Three-Dimensional Learning in 5E Learning Cycle: Electric Circuits

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Abstract

This paper describes a student-centered approach to teaching and learning physics in a high school classroom. The teacher designs and uses a 5E learning cycle to teach series and parallel electric circuits. This article provides an example of the implementation of 5E model for a physics lesson to address three-dimensional learning- science and engineering practices, disciplinary core ideas, and crosscutting concepts. In this lesson, students could make predictions, exchange ideas, and collect and analyze data to construct evidence-based explanations about electric circuits, Ohm`s law. This type of lesson design is effective to enhance students` engagement in scientific practices and develop conceptual understanding.

Keywords: Three-dimensional learning, 5E Learning Cycle, Electric Circuits.

INTRODUCTION

The research on science education reported that scientific inquiry played a role to reflect the scientists' work to understand the nature of science and variety of scientific methods (Schwartz et al., 2023). Duschl (2008) suggested that learners should learn science through engaging in scientists' practices such as asking questions, planning and carrying out investigations, and developing explanations which referred to cognitive, social, and epistemic procedures to develop both knowledge and skills. In parallel, Next Generation Science Standards guided science teachers to develop knowledge and skills to plan and enact science lessons through scientific inquiry, which integrates science and engineering practices with crosscutting concepts, disciplinary core ideas, and characteristics of nature of science to reach performance expectations (NGSS Lead States, 2013). A Framework of K-12 Education (NRC, 2012) suggested that the science lessons should avoid coverage of the content in a shallower way, but science lessons should support students' engagement in science investigations to understand how scientific knowledge is constructed. Science teachers have been suggested to design lesson plans considering not only disciplinary core ideas but also science and engineering practices and crosscutting concepts to develop scientific knowledge while activating the use of science process skills. These suggestions addressed the need for changes in science curriculum, pedagogy, and type of assessments to make students have meaningful learning experiences.

Reform movement in science education aimed to develop scientific knowledge and practices based on evidence through exploration, observation, data collection and analysis, and explain scientific phenomena within more than one set of procedures (Krajcik & Shin, 2023). Krajcik and Shin (2023) called for the implementation of three-dimensional learning through addressing disciplinary core ideas and crosscutting concepts with science and engineering practices. These calls aimed to address the design of science lessons in which students engage in scientific discussions based on their observations and pre-existing knowledge to solve a problem. Social constructivist theories of learning suggested learners to engage in the processes of science such as construction, critique, and justification of knowledge claims as the practices of a scientific community to develop a functional understanding of the characteristics of science (Chinn & Iordanou, 2023; Henderson et al., 2015). Three-dimensional learning supports the integration of science and engineering practices, disciplinary core ideas, and crosscutting concepts in a lesson (Kaldaras et al., 2021). Science and engineering practices encourage learners to ask questions about the topic and events and define problems around them, develop and use different types of models including pictures, diagrams, physical models or simulations. Planning and carrying out investigations are another scientific practice that learners can engage in data collection and analysis and interpretation of results through using mathematical and computational thinking to report relationships, patterns, and measurements. Then, it is important to provide a coherent scientific explanation about the results of the investigation. Learners' different explanations can help them compare the relevance of their claims to support with evidence and justification to engage in scientific argumentation. These practices also help learners obtain and communicate their findings in designed formats such as oral or written presentations. Moreover, crosscutting concepts are a second dimension and beneficial to make connections between science practices and core science ideas in a meaningful way. These concepts are fundamental to nature of science to understand “patterns and cause-and-effect relationships” concepts, mathematical quantities such as “scale, proportion, and quantity” concept in science, and systemic thinking in terms of “systems and system models, energy and matter flows, structure and function, and stability and change” concepts. Disciplinary core ideas are third dimension and address the disciplines of physical science, life science, earth-space science, and engineering, technology, and application of science as well as nature of science to understand how science works and characteristics of scientific knowledge.

Following the suggestions of reform movements, for example, No Child Left Behind (NCLB) Act in 2001, different instructional models have been developed to integrate inquiry-based activities to address the suggestions of science standards and needs of diverse students. These instructional models help to develop an organized logical plan for instructional activities to incorporate cognitive, social, and epistemic aspects of science into science teaching rather than traditional, teacher-centered instruction (Duschl, 2008). As a research-based instructional model, 5E instructional model (Bybee et al., 2006) was developed from the work of Atkin and Karplus (1962) to be able to apply Next Generation Science Standards (NGSS Lead States, 2013). 5E instructional model provided a coherent learning sequence to understand through engagement, exploration, explanation, elaboration, and evaluation phases: to make students experience disequilibrium in their thinking and involve in activities to explore and reconstruct their understanding. Innovative approaches to science teaching and learning suggested that 5E instructional model provided a great promise and potential to improve students` literacy skills such as reading, speaking, and writing along with conceptual understanding (Schwartz et al., 2023). During science investigations, students work in small groups to design a method for data collection and analysis with the appropriate materials and develop an evidence-based explanation. In these activities, students are expected to support their answers for a research question with evidence from the measurements and observations and justification of evidence with scientific principles.

These instructional approaches support teachers to implement three dimensions of scientific knowledge including disciplinary core ideas (DCIs), science and engineering practices (SEPs), and crosscutting concepts in an integrated format. This paper provides an example to understand how to implement 5E instructional model to address performance expectations of three-dimensional science education: science and engineering practices, disciplinary core ideas, and crosscutting concepts. The rest of the paper provides samples for teacher work including design of the lesson, elicitation of student ideas, developing and using models, and results from students’ work. The example investigation shows how high school students can engage in exploration and argumentation with a conceptual change approach.

