A three-volt battery gives each coulomb of charge three joules of energy. The current is still one amp.

8. Round 4: The voltage of the battery returns to one volt. The current in the circuit is two amps. A current of two amps has two coulombs of charge moving by every second.

9. In your log, record how the Electron Shuffle would change under the following conditions:

a) There is a five-volt battery. (Remember: voltage is the energy for each coulomb of charge.)

b) The current is increased to three amps (Remember: current is the number of coulombs that pass through the battery every second.)

c) There is a two-volt battery.

d) The current is increased to five amps.

e) A two-volt battery is replaced with a four-volt battery.

f) The current increases from two amps to three amps.

Part B: Modeling a Series Circuit

1. You will now investigate what happens when there are two light bulbs in the circuit.

a) Describe how the Electron Shuffle could be performed if the circle included two light bulbs, one after the other, and each light bulb must get some energy.

2. Set up the Electron Shuffle circuit as before with a one-volt battery. This time use two light bulbs, one after another, in a series. When an electric charge reaches the first light bulb it will need to drop some of its energy there, but hold onto some of its energy for the next light bulb. All electrons go through the first light bulb and then through the second light bulb. The exact amount of energy dropped at each light bulb depends on the light bulbs themselves. This property is called their electrical resistance. For now, assume that the light bulbs are identical. They need to share equally the energy of each charge. Each charge will drop half of its energy with each bulb (break the pretzel in half). Once the charge has dropped its remaining energy at the second light bulb, it will continue on its path back to the battery for more energy.

a) Since the brightness of a bulb depends on how much energy is used up in the bulb during a given time, how would the brightness of each of the two bulbs in series compare with the brightness of a single bulb hooked up to the battery?

3. In your log, record how the Electron Shuffle would change under the following conditions:

a) Four identical light bulbs are placed in series.

b) The series circuit of two light bulbs has the battery replaced with a three-volt battery.

c) The circuit of two light bulbs has a larger current.

d) The light bulbs are not identical. The first light bulb requires more energy than the second light bulb.

4. In the first rounds of the Electron Shuffle, the bulb received one joule of energy every second. This was modeled by a one-volt battery providing a joule of energy for each coulomb of charge. The charges flowed at the rate of one amp or one coulomb per second. The number of joules per second that a bulb receives determines how bright

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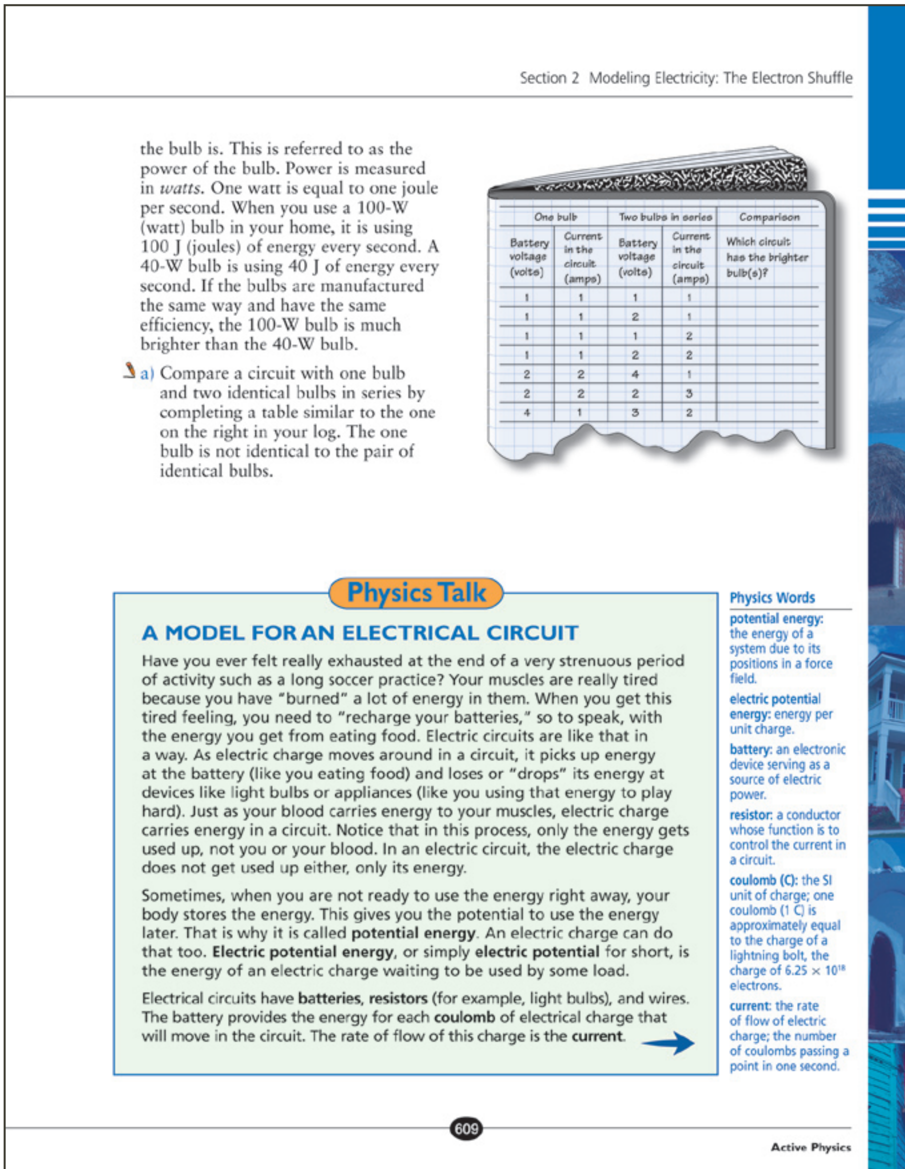
Active Physics

