Research Article https://doi.org/10.12973/eu-jer.12.3.1269

European Journal of Educational Research
Volume 12, Issue 3, 1269 - 1284.

ISSN: 2165-8714
https://www.eu-jer.com/

How Difficult are Simple Electrical Circuit Conceptions? New Findings

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Received: December 1, 2022 ▪ Revised: March 4, 2023 ▪ Accepted: March 24, 2023

Abstract: Research on conceptual understanding is one of the first steps in designing materials to improve learning. Literature reports that students have difficulties analyzing and describing phenomena in electric circuits. This report contributes to students' conceptual difficulties regarding simple electrical circuits by systematically analyzing an open conceptual test answered by 531 first-year engineering students. We found students' reasoning that has not yet been reported in the literature as misconceptions or difficulties. To deepen our understanding of students' difficulties, we chose five students by convenience to interview. We present evidence that there are two main contributions to the taxonomy in this study: the Series Circuit Misconception, which is when students convey that the current through bulbs is the same because they are in series, using that as a mnemonic ignoring any change in the circuit; and the Inverse Parallel Circuit Misconception, that is when students mention that the resistance of the circuit decreases when disconnecting bulbs in parallel, neither are reported in the literature. The results of this study have implications for physics education research in electric circuits and educational practice in the classroom.

Keywords: *Educational innovation, electric circuits, higher education, students' conceptions, students' difficulties.*

To cite this article: Quezada-Espinoza, M., Dominguez, A., & Zavala, G. (2023). How difficult are simple electrical circuit conceptions? New findings. *European Journal of Educational Research, 12*(3), 1269-1284. https://doi.org/10.12973/eu-jer.12.3.1269

Introduction

One of the primary purposes of the physics education research field is to investigate and assess students' conceptual understanding (Docktor & Mestre, 2014). In related investigations on this topic, researchers have found that students come to physics classes having had years of life experience such that they bring a developed and well-established system of common-sense beliefs, sometimes misconceptions, regarding the physical world and how it works (Hestenes et al., 1992). The daily interaction with physical phenomena and the approach that textbooks and teachers' instruction have towards them are some of the elements that lead to these misconceptions—taking the student away from a scientific understanding of the fundamental physics concepts (Eshetu & Alemu, 2018).

Researchers give different names to these pre-existing conceptions of physical phenomena. According to Docktor and Mestre (2014), there are several labels for difficulties revealed in students' understanding of literature, such as preconceptions, naive conceptions, alternative conceptions, and misconceptions. We adopt the term "misconception" with these attributes: they (a) are firmly held, stable cognitive structures, (b) differ from expert conceptions, (c) affect fundamentally how students understand natural phenomena and scientific explanations, and (d) must be overcome, avoided, or eliminated for students to achieve expert understanding. We understand that some researchers may prefer other labels and that some difficulties might not be labeled with any of these terms. In this study, we will call difficulties the latter.

Different methodological approaches in Physics Education Research have studied conceptual understanding extensively, and researchers have used various data collection techniques to understand this learning aspect better. The analyses of open-ended questions, e.g., written explanations and argumentation (Leniz et al., 2020), interviews (John & Allie, 2019), observations (Smith & van Kampen, 2011), and conceptual assessments have helped to define conceptual understanding (Leniz et al., 2017; Mbonyiryivuze et al., 2022; Zavala & Martinez-Torteya, 2020). Trowbridge and McDermott (1980) point out the differences between the understanding of experts and students. The expert (professor) applies concepts based on operational definitions, verbal precision, and mathematical articulation, while students use intuition, experience, and prior instruction (Aktan, 2013; Trowbridge & McDermott, 1980). This

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study defines conceptual understanding as how the student successfully applies current, resistance, and voltage concepts in interpreting simple electric circuits.

Despite all that has been researched on the subject, students continue to have misconceptions not reported in the literature when solving simple electrical circuits. The authors of this article have worked for several years to analyze this subject. We first began by empirically studying all the conceptual models found by other authors. Later, we realized that students' misconceptions are not limited to those reported in the literature.

This article presents research on third-semester engineering students' common misconceptions when solving simple electrical circuit problems after studying the related topics in an electricity and magnetism (E&M) course. Based on the analysis of students' reasoning, our main objective in this report is to demonstrate that students have different reasoning beyond the taxonomy of conceptual models reported in the literature; therefore, this research contributes to the taxonomy of misconceptions and difficulties reported in the literature.

Literature Review

Electricity is one of the areas of physics broadly studied concerning students' conceptual understanding (Leniz et al., 2020). The latest studies report that students have serious difficulties analyzing and describing electrical phenomena (Chang & Shieh, 2018; Eshetu & Alemu, 2018; Frache et al., 2019; Jiang et al., 2018; Kalaya et al., 2019; Manunure et al., 2020; Mbonyiryivuze et al., 2022). The literature has abundant evidence of misconceptions about simple electrical circuits, common even among students who have had formal instruction in the relevant material (Kokkonen & Mäntylä, 2018; Ortega-Alvarez et al., 2018; Villarino, 2018).