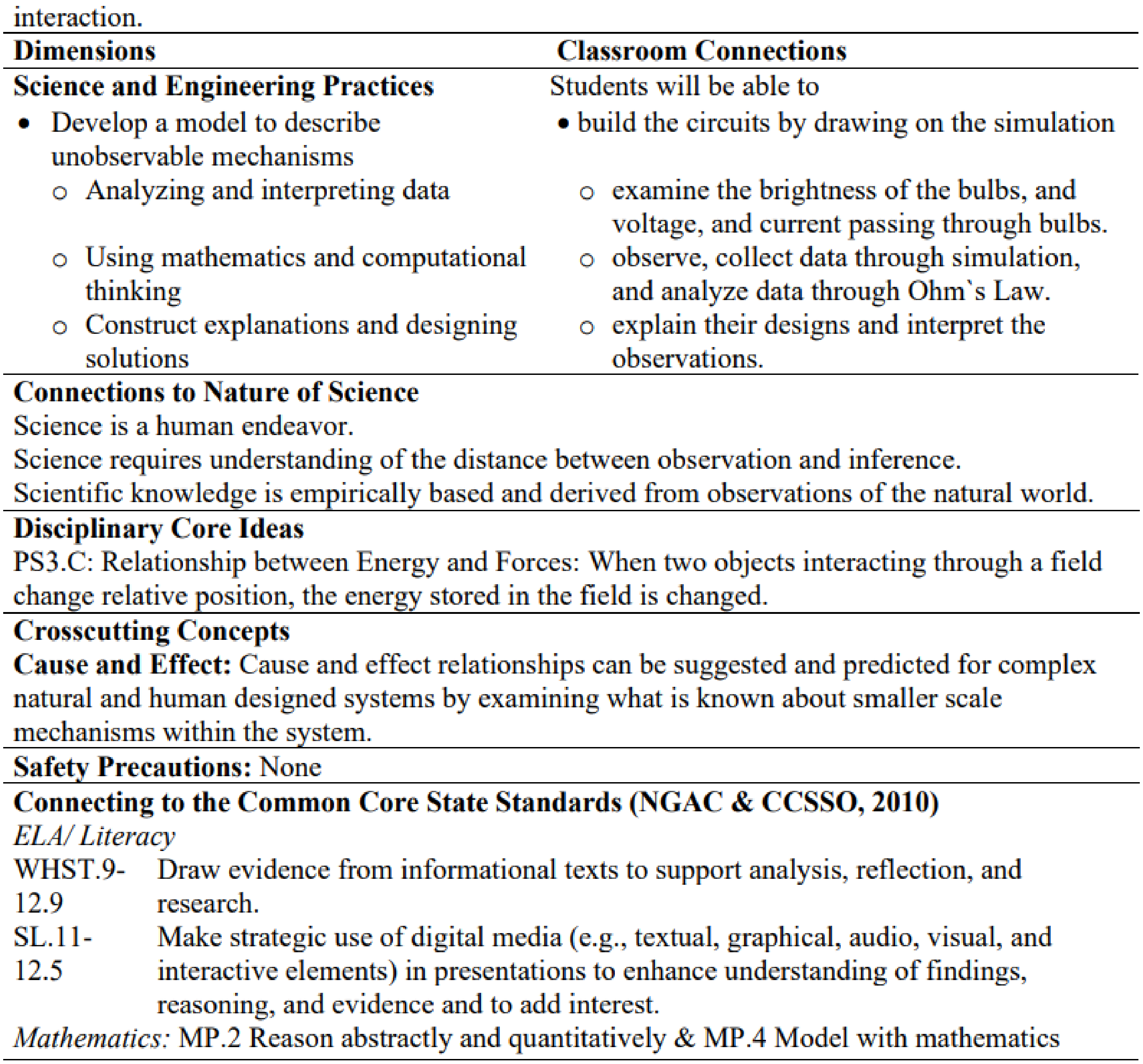
Instructional Model: 5E Learning Cycle

Ford (2015) notes ways to enhance student involvement and conceptual understanding through asking questions, collecting, and analyzing data, drawing conclusions, and communicating results. Several instructional models support science teachers to teach through inquiry to plan and enact assessment tasks (Schwarz et al., 2009). The 5E instructional model aims to develop students' abilities consistent with scientific inquiry and 21st century skills such adaptability and communication (Bybee et al., 2006). Bybee et al. (2006) defines 5E model with the following steps: 1) *Engagement* phase aims to create a disequilibrium in students' minds through eliciting their existing conceptions and enhancing their interest to the new concept. 2) *Exploration* phase aims to address students' wrong conceptions through short investigations that might encourage students to explore, think, and generate new knowledge in a group. 3) *Explanation* phase aims to make students explain their understandings through group work or individual presentations. Teachers also develop explanations to build on students' ideas from engagement and exploration phases. 4) *Elaboration* phase aims to extend students' understanding through more comprehensive investigations and engaging in new experiences. 5) *Evaluation* phase aims to assess whether students acquire the expected learning objectives of the lesson.

To illustrate how science teachers can implement the 5E instructional model, this paper describes the design and enactment of a three-dimensional physics lesson in a high school classroom on Electric Circuits. This lesson is designed by the author as the teacher to help learners compare the brightness of the bulbs in series and parallel to explain the relationship between current, voltage, and brightness by observation on the simulation and use of the Ohm's Law. As pre-knowledge, students need to show the elements in an electrical circuit with their symbols, draw a circuit diagram consisting of bulbs connected in series and parallel, and estimate the variables influencing the brightness of the bulbs in an electric circuit. The lesson engages students in scientific practices including the development and use of models to collect and analyze data, use mathematics and computational thinking, and to construct evidence-based explanations in designing the solutions. As crosscutting concepts, the lesson includes the cause-and-effect relationships to understand the changes in a circuit element as dependent variable by manipulating independent variables. The author exemplifies how to enact the 5E model to address the important elements of the science standards in a two-hour physics lesson in a high school classroom. This article provides a useful organizational framework to promote three-dimensional learning. The lesson’s connections to Next Generation Science Standards (NGSS Leads States, 2013) are provided on Table 1.

Table 1

Connecting to the Next Generation Science Standards (NGSS Lead States, 2013)



Standard: HS-PS3-5. Develop a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

Dimensions	**Classroom Connections**
Science and Engineering Practices	Students will be able to
• Develop a model to describe unobservable mechanisms	• build the circuits by drawing on the simulation
o Analyzing and interpreting data	o examine the brightness of the bulbs, and voltage, and current passing through bulbs.
o Using mathematics and computational thinking	o observe, collect data through simulation, and analyze data through Ohm`s Law.
o Construct explanations and designing solutions	o explain their designs and interpret the observations.

Connections to Nature of Science

Science is a human endeavor.

Science requires understanding of the distance between observation and inference.

Scientific knowledge is empirically based and derived from observations of the natural world.

Disciplinary Core Ideas

PS3.C: Relationship between Energy and Forces: When two objects interacting through a field change relative position, the energy stored in the field is changed.

Crosscutting Concepts

Cause and Effect: Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.

Safety Precautions: None

Connecting to the Common Core State Standards (NGAC & CCSSO, 2010)

ELA/ Literacy

WHST.9-12.9	Draw evidence from informational texts to support analysis, reflection, and research.
SL.11-12.5	Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest.

Mathematics: MP.2 Reason abstractly and quantitatively & MP.4 Model with mathematics

Table 2. *Appropriate timing to implement 5E model*

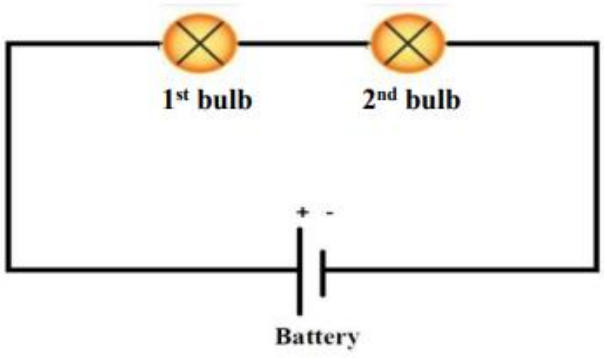
5E Instructional Model	Time required
Engage	10 minutes
Explore	35 minutes
Explain	15 Minutes
Elaborate	40 Minutes
Evaluate	10 Minutes + Homework

The Lesson Task

The author aimed to use the 5E model to design a lesson addressing three-dimensional learning on electric circuit topic (Table 1). The teacher integrated activities in each phase of 5E instructional model in parallel to the purposes (Table 2). The lesson took two class hours (100 minutes). The lesson was prepared to be taught in a high school computer laboratory with 20 high school students. Each student was able to use computers to work on the simulation, answer the questions on the worksheet (see worksheet as Appendix-I). Samples of student responses were provided. The lesson flow was presented below.

Figure 1.

Two identical bulbs connected in series



Engagement (10 minutes). The teacher started the lesson by showing the Figure 1 and asking, ``Do identical two bulbs in series have the same brightness?`` and ``How can we make these bulbs brighter?`` The students were expected to understand that identical two bulbs in series had the same brightness, and the brightness of the bulbs could change through using more efficient wires, adding more identical batteries, and connecting the bulbs in parallel. The teacher emphasized how the type, the length, and cross-sectional area of the wire influence the brightness of bulb as students` prior knowledge. The teacher also referred to how changing the connection type influences the brightness of the bulbs in a circuit. The teacher provided Table 3 on a worksheet to elicit students` prior knowledge about parallel and series connection of bulbs and their brightness. The teacher asked, "Please predict the brightness of bulbs in series and parallel circuits." Before the exploration phase, students were expected to predict the brightness of the bulbs when they connect in series or parallel circuits.

