AP Physics 1 Investigation 9: Resistor Circuits

How do conservation laws apply to a simple series or parallel resistor circuit?

Central Challenge

In this investigation, students explore simple series and parallel resistor circuits with a voltmeter and ammeter and encounter Kirchhoff's rules through inquiry.

Background

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes. In circuits, charges gain energy in the battery and then that energy is dissipated in ohmic resistors as thermal energy, and in bulbs as thermal energy and light. Kirchhoff's loop rule states that the energy gained from the battery is equal to the energy loss in the circuit. In particular, potential differences across resistors in series are added together or combined, and the total is equal to the battery potential difference. Potential differences across resistors in parallel are equal to each other.

Conservation of electric charge is another fundamental conservation principle in physics. All processes in nature conserve electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves within a circuit. Applying conservation of charge to a single point in the circuit, or through a cross-section of any wire in the circuit leads to Kirchhoff's junction rule. The sum of the currents flowing into any point in the circuit is the same as the sum of the currents flowing out of that point, since charge is neither created nor destroyed. This leads to the rules that govern current in simple series and parallel circuits. The currents are the same for two resistors in series, and the currents for two resistors in parallel with a battery add up to the total current through the battery.

These initial investigations in basic circuit behavior are the foundations for further studies in physics, electrical engineering, and general engineering. Such circuits are used as models for body systems in medical school as well. Proper understanding of basic circuit theory will support students in the more challenging aspects of circuits such as advanced circuits (multiple loops and multiple potential sources) and RC circuits.

Real-World Application

Asking students to think of some simple, everyday activities that depend on electric current and circuits will yield answers such as using household lighting or laptop computers and watching television. Even students who do not pursue physics in future studies should understand that the outlets and appliances in their homes are connected in a parallel circuit, where all outlets receive the same voltage. It's also useful for them to understand how jump-starting a car requires putting a working battery in parallel with the dead battery to supply the same voltage. Although most circuits that students are likely to encounter are complex, and contain more than just one resistor, an ability to understand basic wiring or basic properties of household circuitry has great future value for all students, even those who have no ambition to go any further in the sciences.

Inquiry Overview

In this multipart investigation, students use a voltmeter and an ammeter to explore the relationships among the potential differences across the various elements in a circuit and the currents through these same elements. This lab is predominantly guided inquiry. Students are presented with a question to answer, they decide which circuits to investigate, and they use the results of their preliminary investigations to make decisions about additional circuits to study.

In Part I, students construct several circuits using D-cell batteries, miniature screw lamps, bulb holders, and wires. They connect the bulbs in series and parallel and use a voltmeter to discover the relationships among the potential differences across the various elements in the circuit.

In Part II, students use an ammeter to measure the current through the various branches of these circuits and devise a rule for the relationships among the various currents.

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Connections to the AP Physics 1 Curriculum Framework

Big Idea 5 Changes that occur as a result of interactions are constrained by conservation laws.

Enduring Understanding	Learning Objectives
5B The energy of a system is conserved.	**5.B.9.1** The student is able to construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule). (Science Practices 1.1 and 1.4)
	5.B.9.2 The student is able to apply conservation of energy concepts to the design of an experiment that will demonstrate the validity of Kirchhoff's loop rule in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches. (Science Practices 4.2 and 6.4)
	5.B.9.3 The student is able to apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electrical potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. (Science Practices 2.2 and 6.4)
5.C The electric charge of a system is conserved.	**5.C.3.1** The student is able to apply conservation of electric charge (Kirchhoff's junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if the configurations of the circuit are changed. (Science Practice 6.4)
	5.C.3.2 The student is able to design an investigation of an electrical circuit with one or more resistors in which evidence of conservation of electric charge can be collected and analyzed. (Science Practices 4.1, 4.2, and 5.1)
	5.C.3.3 The student is able to use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or branches of the circuit. (Science Practices 1.4 and 2.2)

[**NOTE:** In addition to those listed in the learning objectives above, Science Practice 4.3 is also addressed in this investigation.]