For this research article, it is vital to have an extensive and complete review of students' misconceptions. We present, therefore, a compilation of the latest research on conceptual models reported by Sencar and Eryılmaz (2004), Peşman and Eryılmaz (2010), and Taşlıdere (2013). The three publications have shared references based on their studies (Chambers & Andre, 1997; Cohen et al., 1983; Dupin & Johsua, 1987; Engelhardt & Beichner, 2004; Fredette & Clement, 1981; Fredette & Lochhead, 1980; Heller & Finley, 1992; McDermott & Shaffer, 1992; Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Shipstone, 1988; Shipstone et al., 1988). They primarily applied research techniques to discover the conceptions presented focused on qualitative research methods to investigate students' conceptual understanding. Those are based on their written or spoken reasoning, observations, interviews, and analyses of answers to open questions about simple circuits with identical bulbs, ideal batteries, and non-resistance wires. From the results obtained, we could shape a taxonomy of the conceptual models students have repeatedly presented.

- *Sink or Unipolar Model:* A single wire connection between a device and a power supply is enough to run the electrical device (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).
- *Clashing Current Model:* Positive electricity moves from the positive terminal, and negative electricity moves from the negative terminal of the power supply. Their clashing causes the device to run (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).
- *Weakening Current Model:* Sencar and Eryılmaz (2004) use the name weakening current model, and in Peşman and Eryılmaz (2010), and Taşlıdere (2013), this model was renamed as attenuation model. Current flows in one direction around a circuit and decreases gradually due to its consumption by devices in the circuit.
- *Shared Current Model:* Peşman and Eryılmaz (2010) and Taşlıdere (2013) report this model when devices within the circuit share the electric current equally. Sencar and Eryılmaz (2004), in addition to the above, establish that less current returns to the power supply than initially leaves it.
- *Empirical Rule Model:* The more distant the bulb is from the battery, the dimmer the bulb is (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).
- *Local and Sequential Reasoning Model:* Sencar and Eryılmaz (2004) use local and sequential reasoning models as only one conception. However, Peşman and Eryılmaz (2010) and Taşlıdere (2013) analyzed differently and reformulated this model where the sequential and global reasoning models are taken as different misconceptions. The local reasoning model is when students focus on one point in the circuit (local effects) and ignore what is happening elsewhere (global analysis). Meanwhile, the sequential model is when students think that any change at a point in an electric circuit affects the circuit forward in the direction of the current, not backward.
- *Short Circuit Misconception Model:* Wires in the electric circuit without devices attached to the circuit are irrelevant and can be ignored (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).
- *Power Supply as a Constant Current Source Model:* The power supply within the circuit provides constant electrical current rather than electrical energy. It releases the same fixed current to every circuit (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).

- *Parallel Circuit Misconception Model:* Any increase in the number of parallel resistors increases the total resistance (a resistor is an obstacle to current flow) (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013).
- *Current Flow as Water Flow Model:* Taşlıdere (2013) first reported this model when students think electric current flows within wire-like water flow in a pipe. Most of the current goes straight, and less goes from the wire, which is not straight.

Other conceptual models related to bulbs' relative brightness and power have been reported (Bryan & Stuessy, 2006; Wong et al., 2017). Also, research such as that of Li and Singh (2016) has contributed to analyzing students' reasoning and conceptual difficulties when considering circuits with non-identical bulbs (varying the bulbs' resistance and power) and found some other misconceptions in a circuit. Furthermore, Frache et al. (2019) included the difficulties students of different educational levels have when using fundamental laws of physics, such as Ohm's and Kirchoff's laws. For this study, we limited our analysis to the models described in the literature review in previous sections. Our model is based on identical bulbs, ideal batteries, non-resistance wires, and current through a circuit analysis.

This taxonomy of conceptual models has allowed the design of multiple-choice conceptual questions, which, systematically with many participants, permits the analysis of students' conceptual difficulties. Nowadays, diagnostic tests with conceptual questions facilitate various research interests. Some assess students' understanding when they start physics classes obtaining learning gains (Kortemeyer et al., 2019; Zavala & Martinez-Torteya., 2019). Some others evaluate the effectiveness of research-based courses and teaching tools that improve the students' conceptual learning and understanding (Baser, 2006; Keller et al., 2006; Lin, 2017; McColgan et al., 2017; Pollock, 2009; White et al., 2016).

In the related literature, the most used diagnostic evaluation tests are the Electric Circuits Concept Evaluation (ECCE) test (Sokoloff, 1996); the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) (Engelhardt & Beichner, 2004); and the Electricity and Magnetism Conceptual Assessment (EMCA) test (McColgan et al., 2017).

Implementing those assessment tools under different contextual conditions, mainly in the United States and Europe, has proved that students still hold strong misconceptions about simple electric circuits. Besides, we have conducted studies and found similarities with the results presented before, i.e., students have severe problems understanding concepts underlying simple electrical circuits (Campos et al., 2021; Quezada-Espinoza et al., 2015, 2016; Quezada-Espinoza & Zavala, 2014, 2017; Sokoloff, 1996).

Methodology

531 undergraduate engineering students enrolled in a calculus-based E&M course participated in this study. The primary data sources for the study were the participants' answers to qualitative problems. These problems were designed from an exhaustive review of the literature. We analyzed the written reasoning of students who answered six open independent conceptual questions about the electric current behavior when changes are made in a simple circuit. The circuit comprises identical light bulbs, ideal batteries, and non-resistance wires.

