CAST 2023
Houston, TX

Bright Ideas: Investigating Light Bulbs and Simple Circuits through Guided Inquiry

Experiments

Measuring Electric Current

- Go Direct Current Probe

Conservation of Charge

- Go Direct Current Probe
- Vernier Circuit Board 2

Voltage in a Circuit

- Go Direct Voltage Probe

Workshop Presenter

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Measuring Electric Current

OVERVIEW

The purpose of this investigation is for students to learn how to measure current without direct instruction.

For the Preliminary Observations, demonstrate how to measure current in a simple circuit that consists of a power source, a current-measuring device, and one incandescent light bulb. Students will observe that bulb brightness increases as measured current increases.

Students experimentally determine how to use the current probe to accurately measure the current in a circuit with multiple light bulbs. The circuit will contain another current sensor and a "test" light bulb that will aid them in their observations.

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should know that electric current involves the motion of electric charge. It is advised that this investigation be done before students have measured voltage in electric circuits.

You will probably need to provide students with a key to the symbols used in electric circuits, specifically the symbols used for an ammeter or current probe, a lamp, and battery cells. The lines connecting circuit elements in a circuit diagram is commonly thought to denote wire, but a more accurate meaning is conducting connection. Explain to students that elements connected by a line in a circuit diagram may be in direct contact with each other when constructing the circuit in reality.

LEARNING OUTCOMES

- Understand that ammeters must be connected in series with the circuit element where current is being measured.
- Begin to develop the concept that "resistance" reduces current, that there is little resistance for current to flow through an ammeter, and that current has a tendency to flow along the path of least resistance.
- Learn the conventions of "+" and "–" signs of electric current (if desired by the instructor).

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
PS3.A Definitions of Energy PS3.B Conservation of Energy and Energy Transfer	Patterns Cause and Effect Systems and System Models Energy and Matter	Planning and Carrying Out Investigations Analyzing and Interpreting Data

ESTIMATED TIME

Students should be able to complete this exercise during one 40-minute class, including Preliminary Observations, the investigation, and time for class discussion.

MATERIALS

Make the following materials available for student use. Items in bold are needed for the Preliminary Observations.

computer, Chromebook, or mobile device
data-collection program
data-collection interface (if needed)
batteries or variable power supply
identical small incandescent light bulbs[1]
alligator clip wires
current probe
ammeter
digital multimeter

PRELIMINARY OBSERVATIONS

Start this activity by having a simple circuit setup consisting of a DC variable power supply, a Current Probe, and a single light bulb. Provide some means of displaying the *current* to the students, such as projecting Logger *Pro* software onto a screen or interactive whiteboard. Adjust the voltage so as to change the current through the circuit, first increasing the current, and then decreasing. Finally, set the voltage to zero.

Ask students, "What is necessary for the light bulb to light?" Provide students with time to discuss their ideas in small groups and then as an entire class. Note that you should not mention "voltage" at all in this discussion. Students will observe that the current and the brightness of the bulb change together. Ask them to articulate a general relationship between the brightness of the bulb and the displayed current.

[1] One per station for the Preliminary Observations. Three per station for the investigation.

The current can be varied by changing the number of batteries in the circuit, by varying a potentiometer in series with the bulbs, or by using a commercial variable power supply. Students do not need to be concerned with the operation of the power supply at this time. One observation should be made with no current flowing. Do not reverse the direction of current at this time.

Encourage students to use simple language and words that they understand. Since students were given no information about voltage, redirect groups that include the word "voltage" to focus on what they physically observed and measured. No mathematical relationship has been presented, although some students may present a hypothesis of the relationship.

After the Preliminary Observations and discussion, frame the investigation. Challenge students to determine how to measure the current in Bulbs #1 and #2 using a second current probe (see Figure 1). They can observe the reading from the Test Current Probe in the circuit, and the brightness of the Test Bulb (the third light bulb), but must not attempt to measure the current of the Test Bulb directly. They should not change the settings on the power supply.

Using the measured results as evidence, students should be prepared to convince you and their peers that their technique is robust and reliable.

IMPLEMENTATION

Provide the students the circuit shown in Figure 1. You can choose to provide them with the schematic and equipment, or you can have the circuits pre-constructed to avoid errors in wiring. Reinforce that the three items on the left (a power source, current probe, and light bulb) are part of the test equipment for the experiment.

Note: If you give students the Student Information sheet for this section of the investigation, we recommend NOT including the second page, as it contains hints as to how the Current Probe should be connected. Our experience is that when students engage in the investigation without these hints, their comprehension and understanding of this critical skill is increased.

Give the students another current probe or other ammeter to conduct their test.

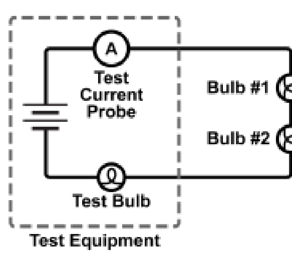


Figure 1

Tell the students they are to conduct measurements on the other two light bulbs in the circuit: Bulb #1 and Bulb #2.