Skills and Practices Taught/Emphasized in This Investigation

Science Practices	Activities
1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.	Students draw schematic circuit diagrams with meter connections and label the currents and potential differences to represent their experimental setup.
1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.	Students use schematic circuit diagrams to enhance their data analysis.
2.2 The student can *apply mathematical routines* to quantities that describe natural phenomena.	Students draw conclusions about the sum of the potential differences around a loop in a circuit. Students draw conclusions about the currents in a multibranch circuit.
4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.	Students decide what measurements to make to determine the rules for adding potentials in series and parallel circuits.
4.2 The student can *design a plan* for collecting data to answer a particular scientific question.	Students are provided general directions but make decisions about how to connect bulbs/resistors in series and parallel and how to organize and record data. Students use an ammeter to measure currents and a voltmeter to measure potential differences.
4.3 The student can *collect data* to answer a particular scientific question.	Students collect and record data from their measurements of the potential differences and currents in the various branches of the circuits they analyze.
5.1 The student can *analyze data* to identify patterns or relationships.	Students draw conclusions from their data, based on their measurements of potential differences and currents.
6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.	Students assess the uncertainties in their measurements to help inform the analysis of their data and support their conclusions.

[**NOTE:** Students should be keeping artifacts (lab notebook, portfolio, etc.) that may be used as evidence when trying to get lab credit at some institutions.]

Equipment and Materials

Per lab group (three to four students):

- Four-cell battery holder
- Three D-cell batteries

- Three to four #14 (round) bulbs and three to four #48 (long) bulbs, plus corresponding bulb holders [**NOTE:** #14 bulbs have a limit of 2.3 volts, so small voltages should be used to avoid burning out too many bulbs. Car brake light bulbs will also work (inexpensive, but 6–12 volts are needed for good measurements) and #40 and #50 miniature screw lamps work as well.]
- Connecting wires (inexpensive alligator clip leads work well)
- Basic multimeters or student single-value meters (voltmeter and ammeter)
- Extra fuses for the ammeters
- (Optional) Basic single pole throw switch

  [**NOTE:** If you teach the CASTLE™ curriculum, all of this equipment is part of the student kits except for the multimeters and the switch.]

Timing and Length of Investigations

- **Teacher Preparation/Set-up:** 20–25 minutes

  Check all bulbs, resistors, batteries, and meters to make sure all are in good working order before you start the lab. This may seem obvious, but a blown fuse in the ammeter (which will happen more than you would like) or a blown bulb will create measurement chaos for students.

- **Prelab:** 20 minutes

  A general discussion on the proper use and connection of multimeters, especially ammeters, is crucial.

- **Student Investigation:** 90 minutes

  Part I: 45 minutes to explore the series and parallel circuits

  Part II: 45 minutes to explore the series and parallel currents

- **Postlab Discussion:** 30–60 minutes

  Students share their results with the larger class in a whiteboard sharing session or "circle style meeting," while other students ask follow-up questions and critique student work.

  [**NOTE:** You may wish to have the postlab discussion for Part I before continuing to Part II on a second day, or you may wish to complete both parts in a 90-minute period and then have the discussion on a second day.]

- **Total Time:** approximately 3–3.5 hours

Safety

Safety is of minimal concern with this lab. The potential difference (1.5–4.5 volts) and current involved in the experiments are of no immediate safety concerns to students. If you choose to use a power supply rather than a battery pack, set the voltage to a fixed maximum around 5V. However, you may want to create good laboratory habits by always using a switch in the circuit and emphasizing proper meter usage.

Preparation and Prelab

This activity is designed to follow an introduction to circuits such as Sections 1–4 of the CASTLE curriculum. The student version of the CASTLE curriculum is available as a free download from PASCO. The equipment is also available for purchase from PASCO (see Supplemental Resources) or other sources that may be more economical. See "Modeling Instruction" in Supplemental Resources for the modified version of the CASTLE curriculum available on the website.