We also interviewed some engineering students to understand better their reasoning and the origins of their conceptual difficulties in solving the open conceptual questions about circuits. We chose five students by convenience who showed having written reasoning relevant to different reasoning beyond the taxonomy of conceptual models reported in the literature. We invited them to deepen our understanding of their reasoning. All the E&M students in this study took a traditional class at a private university in northern Mexico, where the instructors lectured during regular class hours. One requirement for this course is a 1.5-hour lab session conducted once per week. The instructors use different research-based strategies for the circuit's concepts in the lab sessions, such as Tutorials in Introductory Physics by McDermott and Shaffer (2002) and RealTime Physics by Sokoloff et al. (2007). The instructors of the lab sessions were senior undergraduate Physics Engineering students.

Before implementing the open-ended test, all the students involved in this study received traditional lecture-based instruction on circuits in their relevant courses. The open-ended questionnaire asked students to explain their reasoning, and this format helped understand students' thought processes since they had to clarify their reasoning. Analyzing the student responses to the interview questions yielded further insight into student reasoning. In the following two sections, we describe our techniques to collect data in the open-ended and interview questions. The lectures, labs, and all instruments we implemented were in Spanish. We present in this report the translation of the instruments, students' responses, and reasoning.

Open-Ended Conceptual Test

The conceptual problem is an instrument we designed in previous research that has been modified based on empirical results (Quezada-Espinoza et al., 2015). It arose from the need to delve into the misconceptions that the standardized instruments detected to investigate the specific reasoning of the students. The problem consists of six independent questions that start from a base circuit. Then, questions are asked to the students based on specific changes in the circuit (opening a switch, adding and removing light bulbs). Students answered the open-ended test with the midterm exam. Figure 1 presents the central circuit diagram of this test.

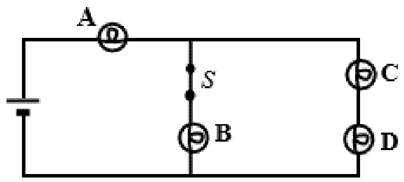

Figure 1. Main Circuit Diagram of the Open-Ended Conceptual Test.

The students answered the following questions to solve the circuit in Figure 1.

a) Rank the light bulbs A, B, C, and D currents.

b) A wire was connected between bulb D terminals. Compare the current through bulb D before and after the wire was connected.

c) The wire was removed, and the switch was opened. Compare the battery's current before and after the switch was opened.

d) Compare the current through bulb A before and after opening the switch.

e) The switch was closed, and a third bulb was connected in series between bulbs C and D. Compare bulb C's current before and after the new bulb was connected between them.

f) Compare bulb D current before and after the new bulb was connected.

Interviews

Based on the work of Engelhardt et al. (2004), the format of the interview was semi-structured, having some pre-planning of the content and questions. We centered our protocol on analyzing the students' responses to the open-ended test to investigate their reasoning. The first author conducted the interviews, and the researcher had no authority relationship with students. At the beginning of the interview, the interviewer welcomed students and explained the purposes of the activity (research purposes with no effect on their E&M class grades). Then, the students read and signed the informed consent, knowing the interviews were audio and video recorded. In the interview, the students reviewed their open-ended test responses, reread each exercise, and explained their reasons for their written responses to the interviewer. The interviewer asked the students whether they wanted to keep their responses without receiving feedback, and the students could confirm their responses or reconsider changing something. At the end of the interview, the interviewer asked students to confirm whether they had provided all the information they wanted to include in the explanation.

To analyze and explain students' reasoning and determine their understanding of simple circuit concepts, we used the framework for student reasoning in an interview reported by Gray et al. (2004). The purpose was to understand students' current reasoning patterns without attempting to change them. This framework consists of four elements:

1) External inputs {I} from the interviewer and the interview environment (e.g., questions, verbal, graphic, and other cues).

2) Tools {T} that the student brings to the interview (e.g., memorized or familiar formulas, laws, and definitions, prior experiences, and knowledge).

3) Workbench {W} encompassing mental processes (e.g., induction, accommodation) that incorporate external inputs {I} and tools {T}.

4) The answer {A} given by the student.

Results

This section presents the results of the open-ended questions and the semi-structured interviews. In each case, we present the results with a general context of students' reasoning using the different models in the taxonomy presented. We also present students' reasoning in each subsection, not the taxonomy. Therefore, we describe those new models not previously reported in the literature.

Open-Ended Conceptual Test: Findings

Question a) Ranking the currents of light bulbs A, B, C, and D (I_A, I_B, I_C, I_D). This question aimed to introduce students to the circuit by answering a typical question, the current ranking. For this item, 158 out of 531 students (29.8%) who answered the conceptual test showed to have misconceptions. We found various answers; Tab. 1 presents the more frequent incorrect answers. In the column on the left, we present the main incorrect rankings. The center column shows the frequency of responses, and the column on the right gives the main types of reasoning given by the students.

Table 1. The More Frequent Responses Given by Students in Question A) of the Open-Ended Conceptual Test.