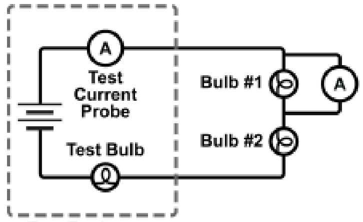


Figure 2

It is likely (but not certain) that most groups will try to measure the current in Bulb #1 by connecting the second ammeter as shown in Figure 2. After students have had time to explore, ask students if they tried this configuration. Allow time for those who have not yet tried this to do so. Discuss their observations with the entire class. Here are a set of suggested questions after students make their observations.

1. Observe that Bulb #1 goes out. What does this imply? (No current is flowing through the light bulb.)
2. Does Bulb #2 still glow? (Yes.) What does this mean? (Current is flowing through Bulb #2, the ammeter (possibly), but not through Bulb #1.)
3. Does the measured current in both ammeters match? (Yes. Note that some students may correctly observe that the current in the Test Current Probe is slightly higher than their current probe, due to the small amount of current going through Bulb #1.)
4. Does the current change when you connect the test meter to Bulb #1 in this way? (Yes. It increases.)
5. Why do you suppose that is the case? (You might leave this as a hanging question to come back to after an exploration of Ohm's Law. Alternatively, discuss a short circuit versus an open circuit.)

Students should notice at least three things:

1. Bulb #1 went out.
2. The Test Bulb and Bulb #2 became brighter.
3. The current in the Test Current Probe increased.

Students must be allowed to determine how to measure current correctly. Someone in the class is usually able to accomplish this and word will typically spread through the class.

ANALYSIS

Give students time to articulate an explanation of the correct way to measure current through multiple components of a circuit. We recommend that students write out their explanations and hypotheses and that they be prepared to state them orally. You may want to have the students draw a circuit diagram, similar to Figure 2, showing the correct method for connecting the current probe to the circuit to measure the current flowing through Bulb #1.

After this is complete, provide students with the second page of the Student Information, which will allow them to strengthen their understanding of the correct method for measuring current.

SAMPLE DATA

A written explanation may be something like this:

> In order to measure the current through each bulb I had to disconnect one of the wires attached to the light bulb and "insert" the ammeter into the circuit, so that the meter was like another light bulb in the circuit. This did not affect the current flowing through the circuit and both lights stayed on. The "test" light bulb did not change brightness.
>
> If I tried to measure the current by placing an alligator connector to each side of a light bulb, the light went out. The other light bulbs got brighter and the current measured increased.
>
> I think the ammeter measures current flowing through itself and it diverts all current if placed "around" a light bulb.

TIPS

1. In the Electronic Resources you will find many useful files, including sample program and a PDF of the student pages so you can print the activity for your students or distribute the file to them electronically. Sign in to your account at **vernier.com/account** to access the Electronic Resources. See Appendix A for more information.

2. Explain that the act of measuring the current in a circuit should not change the current.

3. Encourage your students to think of as many ways to connect the current probe as possible. Connecting the meter the "wrong" way will be as informative as connecting it correctly, because it will allow students to compare the results and develop some ideas as to why the results are different. Ask them what they think is meant by the plus and minus signs on the measurements of current. Ask them if they can explain their answers in terms of direction of flow, "red and black," and "positive and negative" charge.

4. One of the more common issues when measuring current is to short circuit a component by placing the leads on either side of the component. Instruct students to avoid testing/investigating the three items on the left of the circuit diagram in order to protect the equipment from damage.

5. The Test Bulb will be important for student observations. Students should note the brightness of the Test Bulb.

EXTENSIONS

Assign one or more of the following extensions once students have concluded their investigations. While we provide guidance for what to expect from students in response to the extensions, we do not include sample data or conclusions.

1. Once you have correctly connected the Current Probe to measure current through Bulb #1, reverse the leads and observe what happens to the measurement. Trace the circuit from one end of the power source to the other and write a description regarding the direction of current flow.

Students should be able to explain positive current flow as going from the "+" terminal to the "–" terminal. Note that it is important to set up the initial circuit measuring a positive current for this extension.

2. Place a wire across the connections to Bulb #1 and observe what happens to the other light bulbs. How is this similar to the previous observations? What does this imply about an ammeter?

Students should recognize that this is similar to incorrectly placing the ammeter in parallel with a resistance in the circuit. The ammeter provides very little resistance, effectively eliminating the resistance of that portion of the circuit.

3. Add another light bulb in "parallel" with the other two. Ask your instructor for guidance on how to accomplish this, if necessary. Determine how to measure current through Bulb #2.

Guide students to put their Current Probe in the circuit in such a way as to be in series with the component they are trying to measure.

Measuring Electric Current

Let's see if we can figure out how to measure current!

PRELIMINARY OBSERVATIONS

Observe the following electricity demonstrations:

- How to measure the current in a simple circuit consisting of a power supply, current probe, and a light bulb.
- What happens when the current is varied.