The students should already be familiar with the batteries, bulbs, and wires. They should be able to connect two bulbs in series and two bulbs in parallel, and make sure the circuits are in good working order before making measurements.

Give students a thorough tutorial on the use of ammeters and voltmeters in a circuit before beginning this inquiry. If your students are using multimeters, it would be helpful to take a picture of the multimeter setup as a voltmeter and one with it setup as an ammeter. These enlarged images can be projected onto a screen (e.g., in a PowerPoint presentation) for easier viewing. Experience has shown that students in a class of more than 10–12 will not be able to see a demonstration on an average multimeter. These projected images will show students how to set any relevant dials and which inputs to use on the meter for voltmeter and which for ammeter. Also consider color-printing these images for students and having them on laminated sheets or in plastic page covers around the room for students to double check before connecting circuits. It should be reinforced that the ammeter is connected in series, and this connection should be demonstrated for the students. It is highly recommended that students be required to show you their ammeter connections before they close the circuit the first time. This will save a lot of blown fuses.

You may wish to have students use the PhET simulation, "Circuit Construction Kit (DC Only)," to demonstrate that they understand how to connect an ammeter in series (see Supplemental Resources), and then have them use the ammeters with bulbs and batteries and wires. Or the PhET simulation could serve as a homework review after the in-class lab activity.

The Investigation

Part I: Electric Potential Difference in Series and Parallel Circuits

In this first part of the investigation, give students the equipment and the task of determining the relationships between the potential differences across resistors and battery in several different circuits, including the following:

- Two bulbs in series with each other and a battery
- Two bulbs in a parallel with each other and a battery
- Three bulbs in a series–parallel combination: in this case, both one bulb in series with a parallel combination (see Figure 1) and one bulb in parallel with a series combination (see Figure 2).

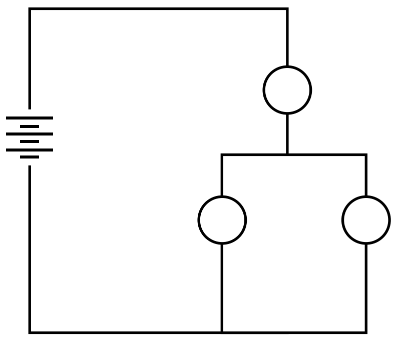

Figure 1

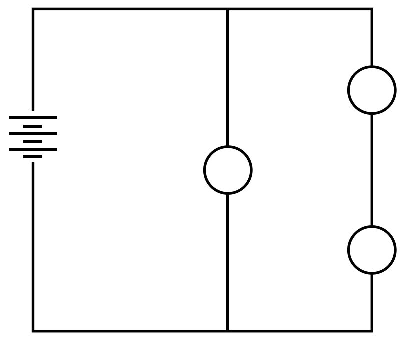

Figure 2

Encourage students to not only investigate the potential differences across each of the bulbs in circuits with two identical bulbs in series or parallel (two #14 round bulbs or two #48 long bulbs) but also in circuits with a long bulb and a round bulb in series, and in circuits with a long bulb and a round bulb in parallel. They should be encouraged to use both types of bulbs in the more complicated three-bulb circuits and possibly to expand to four-bulb circuits. The students should connect the voltmeter in parallel with each individual bulb and with the battery and record the potential differences. It is up to the students to decide how to most efficiently record the data. It is beneficial to students to draw each of the circuits they are studying and record the potential differences next to each circuit element. This helps them see the patterns.

While students are working, circulate and ask them questions to guide their investigation. Some students will record negative potential differences. Question them as to what the meaning of the negative sign is and under what conditions it would be positive. They should be led to see that reversing the leads on the voltmeter gives a positive value for the potential difference.