Part B

Teaching Tip

Prior to starting *Part B*, you can set up an electric circuit with a single bulb connected to a power source, a second circuit with two bulbs, two bulbs in a series, and a third circuit with four bulbs in series. Before the students start the Electron Shuffle, energize the circuit with the single bulb so the students may see the bulb's brightness. As the students perform the various parts of the Electron Shuffle, light the two bulbs in series, and then the four bulbs in series (always using the same voltage), allowing the students to observe how the bulb's brightness changes with the addition of extra bulbs in series. This will confirm what they have concluded from the shuffle.



the bulb is. This is referred to as the power of the bulb. Power is measured in *watts*. One watt is equal to one joule per second. When you use a 100-W (watt) bulb in your home, it is using 100 J (joules) of energy every second. A 40-W bulb is using 40 J of energy every second. If the bulbs are manufactured the same way and have the same efficiency, the 100-W bulb is much brighter than the 40-W bulb.

a) Compare a circuit with one bulb and two identical bulbs in series by completing a table similar to the one on the right in your log. The one bulb is not identical to the pair of identical bulbs.

One bulb		Two bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
1	1	1	1	
1	1	2	1	
1	1	1	2	
1	1	2	2	
2	2	4	1	
2	2	2	3	
4	1	3	2	

Physics Talk

A MODEL FOR AN ELECTRICAL CIRCUIT

Have you ever felt really exhausted at the end of a very strenuous period of activity such as a long soccer practice? Your muscles are really tired because you have "burned" a lot of energy in them. When you get this tired feeling, you need to "recharge your batteries," so to speak, with the energy you get from eating food. Electric circuits are like that in a way. As electric charge moves around in a circuit, it picks up energy at the battery (like you eating food) and loses or "drops" its energy at devices like light bulbs or appliances (like you using that energy to play hard). Just as your blood carries energy to your muscles, electric charge carries energy in a circuit. Notice that in this process, only the energy gets used up, not you or your blood. In an electric circuit, the electric charge does not get used up either, only its energy.

Sometimes, when you are not ready to use the energy right away, your body stores the energy. This gives you the potential to use the energy later. That is why it is called **potential energy**. An electric charge can do that too. **Electric potential energy**, or simply **electric potential** for short, is the energy of an electric charge waiting to be used by some load.

Electrical circuits have **batteries**, **resistors** (for example, light bulbs), and wires. The battery provides the energy for each **coulomb** of electrical charge that will move in the circuit. The rate of flow of this charge is the **current**.