Answer	Frequency	Written Reasonings
1. $I_A>I_B=I_C=I_D$	28%	- after A, all are the same because they are connected in parallel - the current goes directly to bulb A and then divides in two; half goes to bulb B and the other half to bulbs C and D - after passing through bulb A, the current is divided in two; given that bulbs C and D are connected in series, the current is the same - after passing through bulb A, the current is divided into two equal parts - bulbs B, C, and D are connected on the same wire
2. $I_A=I_B>I_C=I_D$	23%	- the current is the same in series but not in parallel - the current was lost when it reached bulbs C and D - bulbs A and B are connected in series
3. $I_A=I_B=I_C=I_D$	9%	- all the bulbs are equal, and the two branches are connected in series - in all the bulbs, the same current flows because they are connected in series - the current is the same because it is a closed circuit - the current is the same because it comes out of the same battery
4. $I_A>I_B=I_C>I_D$	8%	- the current in series decreases as the cable lengthens; in parallel, it remains the same - the current is spent on A; then it is divided equally between B and C, then, after C, it is reduced to D
5. $I_A>I_C=I_D>I_B$	6%	-the current is the same in serial connections - As the current passes through, it becomes smaller

Note: We bolded some students' reasoning in Table 1, which we discuss later in this paper. The rest of the students (27%) showed answers that were not repeated or did not obey some misconception.

Question b). A wire is connected between the terminals of bulb D, as shown in Figure 2. With the new wire connected, we asked students whether the current through bulb D was greater than, less than, or the same as before.

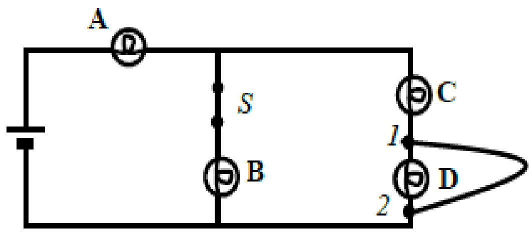

Figure 2. Short Circuit Diagram for Question B) of the Open-Ended Conceptual Test.

For this item, 136 out of 531 students (25.6%) who answered the conceptual test showed to have misconceptions. We designed this question to probe the short circuit misconception, i.e., wires in the electric circuit with no electrical devices connected are ignored when analyzing the circuit. We found that 81% of the students gave reasons consistent with this misconception. We show below some reasoning provided by students.

Same as, because:

... there is no bulb connected to the new wire, so it does not affect the system.

... it would be affected only if you connect a bulb to the new wire.

... the only thing that can decrease the current is resistance.

In addition to the conceptions we wanted to probe (the short circuit misconceptions), we found that 16% of the students responded with reasons corresponding to another misconception, the counterpart of the local reasoning misconception. According to Taşlıdere (2013), the local reasoning misconception is when students focus on one point in the circuit and ignore what is happening elsewhere. The focus is on the local instead of a global analysis. In this case, the students answered as follows.

Greater than, because:

... the resistance decreases when adding the wire.

... the resistance decreases, and the current increases.

... there is less resistance.

As seen in the reasons given by the students, they center their attention on what happens with total resistance in the circuit when the wire is connected between the terminals of bulb D. Although their reasoning is adequate, they are not correctly responding to the question regarding the current through bulb D.

Question c). In this question, we asked whether the current through the battery was greater than, less than, or the same as the current through the battery before opening the switch (See Fig. 3). For this question, 300 out of 531 students (56.5%) who answered showed to have misconceptions.

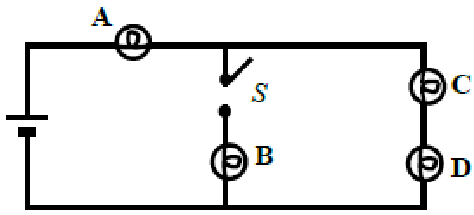

Figure 3. Open Switch Circuit Diagram for Questions C) and D) of the Open-Ended Conceptual Test.

The primary purpose of this question was to test the Power Supply as a Constant Current Source Model misconception, i.e., the battery is a constant electrical current supplier. Of those with a misconception on this question, 39.7% had this misconception. Some of the students' reasonings are below.

Same as, because

...the current is given by the battery, and the battery remains the same.

...the current is always constant.

...the current in a battery never changes.

...the current comes in and out, and the battery is still the same.

As expected, all reasoning writings represent the Power Supply as a Constant Current Source Model misconception.

Question d). In this question, we asked whether the current through bulb A was greater than, less than, or the same as the current through bulb A before opening the switch (diagram of Figure 3). For this question, 355 out of 531 students (66.8%) who answered showed to have misconceptions. Our interest was to determine whether the students could relate the current through the battery to the current through bulb A, expecting they would incur the misconceptions of Power Supply as a Constant Current Source Model and the Sequential Model. The Sequential Model misconception defined by Peşman and Eryılmaz (2010) is when students consider that any change at a point in an electric circuit affects the circuit forward in the direction of the current, not backward. 37.2% (of the 66.8%) of the students had this kind of written reasoning. Some students' reasoning that follows the Sequential Model is below.

Same as, because

... there are no changes before bulb A.

... the switch is after bulb A.

... the change is made after bulb A.

... bulb A is before switch S.

We note that students consider that opening the switch affects the circuit forward in the direction of the current, not backward, where bulb A is located. The criterion to determine this was to detect keywords related to a place, like after or before.

Continuing with question d), we found that 29% of the students wrote reasoning assumed as the Local Reasoning misconception. The local change is focused on instead of a global analysis. Some examples of this reasoning are below.