Your challenge is to build the circuit in Figure 1 and determine how to connect another current probe or ammeter to measure the current in Bulb #1 and Bulb #2. You can *observe* the brightness of the test bulb and the value of the Test Current Probe, but you must not attempt to measure the current in the left side of the circuit (as shown in Figure 1).

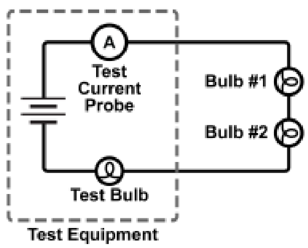


Figure 1 Experimental setup for measuring current in Bulbs #1 and #2

PROCEDURE

1. Brainstorm with your lab partners and determine as many methods as possible to measure the current in Bulb #1 and Bulb #2.

2. Carry out the investigation, and record your data and observations. Make sure all group members have access to the data.

ANALYSIS

1. Use your data and observations to explain how to measure current for a given component in a circuit. Write a brief description of your method. Propose an explanation as to why electric current should be measured this way.

This section to be handed out after the investigation.

2. Consider the circuits in Figure 2. Which of these circuits more accurately measures the current in Bulb #1? Explain why.

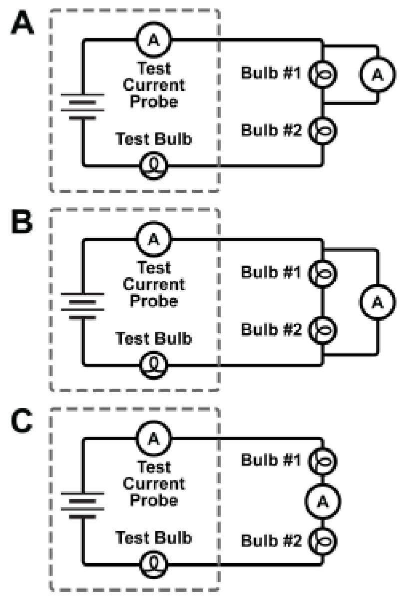


Figure 2

3. Predict what you will observe for the circuits that do not accurately measure the current through Bulb #1. Specifically, comment on the relative brightness of the three bulbs in the circuit. What will be the effect on the current flowing through the circuit as measured by the Test Current Probe and the second current probe/ammeter?

EXTENSIONS

1. Once you have correctly connected the current probe to measure current through Bulb #1, reverse the leads and observe what happens to the measurement. Trace the circuit from one end of the power source to the other and write a description regarding the direction of current flow.

2. Place a wire across the connections to Bulb #1 and observe what happens to the other light bulbs. How is this similar to the previous observations? What does this imply about an ammeter?

3. Add another light bulb in “parallel” with the other two. Ask your instructor for guidance on how to accomplish this, if necessary. Determine how to measure current through Bulb #2.

Conservation of Charge

OVERVIEW

The goal of this activity is for students to develop an understanding of how current behaves in a circuit involving resistors in both series and parallel configurations.

In the Preliminary Observations leading up to this investigation, students should be shown several situations that are intended to build conceptual understanding and counter specific misconceptions by adding light bulbs, in series or in parallel, to a simple circuit consisting of a battery and single light bulb.

With this as background, students are challenged to develop a conceptual model for how current behaves in a circuit with multiple paths. This model should be confirmed with data in a test circuit.

Students will then design and execute an experiment to determine the nature of current flow in simple circuits.

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should be competent at measuring current in a circuit. If students do not have this skill, we highly recommend taking the time to use the investigation "Measuring Electric Current" that precedes this investigation. If time does not allow, give students a refresher on the measurement of current. It is important to emphasize the significance of the positive or negative nature of the value of the measurement. In addition it will be important to provide instructions for measuring current in a complex circuit.

If students have not encountered the resistor symbol in a circuit diagram yet, explain this symbol to students before they do their experiments.

Note that the terms "volt" and "voltage" are not introduced in this activity nor in the preceding investigation "Measuring Electric Current."

LEARNING OUTCOMES

- Understand that moving charge (i.e., current) is conserved in a circuit. At every junction, the current flowing in is equal to the current flowing out.
- Learn that adding resistance in parallel serves to reduce the combined effective resistance by adding pathways for current.
- (Extension only) Understand what is meant by the term "short-circuit."

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
PS3.A Definitions of Energy	Patterns	Developing and Using Models
PS3.B Conservation of Energy an Energy Transfer	Cause and Effect	Planning and Carrying Out Investigations
PS3.C Relationship Between Energy and Forces	Systems and System Models	Analyzing and Interpreting Data
	Energy and Matter	Using Mathematics and Computational Thinking
	Influence of Science, Engineering and Technology on Society and the Natural World	Constructing Explanations and Designing Solutions
	Scientific Knowledge Assumes an Order and Consistency in Natural Systems	Obtaining, Evaluating, and Communicating Information

ESTIMATED TIME

Two 40-minute class periods, with time at the end of the second class for discussion.