Physics Words

potential energy: the energy of a system due to its positions in a force field.

electric potential energy: energy per unit charge.

battery: an electronic device serving as a source of electric power.

resistor: a conductor whose function is to control the current in a circuit.

coulomb (C): the SI unit of charge; one coulomb (1 C) is approximately equal to the charge of a lightning bolt, the charge of 6.25×10^{18} electrons.

current: the rate of flow of electric charge; the number of coulombs passing a point in one second.

one bulb		two bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
1	1	1	1	*1 bulb circuit*
1	1	2	1	*equal*
1	1	1	2	*equal*
1	1	2	2	*2 bulb circuit*
2	2	4	1	*1 bulb circuit*
2	2	2	3	*1 bulb circuit*
4	1	3	2	*1 bulb circuit*

1.a)

Students repeat the Electron Shuffle with two "light bulbs" in series. Each light bulb will receive half the energy of each charge walking past. To avoid breaking pretzels, you may choose to give each "charge" two pretzels, so that each light bulb may receive a whole pretzel.

2.a)

Students should realize that since each light bulb only receives half the energy, each is only one-half as bright as it would have been had it received all the energy from each charge.

3.a)

Each light bulb would only receive one-fourth of a pretzel of energy per second.

3.b)

Each light bulb would receive one and a half pretzels of energy per second.

3.c)

Each light bulb would receive more than one and a half pretzels per second because the charges (students) would be reaching the light bulbs at a faster rate.

3.d)

The first light bulb receives more pretzels per second than the second light bulb.

4.a)

See table at left.

Physics Talk

This *Physics Talk* provides students' with the vocabulary and facts that correspond to the Electron Shuffle model they developed. It also introduces symbols commonly used in

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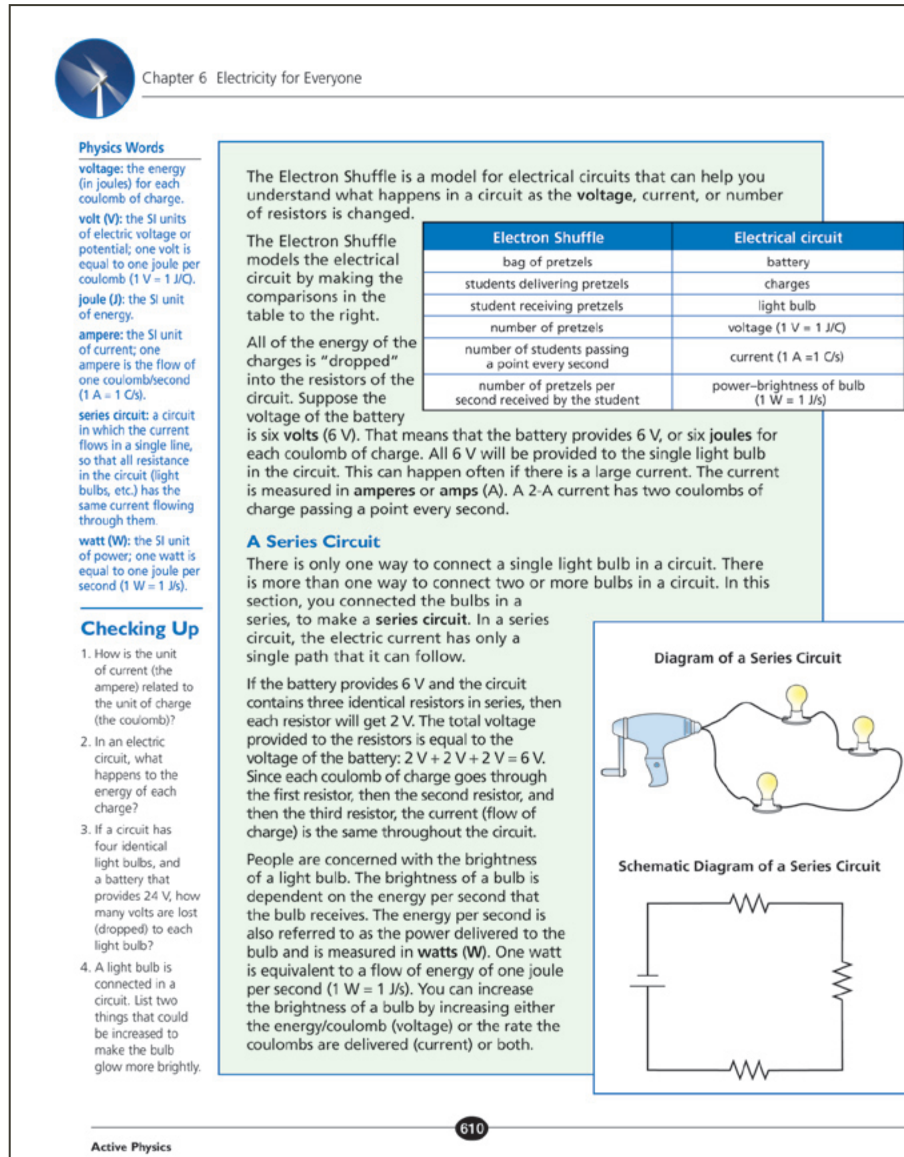
circuit diagrams. It compares an electric circuit to the end of a strenuous exercise or sport like soccer. Students learn how electric charges move around in a circuit, how increased voltage increases the amount of energy each charge carries, and why increased current means more charges carry energy per second.