Same as, because

... opening the switch will not affect bulb A; it only affects bulb B which will not turn on.

... the resistance in bulb A does not change.

... it is still the same bulb.

These students showed in their answers that they ignore what is happening elsewhere in the system, focusing only on bulb A.

Finally, 16% of the students showed a pattern of responses that we consider appropriate to report. We label this type of reasoning as the Inverse Parallel Circuit misconception because their arguments contradict the Parallel Circuit misconception. For the latter, a resistor is an obstacle to current flow, and increasing the number of parallel-connected resistors increases the total resistance. Since "the magnitude of the current through a battery depends on the resistance of the circuit. When the resistance of the circuit increases, the current through the battery decreases; and, when the resistance of the circuit decreases, the current through the battery increases" (Smith & van Kampen, 2011). However, we find that students do not adequately identify the configuration of a circuit (series or parallel) and how changes influence the current that passes through the entire circuit. To illustrate the proposed misconception, we show some written reasoning given by students to question d).

Greater than, because

... there is one less bulb.

... there are fewer bulbs.

... the current increases because bulb B no longer lights.

... if the resistance decreases, the current increases.

... there is no current passing through bulb B.

Students assumed that decreasing the number of parallel-connected bulbs resulted in a decrease in the total resistance.

The switch is closed in the last section for the open-ended conceptual test, and an extra bulb (bulb E) is connected in series between bulbs C and D (see Figure 4). With these changes in mind, the students had to answer questions e) and f).

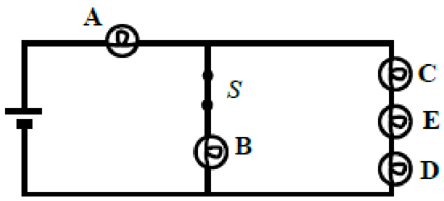

Figure 4. Diagram of the Circuit With the New Bulb Added Between Bulbs C and D for Questions E) and F) in the Open-Ended Conceptual Test.

Question e). We asked students whether the current through bulb C was greater than, less than, or the same as bulb C before bulb E was added to the circuit. For this question, 164 out of 531 students (31%) who answered showed to have misconceptions. We expected to inquire more about the misconception of the Sequential Model since bulb E was added right after bulb C. We found that 26% (out of the 31%) of the students effectively responded with the reasoning that fell into the Sequential Model misconception. Some of their reasoning is:

Same as, because:

... there was nothing connected before bulb C.

... the current decreases after bulb C.

... bulb E was added after bulb C, so it remains the same.

... it is before the new bulb.

Another misconception found fell into the Local Reasoning misconception. 22% of the students ignored the change when bulb E was added to the circuit. 63 out of 164 students (38.4%) answered that the current remained the same because the bulbs were connected in series. Although this type of answer could be considered consistent with the Local Reasoning misconception, the students' justifications marked a pattern in their written reasoning: they repeatedly mentioned that the current remained the same since the bulbs were connected in series. We call this reasoning the Series Circuit misconception. We provide more evidence with students' answers to the following question and the interviews.

Question f). In this question, we asked students whether the current through bulb D was greater than, less than, or the same as the current through bulb D before bulb E was added to the circuit. For this question, 160 out of 531 students (30%) who answered showed to have misconceptions. Our primary purpose was to analyze whether students demonstrate having the Attenuation Model misconception, i.e., an electric current traveling in one direction decreases gradually due to current devices' consumption. Moreover, 23% of students gave answers corresponding to that model, as shown below.

Smaller than, because

… there is a bulb before bulb D.

… bulb E decreases the current of bulb D.

… bulb E acts as a resistance for bulb D.

… bulb E consumes current.

… the current had to pass first through bulbs C and E.

Also, 16.2% of students fell into the Local Reasoning misconception. As in the previous question, they overlooked the new bulb E connected to the circuit; however, 43.1% of that group of students repeatedly answered with the same arguments as in question e), that the current is the same because the bulbs (CED) are connected in series (Series Circuit misconception).

Interviews: Findings

Clinical interviews provided details of how students currently understand simple circuit concepts. They reveal areas where students are confused but cannot always reveal how best to change students' thinking, as this would infringe upon the protocol for clinical interviews (Gray et al., 2004).

At this point, it is essential to remember that the students were asked to review their responses to the open-ended conceptual test, reread each exercise, and explain their written reasoning to the interviewer. Below are relevant parts of the interviews conducted with each student, where misconceptions are evidenced. The students' names were changed with aliases to ensure the participants' privacy.

Jocelyn Interview

In the following conversation, Jocelyn shows how difficult it is to identify the different circuit configurations.

Student

{I} Now, bulb E is added between C and D (Fig. 4). Is the current through bulb C greater than, smaller than, or the same as the current through bulb C before bulb E was added to the circuit?

{W} I said it is the same because they are in the same series. This current (Jocelyn points to the series formed by bulbs C, E, and D) is the same, isn't it? You know, I had many doubts about this question. [Series Circuit misconception]

Interviewer

{I} Why? What were your doubts?

Student

{T} I could not remember if it was in series or parallel when the current changes. [Circuits configuration]

Interviewer

{I} Well, in this case, you are saying that it is the same current because it is in series, isn't it?