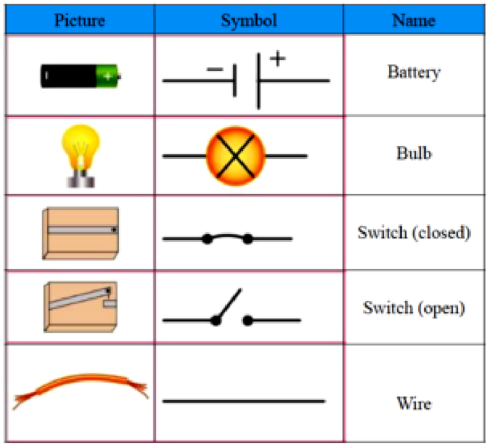
Table 3. *Question To Predict The Brightness Of The Bulbs In Serial And Parallel Circuits*

Connection with	Draw the circuits and estimate the brightness of the bulbs	
	Serial Circuit	**Parallel Circuit**
2 bulbs + 1 battery	*Serial circuits have lower brightness than parallel circuits.*	*Parallel circuit has higher brightness than serial.*
3 bulbs + 1 battery	*This circuit has the lowest brightness.*	*Its brightness will be high, but same as the parallel circuit.*
3 bulbs + 2 batteries	*This circuit's brightness is lower than parallel's brightness*	*Its brightness will be the highest.*

Exploration (35 minutes). In the exploration phase, students made observations and compared their predictions with the observations. Students were guided to use the simulation[1] to observe brightness of the bulbs on each circuit. The teacher reminded the elements of the circuit as bulb, wire, switch, and battery (Figure 2). Students constructed the electric circuits on Table 3 via the simulation. They were also asked to explain how the number of batteries and number of bulbs in a series or parallel circuit changed the brightness of bulbs and estimate how the value of current changed as the independent variables changed.

Figure 2

Elements of an electric circuit



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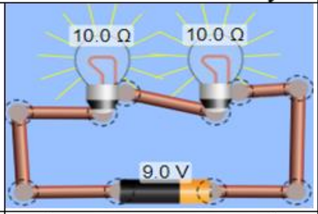
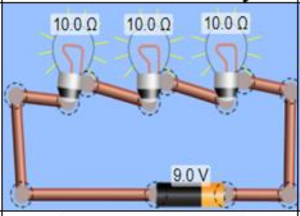
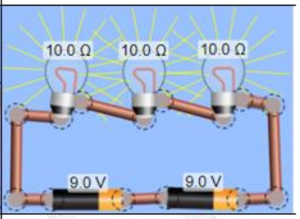
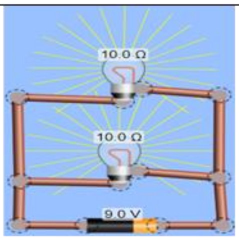
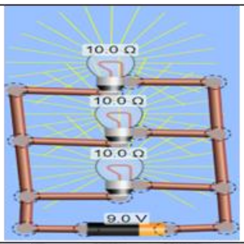
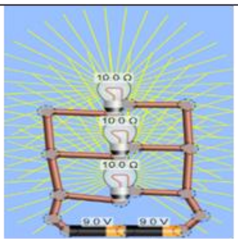
[1] https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html

Table 4

Relationship between voltage, electric current, brightness for series and parallel circuits

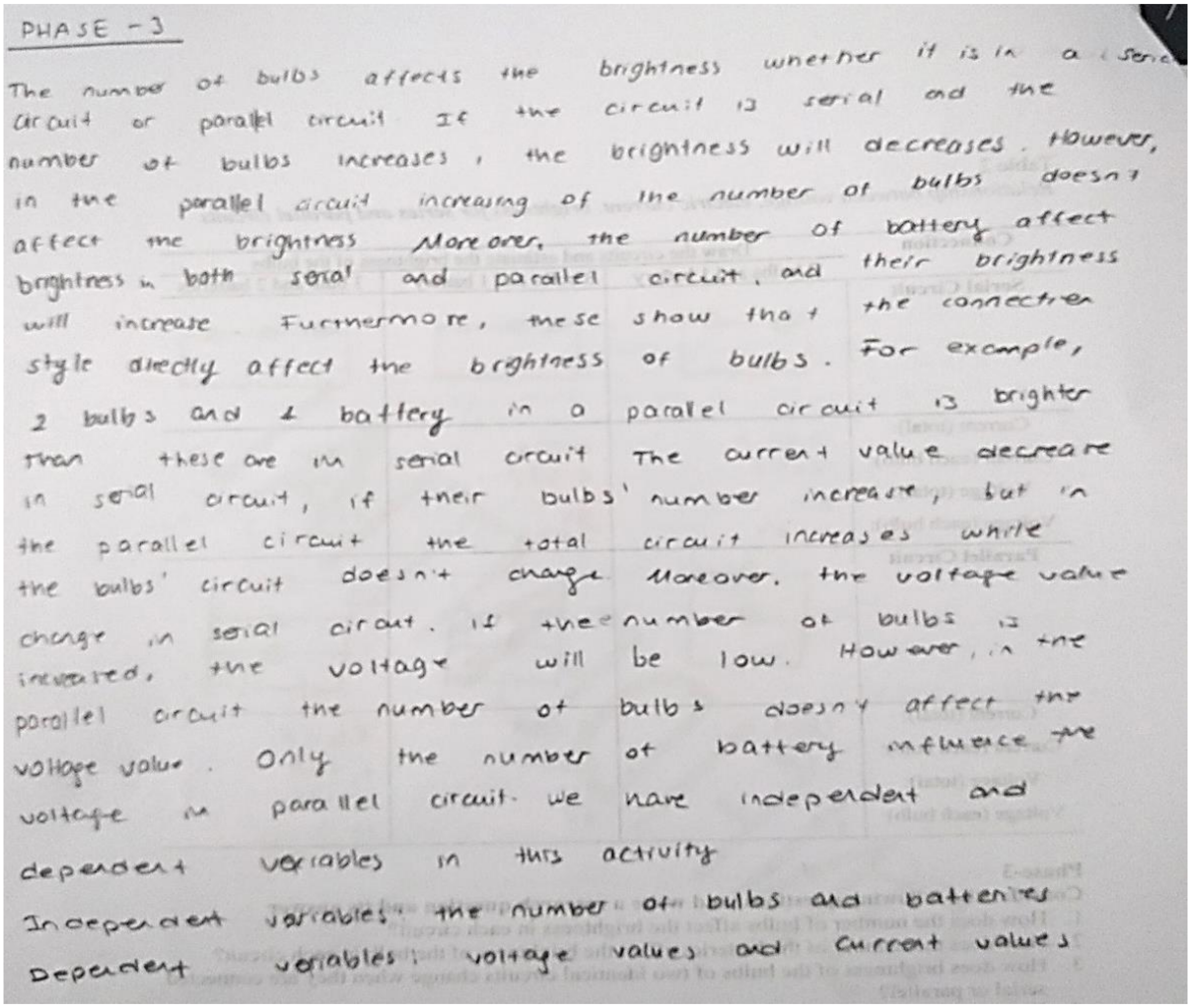
Connection	Draw the circuits and estimate the brightness of the bulbs		
	2 bulbs and 1 battery	3 bulbs and 1 battery	3 bulb and 2 batteries
Serial Circuit			
Current (total):	0.45 A	0.30 A	0.60A
Current (each bulb):	0.45 A	0.30 A	0.60 A
Voltage (total):	9V	9V	18 V
Voltage (each bulb):	4.48V	2.98 V	5.96 V
Parallel Circuit			
Current (total):	1,80A	2.70A	5.40 A
Current (each bulb):	0.90A	0.90A	1, 10A
Voltage (total):	9 V	9 V	18 V
Voltage (each bulb):	9 V	9V	18 V

In this phase, students were expected to make observations about the brightness of bulbs to answer the following questions:

1. How does the number of bulbs affect the brightness in each circuit?
2. How does the number of batteries affect the brightness of the bulb in each circuit?
3. How does brightness of the bulbs of two identical circuits change when they are connected serial or parallel?
4. What are your dependent and independent variables in the experiment?
    a. Dependent variable : b. Independent variable :
5. What are the current and voltage values on each bulb?