Emphasize that in an electric circuit the charge carries energy, supplies it to devices, and then gets more energy, but the amount of charge does not change. Charge is conserved in a circuit. Introduce the physics words and relate these to the Electron-Shuffle model and the analogy of playing soccer using the information in the student text. Check students' understanding of potential energy (stored energy), voltage (electric potential energy per charge), resistors, current, and power. Describe the unit of each physical quantity. Point out that the charge carrying energy does not bring that energy back to the battery. It transfers all the energy it has to the resistors in the circuit.

Tell students that in a series circuit the current has only one way to go; there are no "branches" in the path. All the energy is transferred to the resistors in the circuit. Ask them to describe the series circuits they made in the Electron-Shuffle model in the *Investigate*. Then discuss how the brightness of a bulb is dependent on the energy per second that the bulb receives.

Make connections with the Electron-Shuffle model and the tables students filled out in the *Investigate*. Discuss circuit diagrams and the symbols that represent each component in a circuit. Have students draw a circuit diagram of the circuits they constructed using the Electron-Shuffle model.


Chapter 6 Electricity for Everyone

Physics Words

voltage: the energy (in joules) for each coulomb of charge.

volt (V): the SI units of electric voltage or potential; one volt is equal to one joule per coulomb (1 V = 1 J/C).

joule (J): the SI unit of energy.

ampere: the SI unit of current; one ampere is the flow of one coulomb/second (1 A = 1 C/s).

series circuit: a circuit in which the current flows in a single line, so that all resistance in the circuit (light bulbs, etc.) has the same current flowing through them.

watt (W): the SI unit of power; one watt is equal to one joule per second (1 W = 1 J/s).

Checking Up

1. How is the unit of current (the ampere) related to the unit of charge (the coulomb)?
2. In an electric circuit, what happens to the energy of each charge?
3. If a circuit has four identical light bulbs, and a battery that provides 24 V, how many volts are lost (dropped) to each light bulb?
4. A light bulb is connected in a circuit. List two things that could be increased to make the bulb glow more brightly.

The Electron Shuffle is a model for electrical circuits that can help you understand what happens in a circuit as the **voltage**, current, or number of resistors is changed.

The Electron Shuffle models the electrical circuit by making the comparisons in the table to the right.

Electron Shuffle	Electrical circuit
bag of pretzels	battery
students delivering pretzels	charges
student receiving pretzels	light bulb
number of pretzels	voltage (1 V = 1 J/C)
number of students passing a point every second	current (1 A =1 C/s)
number of pretzels per second received by the student	power–brightness of bulb (1 W = 1 J/s)

All of the energy of the charges is "dropped" into the resistors of the circuit. Suppose the voltage of the battery is six **volts** (6 V). That means that the battery provides 6 V, or six **joules** for each coulomb of charge. All 6 V will be provided to the single light bulb in the circuit. This can happen often if there is a large current. The current is measured in **amperes** or **amps** (A). A 2-A current has two coulombs of charge passing a point every second.

A Series Circuit

There is only one way to connect a single light bulb in a circuit. There is more than one way to connect two or more bulbs in a circuit. In this section, you connected the bulbs in a series, to make a **series circuit**. In a series circuit, the electric current has only a single path that it can follow.

If the battery provides 6 V and the circuit contains three identical resistors in series, then each resistor will get 2 V. The total voltage provided to the resistors is equal to the voltage of the battery: 2 V + 2 V + 2 V = 6 V. Since each coulomb of charge goes through the first resistor, then the second resistor, and then the third resistor, the current (flow of charge) is the same throughout the circuit.

People are concerned with the brightness of a light bulb. The brightness of a bulb is dependent on the energy per second that the bulb receives. The energy per second is also referred to as the power delivered to the bulb and is measured in **watts (W)**. One watt is equivalent to a flow of energy of one joule per second (1 W = 1 J/s). You can increase the brightness of a bulb by increasing either the energy/coulomb (voltage) or the rate the coulombs are delivered (current) or both.