Student

{A} yes [Series circuit misconception]

Interviewer

{I} Even if you made a change in the circuit?

Student

{A} well, yes…isn't it? [Local Reasoning] (…she says that it is the same regardless of the circuit change)

Later, she reinforces her conception that when bulbs are connected in a series, the current is the same irrespective of the changes to the circuit.

Student

{I} Then they asked about the current in bulb D,

{W} and I said it is the same current because it is connected in series

Interviewer

{I} So, is it the same situation as in the last question about bulb C?

Student

{W} Yes, it is the same because they are all connected in series [Series Circuit misconception]

The main difficulty for Joselyn in answering is that she is unsure about the configuration of the circuit from the beginning. This uncertainty leads to misconceptions that are triggered in each question. In this case, we show the reasoning for the proposed new model, the Series Circuit misconception.

John Interview

John is a student who mentioned that he had already studied electrical circuit concepts in a class where he experimented with electrical circuits and numerical problem-solving. During his interview, he showed severe confusion with terms and had difficulty verbalizing his answers.

Student

{W} (Question c), Fig. 3) Because when you disconnect B, these three are in series (Student points to bulbs A, C, and D), and they have greater resistance. Having greater resistance, I think they have a higher voltage, and having a higher voltage, there will be a higher voltage in parallel. [Circuits configuration]

Interviewer

{I} Uhm, ok, but in parallel to what?

Student

{W} Well, these three are in series. If you sum up their resistances, the equivalent resistance will be bigger than the equivalent resistance in the original circuit. I think they are connected in parallel or series with the battery; they have a higher voltage. [Circuits configuration]

Interviewer

{I} Ok, but the question is asking you about the current…

Student

W} Oh, yes, I meant the current. When you sum these three (Student points to A, C, D), you get more resistance, and you get more current when you have more resistance. (Student starts thinking about what he just said) or is it otherwise? [Inverse Parallel Circuit misconception]

John showed difficulty in identifying the correct configuration of the circuit. In addition, it is notable that John used the concepts of voltage and current interchangeably.

Matthew Interview

Matthew had exciting participation because of his reasoning process while the interview was going on because he answered each question aloud. Initially, he showed misconceptions; however, while explaining his answers, he realized that he had made a mistake and began to correct himself.

Student

{W} Ok, bulb A has the greatest current because it is the first, then a parallel is made here (the student points to the first node), and the current is divided. It will go 0.5 and 0.5, or I do not know how it is going to be divided, and here it will have a specific current (student points to bulb C), and then these are going to be the same (student points to bulbs B and D) because they are connected in parallel. Moreover, this will have more because it does not share current with any other bulb (points to C).

Interviewer

{I} That it is precisely what you answered in your test, A>C>B=D

Student

{A} Oh yes, that is what I answered.

Interviewer

{I} So, you are saying that B and D have the same current because they are together; are they in parallel?

Student

{A} Yes

Interviewer

{I} And C is greater because it does not share with another bulb here (in "parallel" as the student says with B and D)

Student

{T} Yes, because when the current…. when the circuit is in series, the current is consumed for the first bulb [Attenuation model misconception]

There are three critical issues that Matthew had. First, he stated that the current is divided into two equal parts after going through bulb A. Then, he said bulbs B and D are parallel because one is next to the other. The third issue is that the current through bulb D is smaller than the current through bulb C due to current devices' consumption in a circuit connected in series. This last issue is reported as a misconception (Attenuation Model); however, Matthew had difficulties identifying the circuit configuration and electric current distribution.

Vincent Interview

Although the students had the opportunity to reformulate their answers, not all did it. Such is the case of Vincent, who assured that his answers were correct. He showed some misconceptions. In this first part of the interview, he had difficulty analyzing the current in a circuit changed from parallel to series.

Interviewer

{I} For this question, a switch is opened, and they ask you, is the current through the battery greater than, smaller than, or the same as the current through the battery before opening the switch? (Fig. 3)

Student

{A} I answered that in the new circuit, there would be a different current to that in the circuit with the switch closed,

{T} because there is one less bulb to illuminate,

{W} so, to me, it seems that the current in the circuit with the open switch that reaches the battery is greater than that of the circuit with the switch closed [Inverse Parallel Circuit misconception]

We label this type of reasoning as the Inverse Parallel Circuit misconception because the argument is the opposite of the Parallel Circuit misconception (which states that a resistor is an obstacle to current flow, assuming that any increase in the number of parallel-connected resistors increases the total resistance). In this case, Vincent believes that by disconnecting a bulb in parallel, the resistance of the circuit will decrease.

Interviewer

{I} Ok, then they ask you about the current in bulb A. Is the current through bulb A greater than, smaller than, or the same as the current through bulb A before opening the switch?

Student

{A} I consider that it is the same in both circuits

{W} because it still does not reach that point where it divides in the way of "lighting B" or "not lighting B." The current from the battery to point A does not have any obstruction in any of the cases, so there is no change, [Sequential Model misconception]

{A} , and in my opinion, bulb A stays with the same current.

The conceptions that Vincent demonstrates entirely agree with what is reported in the literature.

Bruce Interview

Like many of his peers, Bruce uses the concepts of voltage and current interchangeably. One of the moments in which he talks about voltage and current is presented below.