Part II: Current in a Circuit Path

In the second part of the investigation, give students multimeters connected as ammeters or single-value ammeters and ask them to explore the relationships among the currents at various points in the circuit. [**NOTE:** You may wish to conduct this portion of the lab on a second day unless you have 90-minute periods.]

Again, encourage students to explore several different circuits, similar to the ones they explored in Part I. Students should keep track of their results by drawing each of the circuits that they evaluate and labeling the currents near each branch in the circuit drawing. Decide if you want to give them direct instruction in this or simply lead them to realize that this organization helps. Experience has shown that students will simply name the type of circuit and list the currents.

Extension

If some students finish early, you could ask them to create larger circuits with three series or three parallel branches and confirm their findings from the circuits with two branches.

Only simple series and parallel circuits are addressed in the AP Physics 1 curriculum, but if you want to provide students with an additional challenge, suggest a circuit that cannot be analyzed using simple series and parallel resistor combinations, such as the one in Figure 3. This will emphasize the need for the more general form of Kirchhoff's laws, rather than the simplified applications to series and parallel circuits. For example, some students report that "potential differences are the same in parallel and they add up in series." These students may need assistance to generalize this to the conservation of energy form Kirchhoff's rule stated as, "the sum of the potential differences around any closed loop is zero." It is important to have students pay attention to the signs of the potential differences in this circuit. If attention is not paid to which end of the middle bulb is at a higher potential, it might appear that the loop rule is not obeyed for several loops in this circuit.

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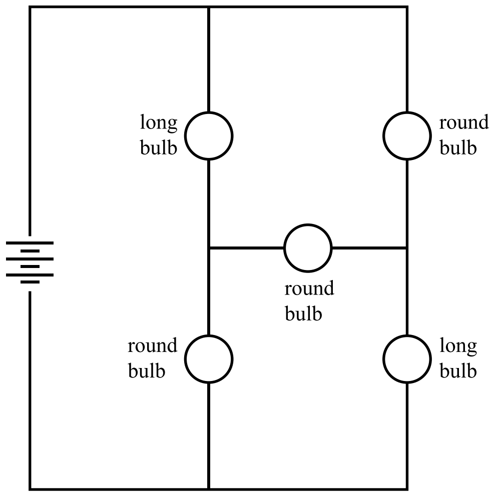

Figure 3

It is critical not to have the bulbs all the same type, as shown in Figure 3, so that different potential differences are measured across each bulb. If all bulbs are of the same type, then no potential difference will be measured across the middle round bulb. The middle bulb could also be a long bulb. The primary constraint here is that the two ends of the bulb cannot be at the same potential or it will not light.

Common Student Challenges

The most common student challenge in this lab is connecting the ammeter in series with the bulb whose current is being measured. Connecting an ammeter in series with just one of two bulbs which are themselves connected in parallel is the most challenging ammeter connection of them all. This activity provides students opportunities to practice these skills in several simple series and parallel circuits.

The most challenging aspect of working with circuits for the first time in a physics lab is training students to use a multimeter or ammeter correctly (i.e., ammeters connected in series with circuit elements and voltmeters connected in parallel with the element being measured). Plan on having plenty of fuses handy! There will be mistakes — just plan on it and be patient with your students. There will undoubtedly be some confusion of the voltmeter usage versus the ammeter usage, and surely a few short circuits with the ammeter will occur as students attempt to measure current by placing the ammeter leads in parallel around a bulb. It is just so tempting to the student!

A very persistent circuit misconception is the idea that current is "used up" in a bulb or resistor. This idea should not find any traction among students if they are asked why the current values are the same at all points around the circuit. A few probing questions to students about this evidence should help to eliminate that persistent student misconception.