Diagram of a Series Circuit

Schematic Diagram of a Series Circuit

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Active Physics

6-2a	Blackline Master
6-2b	Blackline Master

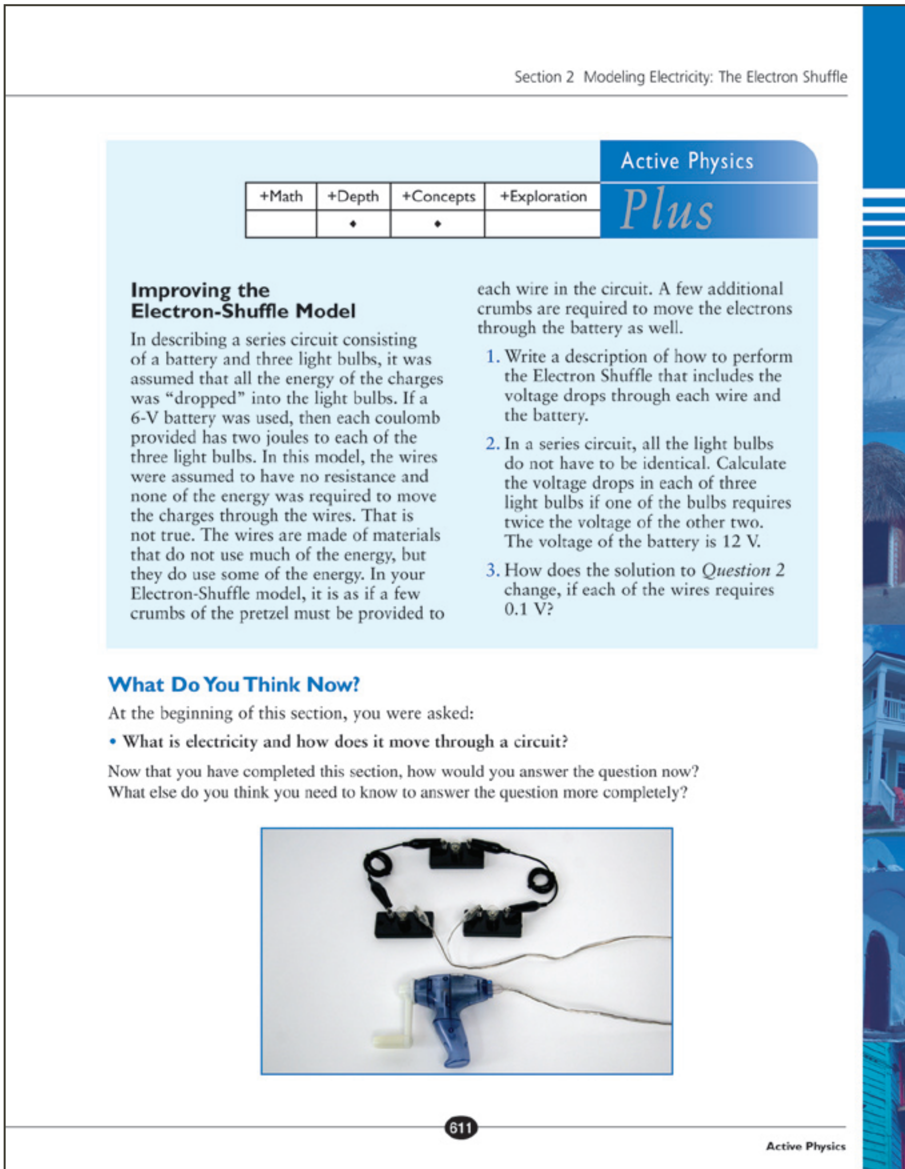
Checking Up

1.

An ampere is the amount of charge going past a point per second. Amperes = Coulombs per second.

2.

Energy is transferred from the battery to the charges and then from the charges to the different resistors in the circuit, such as light bulbs and fans. Some energy gets transferred into heating of the circuit. The moving charges transfer all their energy in the circuit before they return to the battery. No charges are lost. The charge remains constant in the circuit.