Interviewer

{I} Now, a wire is connected between the terminals of bulb D. With the new wire connected, is the current through bulb D greater than, smaller than, or the same as it was before connecting the wire?

{I} What did you answer?

Student

{W} It is the same since the wires do not have resistance; as far as I read about the concept, I think that is the answer [Short Circuit misconception]

Bruce responds to the question, and although he is allowed to respond again, he supports his position.

Interviewer

{I} Now, we return to the original circuit and open the switch. Is the current through the battery greater than, smaller than, or the same as the current through the battery before opening the switch?

Student

{A} I answered that it is greater because it has less resistance.

Interviewer

{I} They are asking you about the current through the battery, right?

Student

{A} Uhum

Interviewer

{I} So, do you keep your original answer?

Student

{A} Mmmh

Interviewer

{I} What do you mean when you say, "greater since you have less resistance?" Where do you have less resistance?

Student

{W} Mmmh, at that moment, I thought that the current or the voltage does not get to B when opening the switch, so I thought that, by logic, having one less bulb connected in the circuit, the current would be greater [Inverse Parallel Circuit misconception]

We can see that Bruce has difficulties identifying a circuit's different configurations.

Discussion

The open-ended conceptual test and the interviews corroborate documented literature that students have previously reported misconceptions about electric circuits (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013). However, they also have misconceptions not documented yet. As seen in Table 1, where students had to rank the currents of the complete circuit, there were many ways in which students answered this question. The present research aims to contribute to the literature regarding misconceptions students have about circuits.

Series Circuit misconception. One of the essential findings of this research is that we notice that students have reasoning that is not in any of the conceptions reported in the literature review section because the arguments given by the students have a different pattern. For example, in Table 1, when students rank the currents of the bulbs as $I_A=I_B=I_C=I_D$, there are several bolded arguments given by students in which they repeatedly mention that bulbs or branches are connected in series. For instance, in the ranking where all the bulbs have the same current, students say, "All the bulbs are equal, and the two branches are connected in series" or "in all bulbs flow the same current because they are connected in series." In other instances, they mention that the current is the same because the bulbs are connected in series.

In some cases, the reasoning is partially correct because the bulbs are actually in series, i.e., bulbs C and D. In other cases, it is incorrect because they are not in series (bulbs A and B). Therefore, there are instances in which the mistakes related to the configuration of the circuits combine with some misconceptions. In this case, we classify these in the *Series Circuits misconception* we are defining.

We coined the conception "*Series Circuits misconception*" to refer to this previously learned mnemonic that students use to explain electric circuits. We interpret the *Series Circuits misconception* as a very naïve piece of knowledge easily accessible to students. Since obtaining it is effortless, some students may understand how to apply it correctly. Other students accessing it do not have another way to explain it; they use it. This mnemonic-type student conception has been previously reported (Hernandez et al., 2022).

Li and Singh (2016) reported in a study with non-identical bulbs that students erroneously consider that "the brightness of both light bulbs in series should be the same." If we consider that our research proposes ideal situations, we can see that this is a misconception that the students have, independently of the given conditions. In previous studies, we noticed this kind of reasoning (Quezada-Espinoza et al., 2015, 2016). However, we had a much smaller number of students, and although we noticed that they had this same type of argument, there was not enough evidence to say there was a pattern in the answers.

This misconception arose from some other questions but with a different approach. When bulb E was introduced in questions e) and f), a proportion of students (12% and 13%, respectively) used the same reasoning: the current was the same because the bulbs were connected in series. However, in this case, although it is the same misconception, it is different because in question a), the misconception was combined with configuration difficulties (difficulties in distinguishing whether the two components are connected in series) and did not involve a sequence in time. On the other hand, there are no difficulties with configuration in questions e) and f) because the bulbs are actually in series, but there is a sequence in time. Students say that after connecting bulb E to the circuit, the other bulbs are still in series, so the current should be the same before and after the bulb is added. It seems that the idea of this misconception is directly related to a broader *Series Circuit misconception*, one that combines configuration difficulties and the other with changes in the circuit.

In the interview, the *Series Circuit misconception* emerged in the conversation with Jocelyn. Although the interviewer asked questions to prompt her to reflect, she maintained her answers, arguing that the current is always the same in series. The literature documented in previous sections does not mention this model (taxonomy of the conceptual models in the literature review above), maybe because it can be confused with the *Local Reasoning misconception* (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013). However, we consider this not a *Local Reasoning misconception* because students are clear in their arguments. There are other instances in which it has been reported that students have difficulties with the series circuit; however, there is no mention of a specific misconception but the difficulty in interpreting series configurations (Khwanda & Kriek, 2020).

Inverse Parallel Circuit misconception. The *Parallel Circuit misconception* states that a resistor is an obstacle to current flow, assuming any increase in the number of parallel-connected resistors increases the total resistance (Peşman & Eryılmaz, 2010; Sencar & Eryılmaz, 2004; Taşlıdere, 2013). Some students in this study argued that the circuit's equivalent resistance would decrease when a bulb connected in parallel is disconnected. We believe that the *Inverse Parallel Circuit* is another misconception since students' arguments contradict the Parallel Circuit misconception. It can be seen that the origin of this problem is that students have difficulty understanding the system of a circuit, the function of each component, and what the current, resistance, and potential difference are. Engelhardt and Beichner (2004) say that students' recognition of diagram representations is essential to their understanding of circuits. However, students have difficulty identifying series and parallel connections in diagrams (Kalaya et al., 2019; Khwanda & Kriek, 2020).