Another aspect of this experiment to keep your eye on is the idea that precision is not that important. The resistors have tolerance (5 percent probably), the bulbs are not always uniform (#14 and #48 bulbs from different batches can have enough variability in the filaments to show slight differences in potential or brightness around multibulb loops), the wires have resistance, the bulbs are non-ohmic, and just general sloppiness in measurement and meter usage can lead students to the incorrect conclusion that electric potential difference can change around a series loop of identical bulbs. You may have to remind students that the measurements of 2.94 volts, 3.03 volts, and 3.10 volts may have slightly different values for these three measurements, but that these small differences are all within the uncertainty of the meters and the uncertainty of the equipment, and they can be generally considered to have equal potential differences. These small variations in potential differences could simply be the result of using six to eight pieces of wire that have a small (but not totally negligible resistance if you are using bulbs) resistance of 0.05 ohms.

If resistors instead of bulbs are used for the experiment, you will probably see higher precision in the measurements, but you would lose the visual value of using the bulbs. Decide what works best for the students' experiments and your teaching style.

The TIPERs book (see Supplemental Resources) has some good conceptual tasks to assess students' understanding and root out alternative conceptions they may have regarding current in series and parallel circuits.

Analyzing Results

How you decide to have students share their results will depend in part on how successful they are at the lab. Have students answer the following guiding questions:

- What can you conclude about how potential differences are related for several resistors in series with a battery?
- What can you conclude about how potential differences are related for several resistors in parallel with a battery?
- How might these conclusions be interpreted from a conservation of energy perspective?
- What can you conclude about how currents are related for several resistors in series with a battery?
- What can you conclude about how currents are related for several resistors in parallel with a battery?
- How might these conclusions be interpreted from a conservation of charge perspective?
- Can you extrapolate these conclusions to more complex circuits with resistors in series and parallel combinations?

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If you see that all of the students have come to the same conclusion, then it may be sufficient to have a class discussion where they summarize the findings and record them in their notes. If students have come to different conclusions, then it is valuable to have them present their findings to the class and argue their positions.

Experience has shown that in Part I of this experiment, students readily come to the conclusion that potential differences add in series and are the same in parallel. They do not always readily come to the conclusion that energy is conserved as a single charge completes a loop in the circuit.

It will probably be necessary to lead them to this conclusion by having them imagine the energy changes for a skier on a hill. The ski lift serves as an analogy for the battery, the skiers for the charges moving in the circuit, and the various ski hills are the different paths around the circuit. Most students have either been skiing or seen skiing on television, so this analogy is very concrete for them. They can imagine walking around the ski hill and observing their changes in potential energy as they go up the ski lift and then walk the various alternate paths down the hill. When they return to their starting point at the bottom of the ski lift, their net change in potential energy is zero for the complete trip. And the same is true for the charges completing a closed loop in a circuit. [**NOTE:** The ski-hill analogy is particularly useful when writing Kirchhoff's loop rule equations and analyzing the potential differences across resistors. But that application isn't used here.]

If skiing proves too unfamiliar or abstract, have them imagine taking the elevator up to the top floor of a building and walking the various staircases back down to the floor where they boarded the elevator. This analogy is slightly less valid, as walking down stairs still requires effort. The simplest example may simply be a playground slide. Students, like the battery, provide energy to climb the ladder, lifting themselves to increase the gravitational potential energy in the system they make with the earth. Then they simply slide back down to their original potential energy level. Brightness can be related to how fast you would speed up, with increased resistance being related to how shallow the slide is.

Uncertainty should be a major postlab topic with the class. Some students may automatically conclude that two potential differences are the same across branches in parallel if they are within 5-10 percent of each other. Other students may conclude they are different. This leads to a discussion of the uncertainty in the meter measurements, resistance of the wires, and uncertainties in the resistances of the bulbs.

Ask students consider the following questions:

- Did the potential difference across the battery vary from circuit to circuit? If so, how did it affect your results?
- How close do two potential difference values have to be in order to be considered equal? What about current measurements?
- What is the maximum allowable uncertainty in the potential and current measurements?