Figure 3

Sample student explanation on the questions



PHASE - 3

The number of bulbs affects the brightness whether it is in a Serie
circuit or parallel circuit. If the circuit is serial and the
number of bulbs increases, the brightness will decreases. However,
in the parallel circuit increasing of the number of bulbs doesn't
affect the brightness. Moreover, the number of battery affect
brightness in both serial and parallel circuit, and their brightness
will increase. Furthermore, these show that the connection
style directly affect the brightness of bulbs. For example,
2 bulbs and 1 battery in a parallel circuit is brighter
than these are in serial circuit. The current value decrease
in serial circuit, if their bulbs' number increase, but in
the parallel circuit the total circuit increases while
the bulbs' circuit doesn't change. Moreover, the voltage value
change in serial circuit. If the number of bulbs is
increased, the voltage will be low. However, in the
parallel circuit the number of bulbs doesn't affect the
voltage value. Only the number of battery influence the
voltage in parallel circuit. We have independent and
dependent variables in this activity.
Independent variables: the number of bulbs and batteries
Dependent variables: voltage values and current values

The teacher aimed to make students develop scientific conceptions on the factors influencing brightness. Students showed the relationship between voltage, electric circuit, and brightness for series and parallel circuits on the simulation and completed Table 4 (Sample student work).

Explanation (15 minutes). After students made observations about the brightness of bulbs, the teacher encouraged students to explain their observations in their own words by answering the questions from "exploration" phase. Students were asked to summarize the change in brightness, current, and voltage values as the number of batteries or bulbs increases. A sample student explanation was provided in Figure 3.

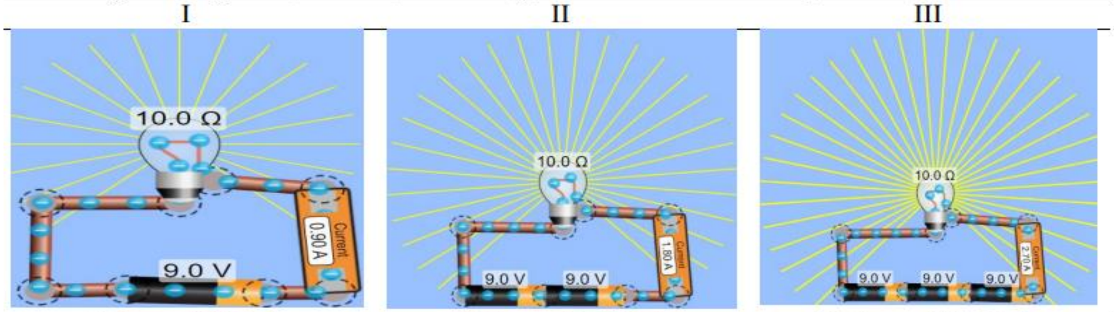
After students' explanations, the teacher emphasized the relationship between the bulb brightness and the current and voltage values across the bulbs in each circuit. The teacher reminded that when the switch was closed in a circuit with a bulb, wires, and a battery (9.0 volt), the bulb lighted up by the energy of the battery, which generated electric current transferred across the vibrating electrons in the conducting wire in a certain time-period. After this explanation, the teacher asked another question:

> *Considering the changes in voltage and current values in series circuits, please draw voltage versus current graph for the circuits on Figure 4.*

The teacher aimed to explain how the electric current changes as the voltage increased. Elaborating on students' explanations, the teacher added that as the number of batteries increased in a series circuit increased the voltage of the circuit elements, the electric current, and brightness of the bulb, but the ratio between voltage and current was constant. The teacher showed the graph on Table 5 to express the mathematical relationship between voltage (V), current (I), and resistance (R) of a bulb as Ohm's Law: V = I x R or I= V/R.

Figure 4

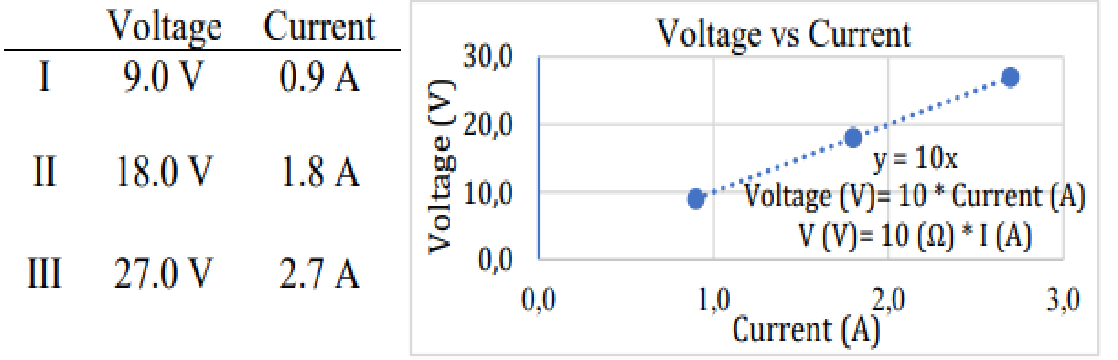
The change in brightness, current, and voltage values as the number of batteries



I	II	III
Voltage: 9.0 Volt Resistance on bulb: 10 Ω Current: 0.9 Ampere	Voltage: 18.0 Volt Resistance on bulb: 10 Ω Current: 1.8 Ampere	Voltage: 27.0 Volt Resistance on bulb: 10 Ω Current: 2.7 Ampere

Table 5

Graphical representation for Ohm's Law



	Voltage	Current
I	9.0 V	0.9 A
II	18.0 V	1.8 A
III	27.0 V	2.7 A

Elaboration (40 minutes). During the elaboration phase of the 5E model, students engaged in an extended activity to explore the relationship between voltage, current, and resistance by Ohm`s Law in series and parallel circuits. Students were expected to use a simulation[2] to construct a simple circuit with one resistor and one battery (I), a series circuit with two resistors and one battery (II), and a series circuit with three resistors and one battery (III) (Table 6).

First, students were expected to predict the voltage and current across A to C terminals and compare their prediction with the measurements using voltmeter and ammeter. After finding the voltage and current values, students were encouraged to understand that current flowing through the series was the same across the terminals. By using the Ohm`s Law (V= I * R), students could also find the total resistance in the series circuit for three conditions. In the exploration and explanation phases, the teacher emphasized that the brightness of the bulb depended on the electric current passing through the circuit, and students were expected to compare the brightness of bulbs with 10 Ω resistance for three circuits on Table 6. This activity showed that although students were able to measure the voltage and current values in three circuits, they were not able to recognize the difference between total resistance of the circuit and each resistance value of resistors.