Problems identifying the different circuit configurations. In this investigation, we realized that engineering students have one problem: they do not know how to identify the characteristics of the various configurations of series, parallel, or mixed electrical circuits, as established by Bryan and Stuessy (2006). Before the interview started, we asked students whether circuits were familiar. All the interviewed students, except John, said it was the first time they remembered seeing topics about electrical circuits. This is a relevant point that influences their conceptual understanding of this topic. We believe that it is one of the origins of their misconceptions, as Frache et al. (2019) also claim. In Table 1, it is evident that students had a precarious understanding of the configurations of the circuits and how the current behaves in an electric circuit. The first question was crucial for filtering the students' understanding of the open-ended conceptual test and helped identify patterns in the students' written reasoning. In agreement with Stetzer et al. (2013), who state that "*instruction that concentrates exclusively on specific configurations of circuit elements or mathematical constructs, such as Kirchhoff's rules, may help students answer similar questions correctly in certain contexts but not in others.*" We believe that well-directed instruction on abstract topics such as current, resistance, and voltage is critical for students to understand these concepts better.

Formulas, computations, and interchangeable use of terms. Only John expressed that he had been previously enrolled in an electric circuit course from interviewed students. The other students said the E&M course was their first time formally studying electric circuits. Although some students used the terms incorrectly or indiscriminately, John was the only student who stopped the interview to corroborate his answers numerically. John needed to write the formulas, substitute, isolate, and calculate the result. It turned out to be very complicated to articulate a response for him. He used the words current, voltage, and resistance randomly, and although he did calculations, his answers were inadequate. As Cohen et al. (1983) mention, in the open-ended conceptual test, many students wanted to apply mathematical algorithms, write down formulas, and analyze the situations presented to them through computations instead of written reasoning. Since we did not have control of the instructors' pedagogical approach, they could understand students' difficulties; however, they might prompt students to use calculations instead of conceptual understanding, as in Moodley and Gaigher (2019).

Conclusions

We investigated the conceptual difficulties of engineering students with simple electrical circuits having identical light bulbs, ideal batteries, and non-resistance wires. 531 students answered an open conceptual test, and five were selected for an interview so the researchers could delve into their reasoning. We designed the open-ended conceptual test from the misconceptions reported in the literature, which we reviewed. The main objective of this work was to report that students have different reasoning beyond the taxonomy of the conceptual models reported in the literature. We have contributed by expanding the number of models.

The analysis led us to find students' reasoning that has not yet been reported in the literature as misconceptions. Although there could be arguments that they might be classified into models already reported, many occurrences force us to isolate these results and show them as significant findings. The easily accessible piece of knowledge *Series Circuit misconception* can appear in different contexts when students analyze the circuit currents without manipulation (e.g., interactive simulations) and when a circuit changes. In both cases, students convey that the current through bulbs is the same because they are in series.

The other misconception reported is what we call the *Inverse Parallel Circuit Misconception*. Students mention that the resistance of the circuit decreases when disconnecting bulbs in parallel.

Additionally, we found that all the misconceptions students may have in analyzing circuits are combined with *problems identifying the different circuit configurations*. Students often confuse whether the elements are in series or parallel, even when those elements are not connected in series or parallel. These difficulties make their interpretation of the circuits harder.

Recommendations

The results of this study have implications for physics education research and educational practice. The Series Circuit and Inverse Parallel Circuit misconceptions are not reported in the literature, and therefore, the taxonomy of misconceptions in electric circuits is expanded. Instructors in the classroom could take these findings to adapt their educational strategies to address these misconceptions and the difficulty for students to understand the circuit configurations. We recommend instructors use active learning strategies that provide students with solid conceptual tools. There are well-established strategies that favor learning created for physics (see Docktor & Mestre, 2014). In those strategies, student-centered learning is promoted, which encourages individual and collaborative reflection, feedback from the teacher to the student, and discussion among peers to promote interactive engagement classes.

Further for research, continuing with the analysis of different students' misconceptions, it seems crucial to us to investigate deeper the origin of these models that help to overcome them. The next step in producing new knowledge is for researchers to consider these findings to study the best way to overcome these difficulties with experimental studies in the classroom. Finally, in future research, it is essential to investigate the physics teaching conceptions of instructors in-depth and generate instances that allow them to prepare better to facilitate learning circuits.

Limitations

This report combines the analysis of open-ended questions of 531 students and the interview of five students from a large private Mexican university in the northern part of Mexico. Since the pre-college educational system in Mexico and the education at this university are similar to what one finds worldwide, we believe the results are reproducible. The limitations are always inherent in the qualitative methodology; however, students' reasoning is consistently analyzed.

Acknowledgments

We acknowledge the technical and financial support of Writing Lab, Institute for the Future of Education, Tecnologico de Monterrey, Mexico, in the production of this work.

Authorship Contribution Statement

Quezada-Espinoza: Conceptualization, design, data collection, analysis, writing the original draft. Dominguez: Writing—review and editing, supervision. Zavala: Writing—review and editing, supervision, final approval.

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