The uncertainty in this lab comes from both the uncertainty in the meters and the fact that the battery is not ideal, and the potential difference across the battery decreases with increasing current. So if three bulbs are in parallel, then there will be a smaller potential difference across the battery than with just one bulb.

It might be helpful at this point to lead a class discussion by creating circuits in the PhET Circuit Construction Kit simulation (see Supplemental Resources). Then the relationships can be observed under ideal circumstances as well as under circumstances of significant internal resistance in the battery. This comparison between ideal and real laboratory results helps reinforce the uncertainties introduced by measurement. The goal is not to quantify the uncertainty to a specific degree, but rather to observe how uncertainties affect the relationships being observed. Thus, a follow-up activity with ideal batteries, resistors, etc., can serve to solidify the relationships between potential difference and current without the obfuscating effects of nonideal circuit elements.

Once the lab is complete, students should understand that current is the same in series elements. Since ammeters measure current, they must be placed in series with the resistor whose current they are measuring. A similar argument can be made for why voltmeters are placed in parallel. The results of this investigation support these requirements for meter connection and should be reinforced at the end of the lab.

Assessing Student Understanding

After completing this investigation, students should be able to:

- Connect several bulbs in various series and parallel combinations;
- Use a voltmeter to measure potential difference;
- Use an ammeter to measure current;
- Describe and apply the relationships among the potential differences around a closed loop in a circuit;
- Explain how conservation of energy is related to the potential differences in a circuit;
- Articulate and apply the relationship between the currents entering any point in a circuit and the currents leaving that same point; and
- Explain how conservation of charge is related to the current flow in a circuit.

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Assessing the Science Practices

Science Practice 1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.

Proficient	Accurately draws circuit diagrams of resistors and bulbs in various combination series and parallel circuits.
Nearly Proficient	Draws circuit diagrams for simple series or parallel circuits, but struggles with combination series–parallel circuits.
On the Path to Proficiency	Draws simple series circuits.
An Attempt	Attempts to draw circuits but the connections to bulbs and/or batteries are incorrect.

Science Practice 1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

Proficient	Connects wires, batteries, and bulbs in simple series and parallel combination circuits based on a diagram provided. Identifies which bulbs are in series and which are in parallel.
Nearly Proficient	Connects a simple series or parallel circuit from a diagram but struggles with more complicated circuits.
On the Path to Proficiency	Connects a circuit with two bulbs either in series or parallel based on a diagram.
An Attempt	Incorrectly connects a simple series or parallel circuit from a diagram.

Science Practice 2.2 The student can *apply mathematical routines* to quantities that describe natural phenomena.

Proficient	Uses mathematical routines to detect patterns in the data and compare potential differences and currents in the circuits.
Nearly Proficient	Makes minor mistakes in the mathematical routines that describe the patterns in the current and potential difference data.
On the Path to Proficiency	Needs significant assistance in applying mathematical routines to describe the current and potential difference data.
An Attempt	Unable to accurately recognize patterns in the mathematical data or apply routines to analyze them.

Science Practice 4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

Proficient	Measures the appropriate potential differences and currents to make comparisons between series and parallel connections and can justify the choice of measurements thoroughly and accurately.
Nearly Proficient	Accurately selects the appropriate data, but the justification is missing a significant physical principle.
On the Path to Proficiency	Accurately selects the data to measure, but cannot justify the choice that was made based on physics principles.
An Attempt	Makes some relevant measurements, but cannot justify how they will help answer the guiding questions.

Science Practice 4.2 The student can *design a plan* for collecting data to answer a particular scientific question.

Proficient	Designs a plan that will allow for determining the loop rule and the point rule for circuits.
Nearly Proficient	Designs a plan for measuring potential differences or currents, but cannot articulate how that plan will lead to a rule for circuits.
On the Path to Proficiency	Needs significant assistance to design a plan to measure potential differences and currents for a circuit.
An Attempt	Attempts to form a plan to measure potential differences and currents, but the plan is ineffective or flawed.