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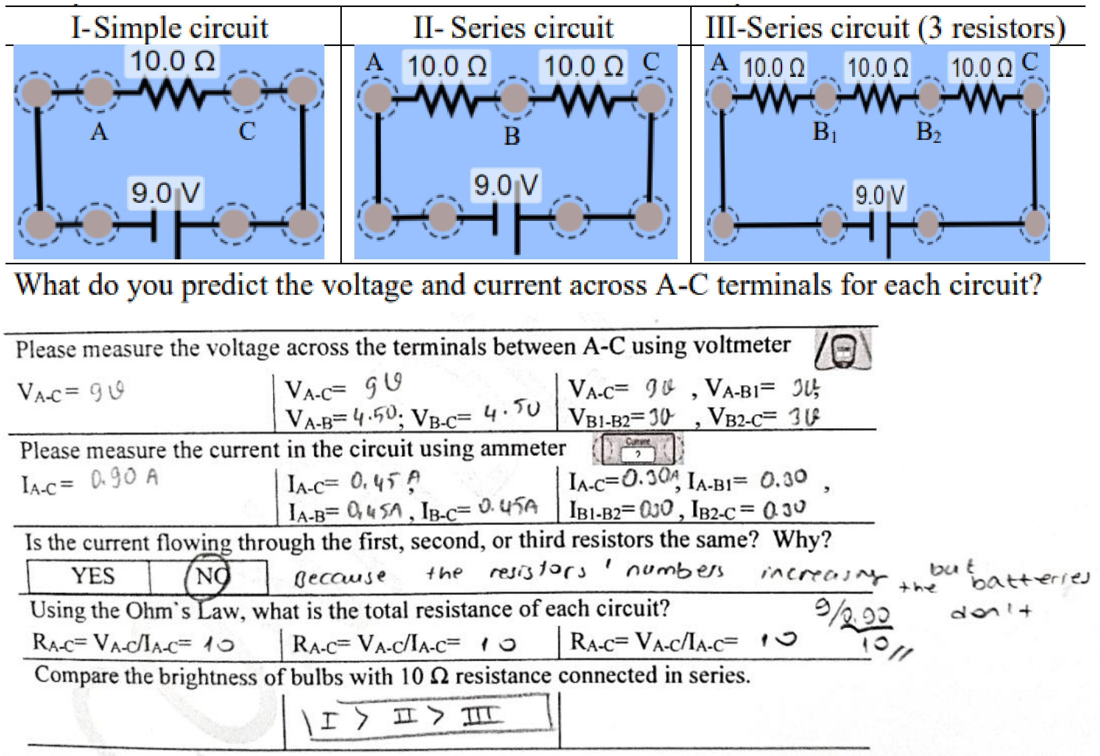
[2] https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html

Table 6

The question to examine series circuits in the elaboration phase



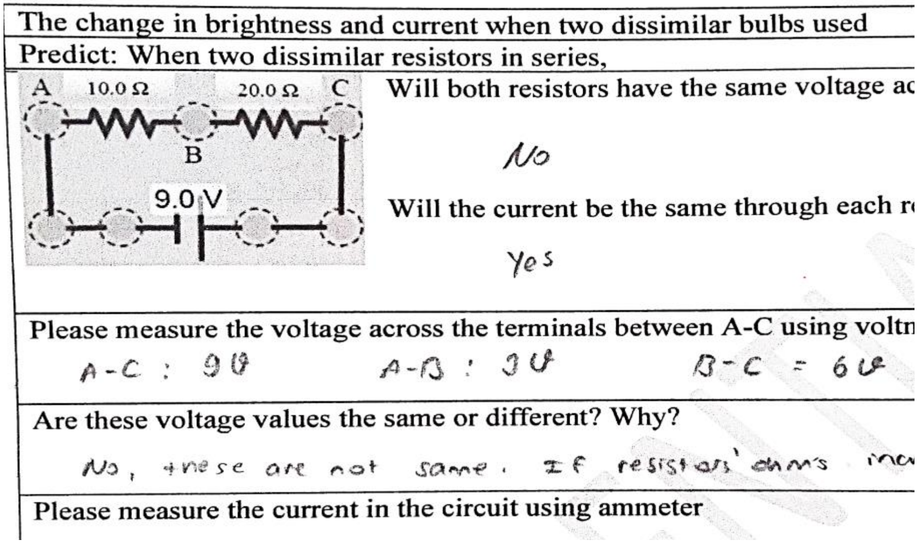
I-Simple circuit	II- Series circuit	III-Series circuit (3 resistors)
What do you predict the voltage and current across A-C terminals for each circuit?		
Please measure the voltage across the terminals between A-C using voltmeter		
V_{A-C}= 9V	V_{A-C}= 9V V_{A-B}= 4.5V; V_{B-C}= 4.5V	V_{A-C}= 9V , V_{A-B1}= 3V V_{B1-B2}= 3V , V_{B2-C}= 3V
Please measure the current in the circuit using ammeter		
I_{A-C} = 0.90 A	I_{A-C}= 0.45 A I_{A-B}= 0.45A , I_{B-C}= 0.45A	I_{A-C}=0.30A, I_{A-B1}= 0.30 , I_{B1-B2}= 0.30 , I_{B2-C} = 0.30
Is the current flowing through the first, second, or third resistors the same? Why?		
YES [✓ NO]	Because the resistors' numbers increasing but the batteries don't	
Using the Ohm`s Law, what is the total resistance of each circuit?		9/0.90 = 10
R_{A-C}= V_{A-C}/I_{A-C}= 10	R_{A-C}= V_{A-C}/I_{A-C}= 10	R_{A-C}= V_{A-C}/I_{A-C}= 10
Compare the brightness of bulbs with 10 Ω resistance connected in series.		
	I > II > III	

In the second part, students were expected to consider two bulbs with different resistance values and to compare whether both resistors had the same or different voltage, current or brightness values. This activity helped students understand that even though the current across each bulb in a series circuit was the same, the voltage and brightness over each resistor was different since the bulbs had different resistance values. The results were shown on Table 7.

In the third part, students worked on parallel circuits that provided more than one path for electrons along a wire to move. Students were expected to predict and measure the voltage and current values across each resistor and compare the brightness of identical bulbs with 10 Ω resistance connected in parallel. The results are shown in Table 8. This part aimed to help students understand that each identical bulb connected in parallel had the same voltage level as the battery in the circuit, the same current value and brightness. However, the total current passing through the circuit was different and larger than the current passing through each resistor. The students were exposed to similar questions in different parts of this phase which helped them realize the differences in questions and make sense of the relationship between brightness and current values.

Table 7

The change in brightness and current when two dissimilar bulbs used



The change in brightness and current when two dissimilar bulbs used

Predict: When two dissimilar resistors in series,

Will both resistors have the same voltage ac

No

Will the current be the same through each r

Yes

Please measure the voltage across the terminals between A-C using voltn

A-C : 9V A-B : 3V B-C = 6V

Are these voltage values the same or different? Why?

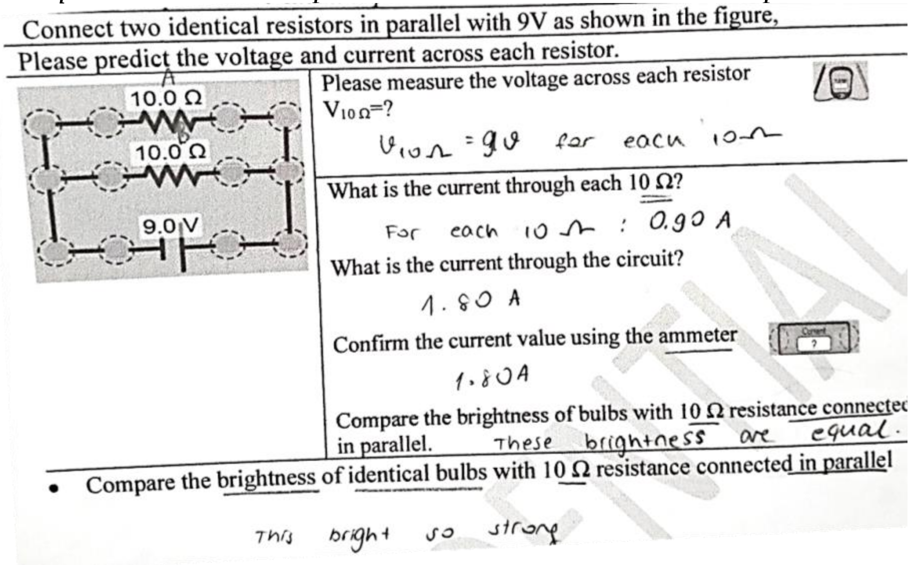
No, these are not same. If resistors' ohm's inc

Please measure the current in the circuit using ammeter

At the end of this phase, the teacher encouraged students to compare the resistance values for simple, series, and parallel circuits (Table 9). Students were expected to explain whether the total resistance in the parallel circuit was less than the simple and series circuits, and calculate the total resistance in the parallel circuit as 9.0 V= 1.8 A * R_{total}, where R_{total}= 5 Ω. The student responses showed that students might misunderstand the relationship between the increase in bulb number and total current in the circuit. This situation reminded the teacher to help students in mathematical calculations to find total resistance.