Section 2 Modeling Electricity: The Electron Shuffle

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
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Improving the Electron-Shuffle Model

In describing a series circuit consisting of a battery and three light bulbs, it was assumed that all the energy of the charges was "dropped" into the light bulbs. If a 6-V battery was used, then each coulomb provided has two joules to each of the three light bulbs. In this model, the wires were assumed to have no resistance and none of the energy was required to move the charges through the wires. That is not true. The wires are made of materials that do not use much of the energy, but they do use some of the energy. In your Electron-Shuffle model, it is as if a few crumbs of the pretzel must be provided to each wire in the circuit. A few additional crumbs are required to move the electrons through the battery as well.

1. Write a description of how to perform the Electron Shuffle that includes the voltage drops through each wire and the battery.
2. In a series circuit, all the light bulbs do not have to be identical. Calculate the voltage drops in each of three light bulbs if one of the bulbs requires twice the voltage of the other two. The voltage of the battery is 12 V.
3. How does the solution to *Question 2* change, if each of the wires requires 0.1 V?

What Do You Think Now?

At the beginning of this section, you were asked:

• **What is electricity and how does it move through a circuit?**

Now that you have completed this section, how would you answer the question now? What else do you think you need to know to answer the question more completely?

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Active Physics

3.

This is a series circuit. The energy is distributed equally among the four identical bulbs, so the voltage drops by 6 V across each bulb.

4.

To increase the brightness of a bulb, the amount of energy per second, or power, delivered to the bulb needs to increase. This can be done by either increasing the amount of energy carried by each charge (the voltage of the battery), or by increasing the rate at which the charges go around the circuit (increasing the current), or by increasing both the voltage (energy per charge) and the current (charge/second).

Active Physics Plus

This *Active Physics Plus* provides an opportunity for students to increase the depth of their understanding and introduces the concept of resistance in wires. Emphasize to students that as the charges travel through the wires and the battery, some of the energy is transferred to the atoms in the wire, causing the wire to warm up. Describe how this is similar to dropping some crumbs of the pretzels in the Electron-Shuffle model.

1.

Descriptions should include each charge dropping a few crumbs from each pretzel along the way to and from the resistor to represent the energy transferred to the wire, and some pretzel crumbs dropped at the battery representing its internal resistance.

2.

If there are three resistors and one requires twice the voltage of the other two, then the 12 V supplied by the battery will be distributed so that the two identical bulbs have a voltage of 3 V and the third bulb has a voltage of 6 V. For example, let the voltage in the two identical bulbs each be V, and the voltage in the bulb requiring double the voltage be 2V. The total for the three bulbs then would be $V + V + 2V = 12$ V or 4 V = 12 volts or $V = 3$ volts. Students could make an analogy that the bulb requiring twice the voltage is similar to two bulbs combined—they receive half of the energy supplied by the battery, and the other two bulbs each receive one quarter of the energy supplied by the battery.

3.

If each wire requires 0.1 V and there are four wires, then there is only 11.6 V to distribute to the bulbs. Of this, half goes to the bulb requiring twice as much voltage (5.8 V), and one quarter goes to each of the identical bulbs (2.9 V).

What Do You Think Now?

Ask students to review their previous answers to the *What Do You Think?* question. Ask them how they would answer this question now and survey the class for how many students changed their ideas. Point out that scientists often change their ideas as they gather more information. Discuss the information in *A Physicist's Response*. Consider highlighting the main aspects of how electrons generate electricity. Find out if students understand why metals are good conductors of electricity. Have them review the *What Do You See?* illustration. Learning the nuances of physics concepts that explain electricity will be easier for students if they are allowed to ask questions and discuss their doubts freely, without hesitation.

Physics

Essential Questions

What does it mean?

How do voltage and current relate to the brightness of a bulb?

How do you know?

How would you know if the Electron-Shuffle model is a useful model of current flow in circuits?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	* Models	Experimental evidence is consistent with models and theories

* Physicists use models to describe and better understand many phenomena. A description of how electricity works is called a "model." The Electron Shuffle is a model that helps support the description of how electricity works. Is a scientific model the same thing as reality, or is it just a convenient (and sometimes limited) description of reality?

Why should you care?

Part of your challenge is to create an outline for a training manual that will help people become acquainted with electrical use. Explain voltage and current using the Electron-Shuffle model and without using the Electron-Shuffle model.

Reflecting on the Section and the Challenge

In this section, you developed a concrete model for the flow of current in a series circuit. You modeled how the voltage of the battery provides energy to each light bulb in the circuit. You have also introduced new vocabulary words in this section. You will get an opportunity to practice this vocabulary in this chapter. You may want to use the Electron Shuffle in your training manual to help others learn about electric circuits. Your wind generator will provide 120 V of electricity, which is identical to the 120 V in your home. This allows all home appliances to work properly with your wind generator.