MATERIALS

Make the following materials available for student use. Items in bold are needed for the Preliminary Observations.

batteries
small incandescent light bulbs
alligator clip wires
computer, Chromebook, or mobile device
data-collection program
data-collection interface (if necessary for your equipment setup)
Vernier Circuit Board (order code: VCB or VCB2)
current probe
LabQuest power supply

PRELIMINARY OBSERVATIONS

Start by conducting the following set of observations:

First observation: Connect a single lamp to a constant voltage source. Explain that you will be adding additional lamps "in the loop" and ask students to predict what will happen. Sketching this will help to show the students that you will be adding the lamps in series. Conduct the experiment with two additional lamps, pausing to ask students what they observe after adding one and then the other. Ask students to articulate a hypothesis for the dimming of the lamps. Prompt them with the questions, "What do you notice about the brightness of the two lamps compared to one another? What does that imply?"

Second observation: Again, connect one lamp to a constant voltage source. Explain that you will be adding another lamp (or two), but connecting it differently, this time in parallel with one of the lamps. Sketch this for student in order to contrast it to the previous observation. Again, ask them to predict what will happen. Add the lamps, one at a time, and ask students what they observe. Ask them to explain how the current changes in each of the situations.

An alternative or additional observation is to create a circuit consisting of a battery and short thread of steel wool in series with a single light bulb. Add additional light bulbs in parallel with the first bulb until the steel wool burns out and creates a break in the circuit. Have the students discuss and explain this phenomenon.

Frame the investigation by challenging students to design an experiment that will allow them to develop a model for current flow in a circuit that has a combination of both series and parallel resistors. They should be thorough in documenting their investigations.

Students should be prepared to convince you and their peers that their approach is sound and that their conclusions are supported by data.

IMPLEMENTATION

Students will need to develop a method for investigating electrical circuits with multiple pathways. From their observations and current measurements they should be able to determine that current is conserved in a circuit.

Provide student groups with a model of a circuit, supplies to create circuits, and a current probe. The schematic in Figure 1 is a good starting point. We recommend revisiting the method of measuring current in a circuit to avoid damaging equipment and measuring current incorrectly. Correctly isolating and measuring the current through a resistor in a circuit with parallel paths can be challenging.

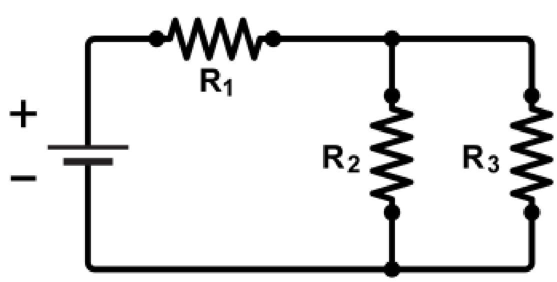


Figure 1 Circuit containing resistors in both parallel and series configurations

The final activity in this investigation is for the students to build their own circuit that has series and parallel elements. Once they have designed their circuit they should calculate the current throughout the circuit based on the model. They may need to assume a specific voltage. After this is complete students can take measurements to confirm their predictions.

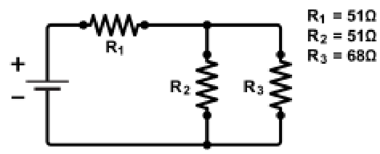
ANALYSIS

Data collected should indicate that the current flowing into a particular node is equal to that leaving the node. Attention to current sign as well as magnitude is important.

Encourage students to annotate their circuit diagrams with arrows indicating the direction and magnitude of the current in order to help reinforce the splitting and combining of the current before and after a node.

SAMPLE RESULTS

Students may sketch several circuits to construct and test. Using resistors of identical resistance is not necessary, but may simplify initial observations.



Resistor	Resistance Ω	Current (mA)
R_1	51	62.8
R_2	51	35.2
R_3	68	26.4

Figure 2 Sample data for current in a circuit

The data can be displayed graphically, which makes it easy to identify the relationship between the current entering a node and that leaving the node. A data table can be equally effective in communicating this data.

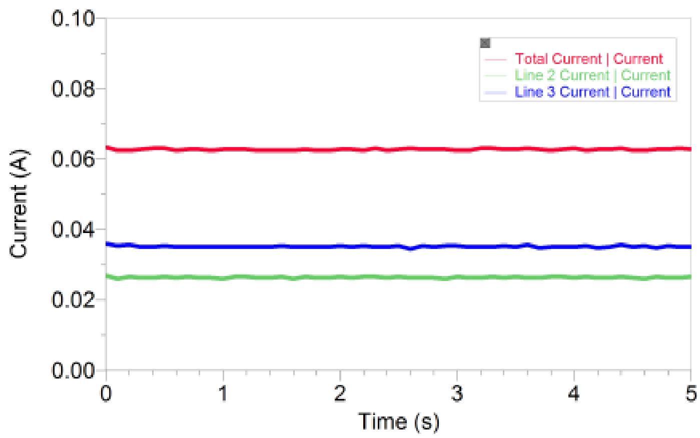


Figure 3 Sample data displayed in a graph

TIPS

1. In the Electronic Resources you will find many useful files, including sample program and a PDF of the student pages so you can print the activity for your students or distribute the file to them electronically. Sign in to your account at **vernier.com/account** to access the Electronic Resources. See Appendix A for more information.