Table 8

The question to examine parallel circuits in the elaboration phase



Connect two identical resistors in parallel with 9V as shown in the figure,

Please predict the voltage and current across each resistor.

Please measure the voltage across each resistor

$V_{10\,\Omega}$=?

$V_{10\Omega} = 9V$ for each 10Ω

What is the current through each 10 Ω?

For each 10 Ω : 0.90 A

What is the current through the circuit?

1.80 A

Confirm the current value using the ammeter

1.80A

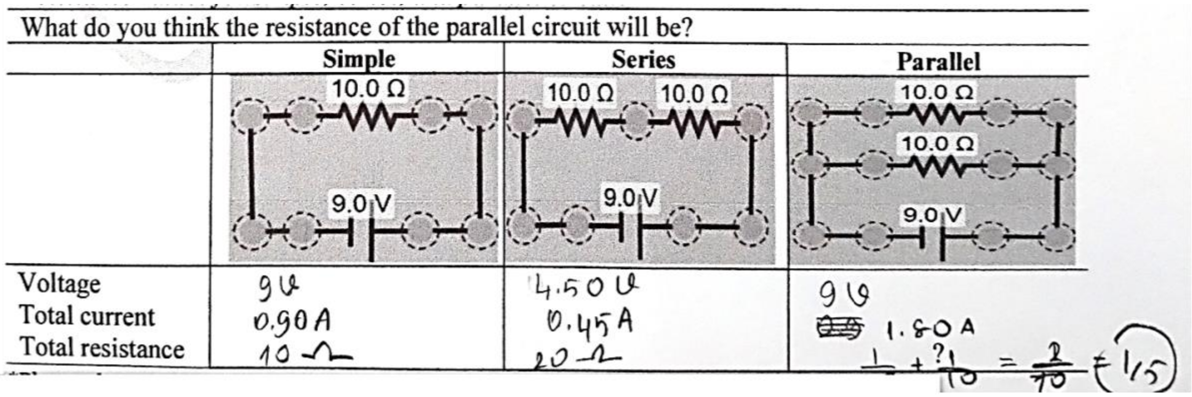
Compare the brightness of bulbs with 10 Ω resistance connected in parallel. These brightness are equal.

- Compare the brightness of identical bulbs with 10 Ω resistance connected in parallel

This bright so strong

Table 9

Resistance values for simple, series, and parallel circuits



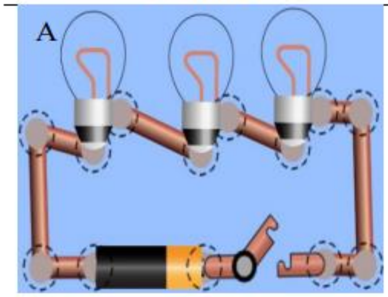
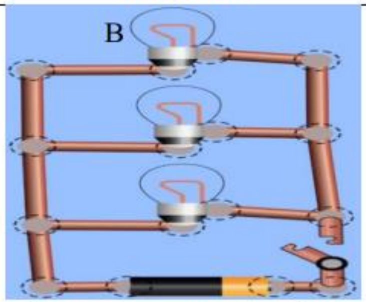
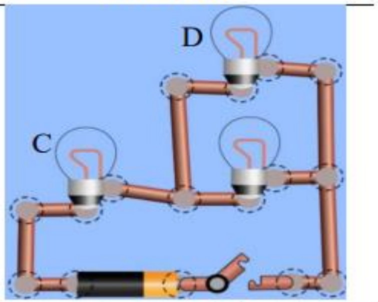
What do you think the resistance of the parallel circuit will be?

	Simple	Series	Parallel
	10.0 Ω 9.0 V	10.0 Ω 10.0 Ω 9.0 V	10.0 Ω 10.0 Ω 9.0 V
Voltage Total current Total resistance	9V 0.90A 10 Ω	4.50 V 0.45A 20 Ω	9V 1.80 A $\frac{1}{} + \frac{?1}{10} = \frac{2}{10} = 1/5$

Evaluation (10 minutes + Homework). In the evaluation part, the teacher aimed to assess students` understanding of how connection type influences the brightness, voltage, and current values across the bulbs with the same resistances (Table 10). This question was the indicator of students` learning of bulbs in parallel circuits having higher brightness and current values, but less voltage values than bulbs in series circuits; in mixed circuits, one bulb connected in series to two parallel bulbs had higher brightness and current values, but less voltage value. At the end of the lesson, students were given homework to write the report of this investigation to answer the following questions:

Table 10

The question for the evaluation phase

I-Series	II-Parallel	III-Mixed
		
Identical three bulbs with 10 Ω resistance are connected in three ways- series, parallel, and mixed. Compare the voltage, current, and brightness values across A, B, C, and D bulbs when the switches are closed.		

1- What is the overarching question of the investigation?
2- How do you answer the question?
3- What methods do you use to gather data and answer the question?
4- What is the scientific rationale for the answer to the question?
5- Please include “Introduction, Methods, and Results” sections in your report.

A sample of student investigation report is attached as Appendix-II.

CONCLUSION

This lesson provided an opportunity to integrate student-centered approaches in a two-hour physics classroom to enhance students’ experiences with three-dimensional learning (Kaldaras et al., 2021; Nordine, et al., 2019). In this lesson, the integration of 5E instructional model supported the use of science and engineering practices with disciplinary core ideas and crosscutting concepts to actively engage students in science learning (NGSS Lead States, 2013; NRC, 2012). The design of this lesson included 5E instructional model to develop a model of series and parallel circuits to conceptualize the variables depending on the change in brightness of bulbs through analyzing and interpreting data, using computational and mathematical thinking, and constructing explanations. During the lesson, students were able to build circuits on a computer simulation to examine the brightness of bulbs as the number of bulbs and battery changed. Students collected data through simulation, analyzed the data to explain Ohm’s law and explained their interpretations of data based on the scientific laws.

This activity presented the effectiveness of the lesson on students’ qualitative and quantitative analysis of Ohm`s Law: Different phases of the model included making predictions, peer collaboration, development and use of modelling, mathematics, and technology, making observations and data analysis, and constructing explanations. In terms of characteristics of science, this lesson emphasized the role of observation and inference to make empirical-based scientific explanations. Investigation of brightness of bulbs in different circuits supported students to make cause-and-effect relationships between the number of bulbs and batteries and number of resistances or dependent and independent variables in the circuits. In short, this lesson is suggested to assist students to use technology in developing visual, graphical, and mathematical models as a way to develop scientific reasoning.

At the end of the lesson, students reflected on their learning experience in an activity designed for three-dimensional learning. The instructor asked, “How do you define your learning experience in this activity?”, one of the students responded as follows:

> *This activity included a lot of related questions to help us understand the main idea. It was easy since we did not have to work with equipment, we used simulations on the computer. I think simulations helped us do the measurements correctly. I could understand how to look at the data, draw a graph, and make explanations based on the results. This learning experience was valuable for me.*

In this work, three-dimensional learning was effectively used within the 5E instructional model to enact student-centered instruction. Students were able to engage in science and engineering practices such as developing and using models, to understand the relationships between energy and forces as disciplinary core ideas, and to make cause-and-effect relationships as crosscutting concepts. Students’ engagement in three-dimensional learning also enhanced their understandings of nature of science and scientific process skills.