Physics to Go

1. Make a chart with two columns, the first one labeled "Word" and the other labeled "Meaning."
   a) In the first column make a list of "electricity words." These are words that you have heard used in connection with electrical units of measurement, parts of electrical systems, or how electricity behaves.
   b) In the second column write what you think each word means or describes.

Physics Essential Questions

What does it mean?

An increase in voltage and/or an increase in current will make a bulb brighter. The brightness of a bulb depends on the energy provided to the bulb in a given time (the power).

How do you know?

Predictions can be made about what will happen to the current in a circuit based on the Electron-Shuffle model and then checked to see if this is what happens in an actual circuit.

Why do you believe?

A model must always be distinguished from the phenomenon. A model is useful to the extent that it is able to accurately predict the results of an experiment, as it is a limited description of reality that is used to help understand phenomena and gain insights. See *Students' Prior Conceptions* of this section for some limitations of the Electron-Shuffle model.

Why should you care?

Explanations should include the following:

Electron-Shuffle model—The voltage of the battery is equivalent to the number of pretzels given to each charge. The current of the circuit is equivalent to the rate at which the charges pass through the light bulb. Voltage is the energy per charge (joules/coulombs). Current is the rate of flow of charge (coulombs/s).

Reflecting on the Section and the Challenge

Ask students to summarize what they have done in this section. Emphasize that they developed a model for the flow of current in a series circuit that can also be used to describe how energy is transported to a device in the circuit. Remind them that they have been introduced to many new physics terms and that they will need to use these terms and describe them in their training manual. Point out that their wind generator will provide the same standard voltage as in their homes, 120 V.

Physics to Go

1.a) and b)

Students' charts will vary but should contain the following words and information:

Electricity Words	Meaning
Electricity	Electricity is energy due to electric charges. It can be static (charges don't move) or dynamic (charges move).
Current	The rate that charges move by a given point or cross section, given in Amperes or Coulombs/second
Voltage	The potential energy per charge, also called the electric potential, measured in volts. 1 V = 1 Joule/Coulomb
Resistor	An electronic device that resists electric current (Students don't know yet, but the resistance is measured in Ohms.)
Power	The rate at which energy is used, measured in watts. 1 Watt = 1 Joule/second
Electric Potential	The voltage or the potential energy per charge
Charge	A property of matter. Electrons have a negative charge of 1.6×10^{-19} C. One Coulomb of charge is composed of 6.25×10^{18} electrons.

NOTES

CHAPTER 6

2.

Students' increased the voltage of the battery when they ran the Electron-Shuffle model; however, they did not add another battery. Students should infer from what they know of series circuits that the electrons go through carrying more charge when the batteries are in series.

2.a)

A charge would pick up 1 pretzel (1 V) from each battery, so it would pick up two pretzels or two volts after going through two batteries in series.

2.b)

If a light bulb were connected in a series circuit with two batteries in series, as the charge moves around the circuit (the current) it picks up 1 V from each battery (a total of 2 V), and transfers the 2 V to the bulb on the way back to the batteries. Some students may mention some of the energy being transferred to the heating of the wires and battery.

2.c)

When the voltage increases, the brightness increases. The light bulb would be brighter because although the current doesn't change, the voltage is twice as much as it would be with a single battery. This means that with two batteries, twice the amount of energy is delivered to the bulb per second.

3.

Students should have the following:

One bulb		Three bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
1	1	3	1	*same*
1	1	1	3	*same*
1	1	6	2	*three bulbs*
4	2	9	1	*one bulb*
2	3	3	3	*one bulb*
4	1	3	2	*one bulb*

4.