2. Students may struggle with measuring the current through single resistors for more complicated circuits. You may wish to require students to demonstrate their competency prior to conducting their investigation. This can ensure data collected is from the intended parts of the circuit.

3. The authors highly recommend reading chapter 7 "Current Electricity" of *Teaching Introductory Physics* by Arnold Arons (Wiley, 1997) for insights into guiding students toward deep understanding electricity.

EXTENSIONS

Assign one or more of the following extensions once students have concluded their investigations. While we provide guidance for what to expect from students in response to the extensions, we do not include sample data or conclusions.

1. Compare the time required to deplete a battery when applied to a circuit in series and in parallel. Explain this in the context of conservation of charge and other observations in this investigation.

A parallel circuit will offer less resistance to the flow of current and will deplete a battery faster.

2. Starting with two bulbs in series with a battery, place an additional wire so that each end is in contact with the terminals of one of the bulbs. Describe your observations terms of current flow and explain in terms of your model. Is this a "short circuit" or an "open circuit"? Explain.

This would allow current to flow freely through the wire, effectively reducing the resistance of the circuit, and essentially eliminating the current flowing through the light bulb in question. This light bulb will go out (or at least dim significantly). This describes a short circuit. If the second bulb were not in place there would be no resistance in the circuit and the battery would lose its charge quickly.

3. Research fuses and circuit breakers to provide a comparison of these two safety mechanisms and explain how that relates to the phenomena noted in the circuit in Extensions 1 and 2.

Both fuses and circuit breakers protect circuits by creating a gap in the circuit. In the case of fuses, a small strip of metal will reach a melting point and break when a certain level current moves through the fuse. The circuit breaker is a similar device that opens the circuit, usually through some stored mechanical energy such as a spring.

Conservation of Charge

Imagine you are canoeing down a river. Downstream you notice a large island. As you approach, it is not entirely clear which side of the island the river current will carry you. What do you experience/observe about the river as you approach and pass by the island?

PRELIMINARY OBSERVATIONS

Observe the following electricity demonstrations:

- A single light bulb connected to a battery, then additional lights added in series
- A single light bulb connected to a battery, then additional light bulbs added in parallel

Your task is to design an experiment that focuses collecting data to develop a model that explains the nature of current in circuits. Your model should be valid for series circuits, parallel circuits and combinations of the two.

Your initial investigation will be made using the circuit in Figure 1:

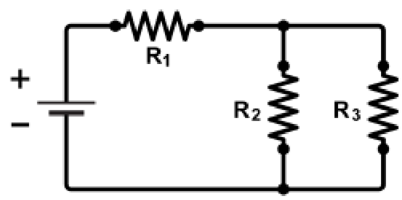


Figure 1

PROCEDURE

1. Discuss and decide what variables you will consider in the process of constructing a model for describing the current flow in a circuit.

   - Consider any knowledge you have gained from previous coursework.
   - Conduct research as needed.

2. Develop a purpose and a procedure for your investigation.

   - Your purpose should ask a question or propose a model related to the nature and properties of current in simple circuits.
   - Include an explanation of the equipment you will use.
   - Decide how much data and what observations to take in order to have enough information to satisfy your purpose and stand up to questioning by your peers.

3. Carry out the investigation and record your data and observations. Make sure all group members have access to the data.

ANALYSIS

Evaluate your data and develop a model based on this data to explain the phenomena you have observed. The model should allow you to predict the amount of current through any portion of a circuit consisting of resistors in series and parallel.

Use your model to explain the demonstrations conducted during the Preliminary Observations.

Construct a new circuit that contains both series and parallel elements. Predict the values of the current through each component. Measure the current through each component to verify your model. If your prediction does not match your measured values, revisit your model and adjust it as necessary.

EXTENSIONS

1. Compare the time required to deplete a battery when applied to a circuit in series and in parallel. Explain this in the context of conservation of charge and other observations in this investigation.

2. Starting with two bulbs in series with a battery, place an additional wire so that each end is in contact with the terminals of one of the bulbs. Describe your observations terms of current flow and explain in terms of your model. Is this a “short circuit” or an “open circuit”? Explain.

3. Research fuses and circuit breakers to provide a comparison of these two safety mechanisms and explain how that relates to the phenomena noted in the circuit in Extensions 1 and 2.

Voltage in a Circuit

OVERVIEW

The goal of this activity is for students to develop an understanding of how voltage behaves in a circuit involving resistors in both series and parallel configurations.