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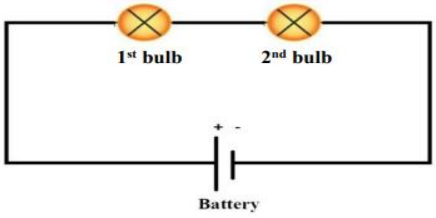
APPENDIX 1: ELECTRIC CIRCUITS

Phase-1: Engagement (10 Minutes)

Please answer the following questions:

- Do identical two bulbs in the series have the same brightness?
- How can we make these bulbs brighter?
- How does changing the connection type influence the brightness of the bulbs in a circuit?
- Please predict the brightness of the bulbs in series and parallel circuits on Table below.

Two identical bulbs connected in series



Question to predict the brightness of the bulbs in serial and parallel circuits

Connection with	Draw the circuits and estimate the brightness of the bulbs	
	Serial Circuit	**Parallel Circuit**
2 bulbs + 1 battery		
3 bulbs + 1 battery		
3 bulbs + 2 batteries		

Phase-2: Exploration (30 minutes)

Figure shows the elements of an electric circuit as bulb, wire, switch, and battery.
Please make the observations on the simulation[3] and answer the following questions to complete Table below:

1. How does the number of bulbs affect the brightness in each circuit?
2. How does the number of batteries affect the brightness of the bulb in each circuit?
3. How does brightness of the bulbs of two identical circuits change when they are connected serial or parallel?
4. What is the current value in total and over each bulb?
5. What is the voltage value in total and over each bulb?

Elements of an electric circuit

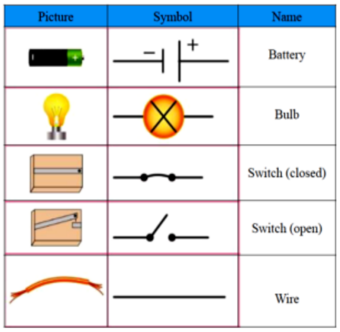


Table
Relationship between voltage, electric current, brightness for series and parallel circuits

Connection	Draw the circuits and estimate the brightness of the bulbs		
	2 bulbs and 1 battery	3 bulbs and 1 battery	3 bulb and 2 batteries
Serial Circuit			
Current (total): Current (each bulb): Voltage (total): Voltage (each bulb):			
Parallel Circuit			
Current (total): Current (each bulb): Voltage (total): Voltage (each bulb):			

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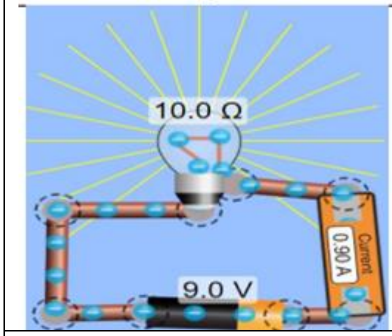
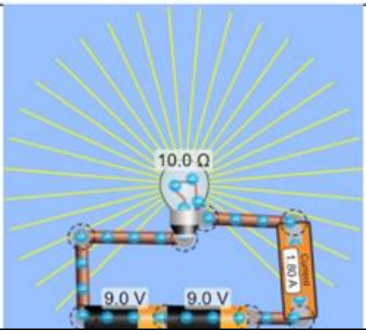
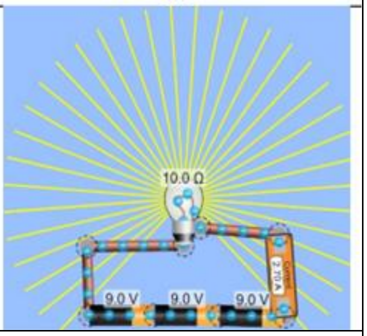
[3] https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html

Phase-3: Explanation (15 minutes)

Following questions are used to discuss the results of exploration

1. How does the number of bulbs affect the brightness in each circuit?
2. How does the number of batteries affect the brightness of the bulb in each circuit?
3. How does brightness of the bulbs of two identical circuits change when they are connected serial or parallel?
4. How does the current value change as we increase the number of bulbs and batteries in series and parallel circuits?
5. How does the voltage value change over each bulb in series and parallel circuits?
6. What are your dependent and independent variables in the experiment?
    a. Dependent variable:
    b. Independent variable:
7. Please summarize the change in brightness, current, and voltage values as the number of batteries increases on Table below.
8. Considering the change in voltage and current values in series circuits, please draw voltage versus current graph and explain the Ohm's law on Table below.

The change in brightness, current, and voltage values as the number of batteries increase		
I	II	III
		
Voltage: 9.0 Volt Resistance: 10 ohms Current:	Voltage: 18.0 Volt Resistance: 10 ohms Current:	Voltage: 27.0 Volt Resistance: 10 ohms Current:

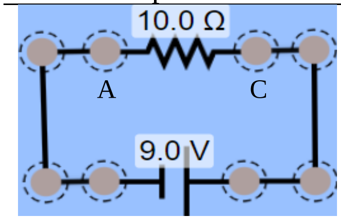
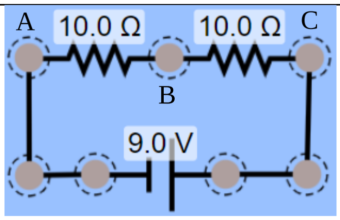
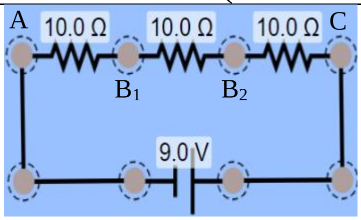
Graphical representation for Ohm's Law

	Voltage	Current	
I	9.0 V		
II	18.0 V		
III	27.0 V		

Phase-4: Elaboration (35 minutes)

1) Please use a simulation[4] to construct:
    - a simple circuit with one resistor and one battery (I),
    - a series circuit with two resistors and one battery (II),
    - a series circuit with three resistors and one battery (III).
2) Please answer the following questions.

Examine series circuits in the elaboration phase

I-Simple circuit	II- Series circuit	III-Series circuit (3 resistors)
		
What do you predict the voltage and current across A-C terminals for each circuit?		
Please measure the voltage across the terminals between A-C using voltmeter		
V_{A-C} =	V_{A-C}= V_{A-B}= ; V_{B-C}=	V_{A-C}= , V_{A-B1}= , V_{B1-B2}= , V_{B2-C}=
Please measure the current in the circuit using ammeter		
I_{A-C} =	I_{A-C}= , I_{A-B}= , I_{B-C}=	I_{A-C}= , I_{A-B1}= , I_{B1-B2}= , I_{B2-C} =
Is the current flowing through the first, second, or third resistors the same? Why?		
YES	NO	
Using the Ohm`s Law, what is the total resistance of each circuit?		
R_{A-C}= V_{A-C}/I_{A-C}=	R_{A-C}= V_{A-C}/I_{A-C}=	R_{A-C}= V_{A-C}/I_{A-C}=
Compare the brightness of bulbs with 10 Ω resistance connected in series.		

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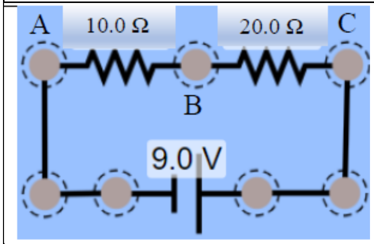
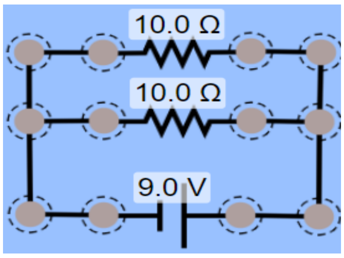
[4] https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html

3) Consider two bulbs with different resistance values and compare whether both resistors had the same or different voltage, current or brightness values.