Students should have the following:

Two bulbs in series		Three bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
2	1	3	1	*same*
2	1	3	2	*three bulbs*
4	1	6	2	*three bulbs*
2	4	6	1	*two bulbs*
2	4	6	3	*three bulbs*
4	1	6	2	*three bulbs*

2. Suppose you had two one-volt batteries in series.
   a) How many pretzels would a "charge" pick up passing through both batteries in the Electron Shuffle?
   b) Predict what would happen if a light bulb were to be connected with two batteries in series and explain using your physical model of current and voltage.
   c) Would the light bulb be brighter? (Remember: Brightness is dependent on the energy per second delivered to the bulb.)
3. Compare a circuit with one bulb and three identical bulbs in series by completing the table in your log:

One bulb		Three bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
1	1	3	1	
1	1	3	1	
1	1	1	3	
1	1	6	2	
4	2	9	1	
2	3	3	3	
4	1	3	2	

4. Compare a circuit with two bulbs and three identical bulbs in series by completing the table in your log:

Two bulbs in series		Three bulbs in series		Comparison
Battery voltage (volts)	Current in the circuit (amps)	Battery voltage (volts)	Current in the circuit (amps)	Which circuit has the brighter bulb(s)?
2	1	3	1	
2	1	3	1	
2	1	3	2	
4	1	6	2	
2	4	6	1	
2	4	6	3	
4	1	6	2	

CHAPTER 6

SECTION 2 QUIZ

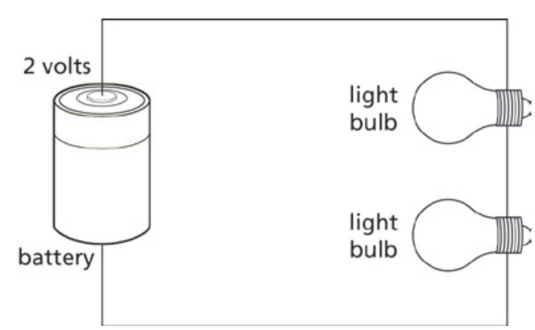
6-2c **Blackline Master**

1. 1 V is equal to
   a) 1 J/N.
   b) 1 J/C.
   c) 1 C/N.
   d) 1 C/J.

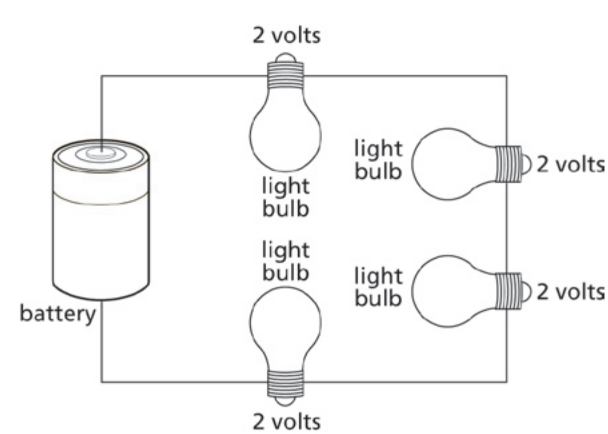
2. An ampere is equal to a
   a) coulomb/joule.
   b) volt/second.
   c) coulomb/volt.
   d) coulomb/second.

3. A current of 6 A flows through a light bulb for 12 s. How many coulombs of charge pass through the light bulb during this time?
   a) $\frac{1}{2}$ C
   b) 2 C
   c) 72 C
   d) 48 C

4. In the circuit shown at right, a battery of 2 V is connected to two identical light bulbs. If the current in the circuit is 2 A, how much voltage and current does each light bulb receive from the battery?
   a) 1 V and 1 A
   b) 2 V and 2 A
   c) 1 V and 2 A
   d) 2 V and 1 A



5. In the circuit shown at right, a battery is providing energy to a circuit with four identical light bulbs. If the current in the circuit is 2 A, and the voltage across each light bulb is 2 V, what is the potential difference (voltage) supplied by the battery?
   a) 1 V
   b) 2 V
   c) 4 V
   d) 8 V



SECTION 2 QUIZ ANSWERS

1. b) 1 V is equal to 1 J/C. A volt is a measure of how much energy each charge carries.

2. d) 1 A is equal to 1C/s. This is a measure of current or how much charge goes past a point or surface in a given time.

3. c) 72 C. Since 6 A flows for 12 s, the total amount of charge is given by $Q = It = (6\text{ A})(12\text{ s}) = 72\text{ C}$

4. c) 1 V and 2 A. Since the bulbs are in series, the voltage is shared equally among the bulbs; each bulb receives 1 V. The current does not change as it goes from one bulb to the next, so the current through each bulb is 2 A.

5. d) 8 V. Each of the four bulbs is identical and in series, therefore the voltage supplied by the battery is shared equally. Because there is a drop of 2 V across each bulb, and the voltage is shared equally, the total voltage is equal to the sum of the voltage drops, or 8 V.