In the initial observation, students observe a circuit consisting of a single battery and a single resistor/light bulb. A volunteer will measure the voltage across both the battery and the resistor/light bulb. Students predict the result of adding a second battery in series and measuring the total voltage. After observing this, students predict what the voltage would be if one of the batteries were turned around.

Students are provided with a diagram of a series circuit consisting of three batteries and two resistors, as well as supplies to construct circuits (including three resistors—two of the same resistance and another that is different). The students' challenge is to try as many combinations as necessary to understand the relationship between the voltages of the components in a series circuit.

The class should reconvene and discuss their results. Then, students predict the result of replacing one of the resistors present with a resistor of different value. This is followed by a class/group discussion and testing of the predictions.

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should understand the elements of a complete circuit and how to measure voltage across individual components in a circuit. If students have never measured voltage before, it is probably sufficient to demonstrate the technique before the Preliminary Observations.

Students should also be familiar with circuit diagrams and the symbols used in them.

LEARNING OUTCOMES

- Learn that the supplied electrical potential (i.e., voltage) is shared across resistances in a circuit. In other words, the voltage measured across each component and source in a circuit loop should add to zero.
- Understand that the sign of the measured voltage is an indication of an increase or decrease of electrical potential.

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
PS3.A Definitions of Energy PS3.B Conservation of Energy and Energy Transfer	Patterns Cause and Effect Systems and System Models Energy and Matter	Developing and Using Models Planning and Carrying Out Investigations Analyzing and Interpreting Data Constructing Explanations and Designing Solutions Obtaining, Evaluating, and Communicating Information

ESTIMATED TIME

Two 45-minute class periods, with time at the end of the second class to conclude class discussion.

MATERIALS

Make the following materials available for student use. Items in bold are needed for the Preliminary Observations.

batteries (each group needs 3 batteries)
battery holders
small incandescent light bulbs
alligator clip wires
computer, Chromebook, or mobile device
data-collection program
data-collection interface (if necessary)
Vernier Circuit Board 2 (order code: VCB2)
voltage probe
2 resistors (with the same resistance values) and 1 additional resistor (with a different resistance)

PRELIMINARY OBSERVATIONS

Start the class by conducting the following set of observations:

Create a simple circuit consisting of a single battery and a single light bulb or resistor (see Figure 1). Have a student measure and announce battery's voltage and the resistive element's voltage. Have the student reverse the leads of the voltage probe and announce what is different.

Ask the students to predict the result of adding a second battery in series and measuring the total voltage across both batteries. Have a student perform this measurement.

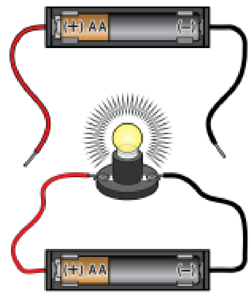


Figure 1 Example of equipment for Preliminary Observations

Ask the students what the total voltage would be if one of the batteries were turned around. Allow them time to consider this question and discuss with their lab partners. Have a student perform this measurement. In each case the resistive element's voltage should be measured as well.

After the Preliminary Observations and discussion, frame the investigation. Challenge students to determine the relationship between the voltages in a series circuit. The circuit will consist of a single loop with five components—three batteries and two identical resistors. Students will investigate the voltages of the components, changing their order and orientation, in order to try to understand how voltage behaves in a circuit.

Students should be prepared to convince you and their peers that their approach is sound and that their conclusions are supported by data.

IMPLEMENTATION

Students will need to develop a method to investigate the voltages of a single loop electrical circuit.

After the students have conducted their experiments and developed their models, provide students with another resistor of a different value and have them test their model with resistors of different values.

ANALYSIS

Student results should indicate that, within some degree of uncertainty, voltages around a circuit add to zero. Or put another way, the voltage gains are equal to the voltage drops.

Attention to voltage sign as well as magnitude is important. Consider recommending that each group decide on a convention for connecting the voltage probe leads to the circuit elements. For example, they might decide that, as they move counterclockwise around the circuit, the red lead for the voltage probe will always be "ahead" of the black lead.

SAMPLE RESULTS

An example test plan and report of findings you might expect from students:

1. We have (3) AA rechargeable batteries (~1.5 V) and (2) 51 Ω resistors. They will be connected in series at all times in this investigation.

2. In order to understand voltage across the batteries and light bulbs in a circuit we will measure the voltage across each component in the following scenarios:
   a. Battery 1 [+ –], Battery 2 [– +], Battery 3 [+ –] then to the two resistors.
   b. Battery 1 [+ –], Battery 2 [– +], Battery 3 [– +] then to the two resistors.
   c. We will also move the resistors in between the batteries. (Our hypothesis is that this will not matter, but figured we should verify that.)
3. All batteries linked + to – then to the two resistors (R_1 and R_2).

4. When we measure the voltage we will make sure that the black lead is on the side of the component that is on the same side as the + terminal on Battery 1.