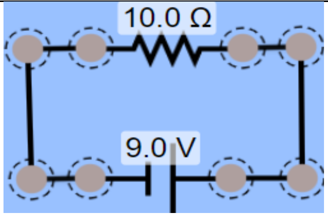
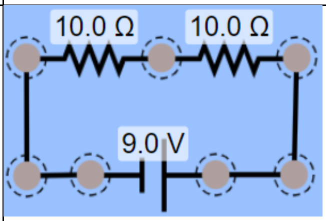
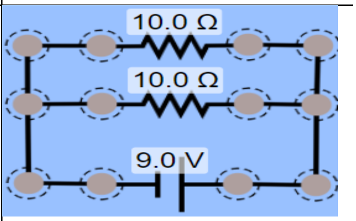
The change in brightness and current when two dissimilar bulbs used
Predict: When two dissimilar resistors in series,
 Will both resistors have the same voltage across them? Will the current be the same through each resistor?
Please measure the voltage across the terminals between A-C using voltmeter
Are these voltage values the same or different? Why?
Please measure the current in the circuit using ammeter
Using the Ohm’s Law, what is the total resistance of each circuit?
Compare the brightness of bulbs with 10 ohm and 20-ohm resistances connected in series.

4) Please explore the elements of a parallel circuit.

<table>
<tr><td colspan="2">Connect two identical resistors in parallel with 9V as shown in the figure,</td></tr>
<tr><td colspan="2">Please predict the voltage and current across each resistor.</td></tr>
<tr><td rowspan="2"> </td><td>Please measure the voltage across each resistor
$V_{10\,\Omega}$=?</td></tr>
<tr><td>What is the current through each 10 Ω?
What is the current through the circuit?
Confirm the current value using the ammeter
Compare the brightness of bulbs with 10 Ω resistance connected in parallel.</td></tr>
</table>

5) Compare the brightness of identical bulbs with 10 Ω resistance connected in parallel

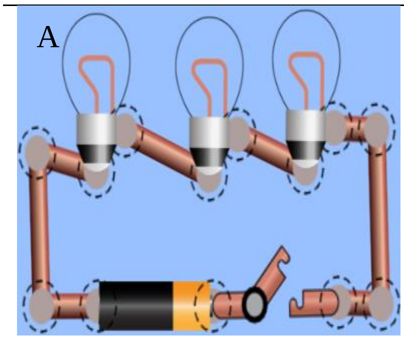
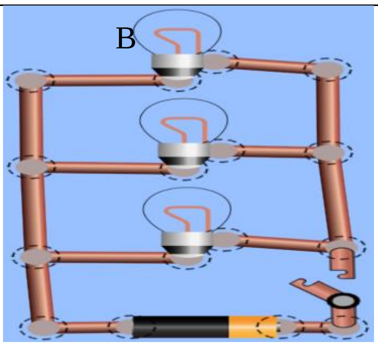
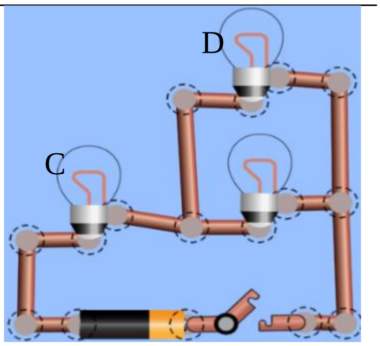
6) Explain whether the total resistance in the parallel circuit was less than the simple and series circuits, and calculate the total resistance in the parallel circuit

<table>
<tr><td colspan="4">What do you think the resistance of the parallel circuit will be?</td></tr>
<tr><td></td><td>Simple</td><td>Series</td><td>Parallel</td></tr>
<tr><td></td><td> </td><td> </td><td> </td></tr>
<tr><td>Voltage
Total current
Total resistance</td><td></td><td></td><td>?</td></tr>
</table>

7) Please compare the total resistance values for the simple, series, and parallel circuits.

Phase-5: Evaluate (10 minutes + Homework)

Explain how connection type influences the brightness, voltage, and current values across the bulbs with the same resistances on Table below.

I-Series	II-Parallel	III-Mixed
		
Identical three bulbs with 10 Ω resistance are connected in three ways- series, parallel, and mixed. Compare the voltage, current, and brightness values across A, B, C, and D bulbs when the switches are closed.		

Answer the following questions:

1. What is the overarching/general question of the investigation?
2. How do you answer the question? OR What is the answer for the question?
3. What data do you use to answer the question? How do you analyze the data?
4. What is the scientific rationale of your interpretation of data?

APPENDIX-II: Sample Investigation Report

Introduction

We have been studying electric circuits in class. To be able to work with electric circuits, we should have known the basic terms of electricity such as bulb, resistance, current, and voltage. We noticed that there is a relationship within these terms and to be able to explore the relationship we use a simulation in our investigation. Our goal for this investigation was to figure out the effect of connecting electrical circuits differently on voltage, brightness, and current. To be able to analyze and interpret data, we should have the mathematical knowledge to understand the relationship between variables and also knowledge of graphs to read and draw. The guiding question was "How does connection type influence brightness with the same resistance?". With the help of this guiding question, we were able to construct an investigation to conclude.

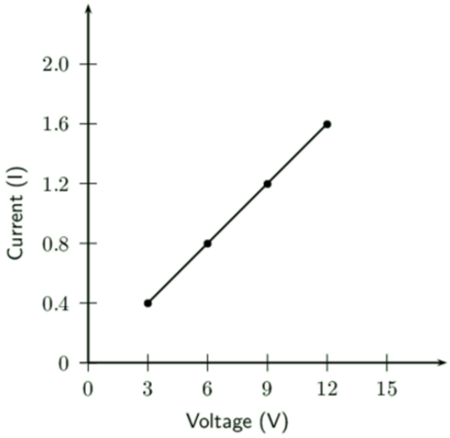
Method

To answer this question, we used some scientific methods. Firstly, we observed the different circuits that are connected in different ways or have different numbers of bulbs or batteries. Then, we gathered our data and analyzed it step by step. While we were analyzing the data, we used our mathematical thinking. After we used these methods, we could construct some explanations, and draw representations and models. Most importantly, thanks to using technology for simulations, we can do this investigation. Moreover, these investigations show that science is based on empirical evidence in terms of doing this. Furthermore, we understand that science includes some laws and these laws define the relationship between dependent and independent variables.

Results

We figured out how the connection type influences the brightness with the same resistance which means how independent variables influence the dependent variables. For this, we observed different electric circuits. As a result of our findings, when we looked at two circuits connected in series and parallel with the same number of bulbs and batteries, we discovered that the bulbs connected in parallel burned brighter.

The graph below includes information about the data we find that the total current increases at the rate of increase of the total voltage. As can be seen from the graph, the relationship between voltage and current is directly proportional.



This analysis suggests voltage and electric current are directly proportional. If you keep the resistance constant and increase the voltage, the current will increase. The voltage in the bulbs in the parallel circuit receives the total voltage directly, but in the series connected, the total voltage is shared according to the number of bulbs. Thus, taking into account the directly proportional relationship between voltage and current, the current flowing through the bulbs connected in parallel is higher so, brightness is higher.

This evidence is based on an important scientific idea. Which is Ohm’s Law. Ohm's law states that if all physical parameters and temperature stay constant, the voltage across a conductor is directly proportional to the current flowing through it. When we interpret the data, we have obtained through our investigation, we have reached results that support Ohm's Law.