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Science Practice 4.3 The student can *collect data* to answer a particular scientific question.

Proficient	Collects accurate data in a methodical way and records the data in an organized fashion. Accurately connects a voltmeter to measure the potential differences across various elements in a circuit and the total potential difference across the circuit. Connects an ammeter to measure the current in each branch of the circuit, and then connects the ammeter to measure the total current through the battery.
Nearly Proficient	Collects data that is missing a few minor pieces or is disorganized in its presentation. Accurately connects a voltmeter to measure the potential differences across various elements in a circuit, and connects an ammeter in a simple series circuit to measure the current.
On the Path to Proficiency	Collects data with major gaps, and the presentation lacks any organization. Accurately uses a voltmeter to measure potential difference, but incorrectly uses an ammeter in parallel with the bulb or battery in question.
An Attempt	Collects inaccurate or incomplete data and provides no organization for this data. Connects a voltmeter in series with the circuit to measure the potential difference across each bulb.

Science Practice 5.1 The student can *analyze data* to identify patterns or relationships.

Proficient	Analyzes the data to accurately determine the rules for voltages and currents in resistor circuits.
Nearly Proficient	Identifies patterns in the potential differences and currents, but unable to form a complete conclusion from this analysis.
On the Path to Proficiency	Forms some accurate analysis of the potential differences and currents, but unable to come to an accurate conclusion.
An Attempt	Attempts to analyze the data but there are major errors in his or her analysis.

Science Practice 6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.

Proficient	Predicts changes in the voltages and currents in the various elements in the circuit if more resistors are added in series or parallel.
Nearly Proficient	Makes accurate predictions about how adding bulbs in a simple circuit will affect the potential differences and currents but not in more complex circuits.
On the Path to Proficiency	Makes accurate predictions about changes in potential difference and current but only in the most simple series or parallel circuits.
An Attempt	Makes incorrect predictions about the changes in current or potential difference.

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Supplemental Resources

"CASTLE Kit." PASCO. Accessed September 1, 2014. http://www.pasco.com/prodCatalog/EM/EM-8624_castle-kit/.

"Circuit Construction Kit (DC Only)." PhET. University of Colorado Boulder. Accessed September 1, 2014. http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc.

Fredette, Norman, and John Lochhead, "Student Conceptions of Simple Circuits." *The Physics Teacher* 18, no. 3 (1980): 194–198. [*This is one of the classic papers in PER (Physics Education Research) regarding students' understanding of a circuit and is a must read for all physics teachers. It uses a classic question/activity to determine if college freshman electrical engineering majors understand the nature of a complete circuit (lighting a bulb). The article further demonstrates students' misconceptions with case study interviews that reveal some typical struggles students have with circuits.*]

Hieggelke, Curtis J., David P. Maloney, Stephen E. Kanim, and Thomas L. O'Kuma. *E&M TIPERS: Electricity and Magnetism Tasks: Inspired by Physics Education Research*. Boston: Addison-Wesley, 2005.

"Modeling Instruction." Arizona State University. Accessed September 1, 2014. http://modeling.asu.edu/.

Steinberg, Melvin S., and Camille L Wainright. "Using Models to Teach Electricity — the CASTLE Project." *The Physics Teacher* 31, no. 6 (1993): 353–357.

Stetzer, Makenzie R., Paul van Kampen, Peter S. Schaffer, and Lilian C. McDermott, "New Insights into Student Understanding of Complete Circuits and the Conservation of Current." *American Journal of Physics* 81, no. 2 (2013): 134–143. [*This paper confirms that many of the misconceptions that the Fredette and Lochead study brought to light in 1980 still exist in abundance with university physics students, and provides advanced ideas on how to teach students about circuits (multiple battery sources/circuit elements). The paper reveals strongly-held student misconceptions and suggests how to combat them with instructional changes.*]