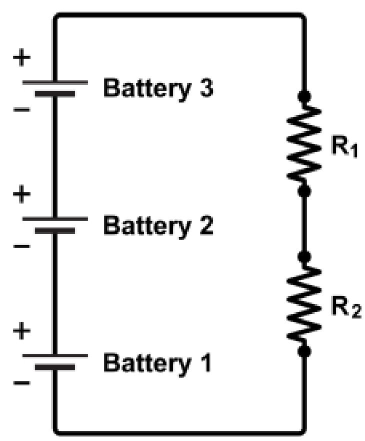


Figure 2 Sample sketch of circuit

Data were collected using a Differential Voltage Probe. The values for the different runs are presented in Tables 1–3. Another way for students to record their data is on a large, clear circuit diagram, with the measured values next to each component.

Table 1: Trial #1 - [+ –][+ –][+ –]	
Component	Voltage (V)
Battery 1	1.337
Battery 2	1.050
Battery 3	1.323
Resistor 1	–1.835
Resistor 2	–1.824

Table 2: Trial #2 - [**+ –**][**– +**][**+ –**]	
Component	Voltage (V)
Battery 1	1.337
Battery 2	–1.042
Battery 3	1.333
Resistor 1	–0.799
Resistor 2	–0.793

Table 3: Trial #3 - [**+ –**][**– +**][**– +**]	
Component	Voltage (V)
Battery 1	1.339
Battery 2	–1.062
Battery 3	–1.342
Resistor 1	0.522
Resistor 2	0.519

Sample Observations

We noted that when we reversed the orientation of a battery the voltage registered as "–" on our LabQuest 2. The values of the batteries seemed to be consistent, only the sign changed. However, the voltages of the resistors changed with each change in orientation of a battery.

We moved components around during each run, but this did not affect the values or the sign of the voltages we measured.

We also displayed the data in a bar chart using Logger *Pro* software in order to help us see the relationship visually (see Figure 3). The top graph in Figure 3 shows all three batteries oriented the same direction, with the + end closest to resistor R1. The middle graph shows that we reversed the direction of Battery 2. In the final experiment (bottom graph) we reversed both Battery 2 and Battery 3.

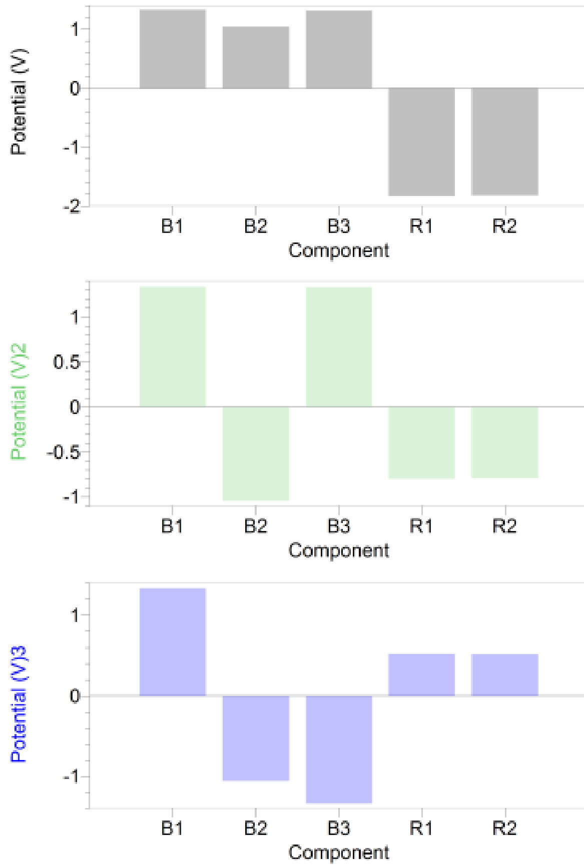


Figure 3 Data displayed using Vernier Logger Pro software

Sample Analysis and Hypothesis

We believe that the voltages should always add up to zero as you measure around the circuit. If we replace one of the resistors in the circuit with a different one, we believe the voltage of the batteries will remain the same, but the two voltages of the resistors will change. The sum of all the voltages should still be zero.

TIPS

1. In the Electronic Resources you will find many useful files, including sample program and a PDF of the student pages so you can print the activity for your students or distribute the file to them electronically. Sign in to your account at **vernier.com/account** to access the Electronic Resources. See Appendix A for more information.

2. If you use the Vernier Circuit Board 2 (order code: VCB2) instead of having students construct circuits from scratch, we recommend taking time to reinforce that the circuits are constructed in a single loop. We do not recommend using the original Vernier Circuit Board (order code: VCB), as it has room for only two D batteries.

3. You may want to provide students with light bulbs so students can see the results of their experiments. Recognize that the resistance of the light bulbs will change as the bulbs heat up.

4. Because the sign of the voltage is an important element of this investigation it is helpful to lay out the circuit in a way that clearly shows the circuit is a single loop. This way, students can consistently measure the polarity of the components, as well as the magnitude of the voltage.

5. Kirchhoff's second law (also called Kirchhoff's loop rule) is often described as an application of the conservation of energy. It may useful to make this connection, either before or after the students explore the nature of voltage around a loop.

6. The authors highly recommend reading chapter 7 "Current Electricity" of *Teaching Introductory Physics* by Arnold Arons (1997) for insights into guiding students toward deep understanding of electricity.

EXTENSIONS

Assign one or more of the following extensions once students have concluded their investigations. While we provide guidance for what to expect from students in response to the extensions, we do not include sample data or conclusions.

1. Consider circuits with multiple current pathways, and determine how voltage behaves in this scenario.

Tapping into previously developed knowledge, students may confirm the following points:

- Parallel portions of circuits have the same voltage drop.
- The voltage from any power supply in any loop is equal to the voltage drops across the components.

2. Investigate both current and voltage in a variety of circuits in order to develop a comprehensive explanation of voltages and current in simple circuits with multiple paths.

Tapping into previously developed knowledge, students may confirm the following points:

- Parallel portions of circuits have the same voltage drop.
- Portions of a circuit in with components in series have the same current flowing through them.
- The current flowing into a junction is the equal to the current flowing out of a junction.

3. Research voltage dividers and how they are used in modern electronics. Build a voltage divider circuit that will allow you to determine the resistance of an unknown resistor.

A voltage divider has a known voltage applied over two resistors in series. One resistor is integral to the voltage divider and its value is known; the value of the other resistor is unknown. By measuring the voltage across the known resistor you can calculate the unknown resistance.

To determine the voltage across the unknown resistor, subtract the voltage at the known resistor from the total voltage. The current is the same in both resistors, so $V_1/R_1 = V_2/R_2$. This allows you to calculate the unknown resistance.

4. Replace each of the light bulbs in this investigation with LEDs. Add a single (approximately) 100 Ω resistor in series with each LED. Note how the LEDs behave as you test different battery configurations.

Red LEDs will work better than other colors.

The resistor will provide protection for the LEDs. Students should observe that the LEDs only allow current to flow one direction. When the batteries are reversed in direction, the LEDs will not light up.

Students may also determine that LEDs may require a certain minimum voltage to light up at all.

Voltage in a Circuit

Imagine you are at the top of a ski slope, looking down over the run. You point your skis down the hill and take off. You feel the pull of gravity as you ski down the run. Finally you end up at the bottom of the run. How do you get back up to the top of the run?

PRELIMINARY OBSERVATIONS

Observe the following electrical circuit demonstrations:

- Measure the voltage of a single battery.
- Predict the total voltage you would expect to see if you stack two batteries together. Then, test your prediction by stacking two batteries and measuring the voltage.
- What happens when you turn one of the batteries around? Test your prediction.

PROCEDURE

Your task is to create a circuit that consists of a single loop. The circuit will contain five components: three batteries and two resistors. Investigate the voltages of the components, changing their order and orientation in order to try to understand how voltage behaves in a circuit. Develop a model that explains your results.

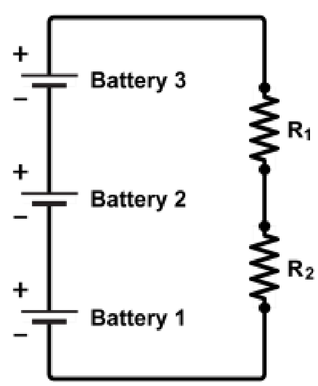


Figure 1 Schematic of initial circuit

1. Discuss and decide how you will conduct your investigation of the voltage in a circuit. Consider any knowledge you have gained from previous coursework while making your plan.

2. Develop a purpose and a procedure for your investigation.

    - Your purpose should ask a question or propose a model related to the nature and properties of voltage in simple circuits.
    - Include a list of equipment and an explanation of how the equipment will be used.

- Decide how much data and what observations to take in order to have enough information to satisfy your purpose and stand up to questioning by your peers.

3. Carry out the investigation and record your data and observations. Make sure all group members have access to the data.

ANALYSIS

Evaluate your data and develop a model based on this data to explain your data and observations. The model should address how you might predict the amount of voltage across any component in a simple circuit.

Change one of the resistors in your circuit so that you have resistors of unequal resistance. Are the results consistent with your model? If not, modify your model to account for this new data.

Re-read the first paragraph in the introduction to this investigation. How is the content of that paragraph related to your model?

EXTENSIONS

1. Consider circuits with multiple current pathways, and determine how voltage behaves in this scenario.
2. Investigate both current and voltage in a variety of circuits in order to develop a comprehensive explanation of voltages and current in simple circuits with multiple paths.
3. Research voltage dividers and how they are used in modern electronics. Build a voltage divider circuit that will allow you to determine the resistance of an unknown resistor.
4. Replace each of the light bulbs in this investigation with LEDs. Add a single (approximately) 100 Ω resistor in series with each LED. Note how the LEDs behave as you test different battery configurations.

