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A Systematic Literature Review of Misconceptions in Linear Circuit Analysis

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Abstract

Misconceptions in circuit analysis have been investigated by many researchers. However, we could not find a literature review from the last 20 years. We conducted a systematic literature review on circuit analysis misconceptions from the last 20 years, finding 15 articles meeting the search criteria, relevance, and accessibility. In total, the articles identified 20 misconceptions (e.g., term confusion in physics, algebraic manipulations, and failure to consider local changes in context of entire circuit), which we grouped into 8 misconception categories (e.g., Physics, Math, Sequential reasoning, and Application of Ohm's Law). Interestingly, none of the articles addressed the misconceptions, which may be low-hanging fruit. We also created a conceptual dependency graph to help point out foundational misconceptions within the misconception categories, yielding Physics, Math, and Application of Ohm's Law as the most foundational misconceptions. Physics had 5 misconceptions (the most) and in total cited by 7 articles. Within Physics, the most cited was term confusion, cited by 4 articles. Math had 2 misconceptions, cited by 3 articles. Application of Ohm's Law had 2 misconceptions, cited by 7 articles. Interestingly, none of the articles attempted to address misconceptions. Thus, there appears to be a need for research that addresses misconceptions. We might suggest focusing on prevalently reported misconceptions, such as physics term confusion and appropriate application of Ohm's Law.

Introduction

Misconceptions in circuit analysis have been investigated by many researchers, and researchers have identified numerous issues: Conceptual [1][2][3][4], term confusion [5][6], fundamental mathematical skills [7][8], incomplete metaphor [9][10], and diagnostics to identify such misconceptions [5][11]. Further, researchers have investigated many aspects: Community college through research university levels, laboratory and lecture settings, and across different learning materials.

However, there does not appear to have been a systematic literature review of this work in over 20 years. Thus, we undertook a literature search to provide a more updated systematic review of misconception research.

Misconceptions are important to identify and address because such misconceptions may follow the student into subsequent courses. Thus, focusing on linear circuit analysis is important because linear circuit analysis is a foundational course in electrical engineering. The concepts learned in linear circuit analysis, such as Ohm’s Law, source transformations, and basic calculations for solving for voltage, resistance, and current in circuit components, are built upon in later courses, such as digital system design and semiconductor devices. Thus, misconceptions found in linear circuit analysis may persist. Such misconceptions can arise from various sources, such as textbooks [10][12], previous courses, classroom lectures, or laboratory experiences [13].

In this paper, we systematically reviewed the literature on circuit analysis misconceptions. We analyzed the literature by analyzing the research methodologies, categorizing the misconceptions, enumerating the types of research, and building a conceptual dependency graph.

Methods

The goal of our literature search was to identify research conducted in the past 20 years that was relevant to misconceptions in circuit analysis engineering courses, typically taken by students in their first year. To that end, the search was conducted in Google Scholar [14] using the search: *misconceptions "circuit analysis" "electrical engineering" "first-year" -electrochemistry*

The notation means: Each search term is either a single word or combined words (inside double-quotes). Combined words must be found together and as written. The search terms are combined using an AND Boolean operation. A NOT operation was applied to "electrochemistry".

To identify the topic of linear circuit analysis, the broader term “circuit analysis” was included, as specifying “linear circuit analysis” narrowed the results to 6 papers and eliminated relevant articles. The term “electrical engineering” was included to pinpoint research done within engineering courses. Because circuit analysis is done across multiple courses, the term “first-year” was included to identify papers relevant to the topics taught in the beginning foundational circuit analysis courses. "First-year" in many papers refers to the first year of learning the major-specific topics. Many articles were specific to electrochemistry, so -*electrochemistry* was included to eliminate electrochemistry articles.

We included peer-reviewed articles and dissertations between the years 1997 to 2018. Our main inclusion criteria required articles to specifically discuss misconceptions relevant to topics taught in basic circuit analysis engineering courses (e.g. articles discussing more advanced engineering courses, such as electromagnetism, were discounted).

For each article, the following data was extracted: The location of where the research was conducted, the number of participants in the study, the type of study conducted, and every misconception identified. We noticed often several papers would refer to the same misconception but using different terminology, so we selected the most succinct term that well-described the misconception.

Literature review results

A total of 93 articles were found from this search. 72 were found to be irrelevant to our topic. 6 articles were unable to be accessed. Thus, 15 articles met the inclusion criteria. This section briefly describes each article.

Several researchers relied on validated assessments to develop their diagnostic test. Some tests included questions from combination of validated assessments. Hussain picked 12 questions specific to Thevenin and Norton equivalents [15] from assessments developed by Engelhardt (DIRECT) [5] and Sabah [16]. Other tests used a subset of questions from only one validated assessment. For example, Underwood [17] used a selection of questions from the Circuits Concept Inventory (CCI) [11] for a diagnostic test.

Some researchers developed their own in-house assessments [18][19][20]. Smaill developed an in-house assessment based on previous work [5][21][22], which included 20 multiple choice and 2 free response questions. Students had 30 minutes to complete the questions [18][19][20]. Smaill administered the assessment to three groups of students: 560 students in 2007 [19], 543 students in 2008 [18], and over 1600 students from 2007 to 2009 [20]. Participants consisted of students from New Zealand and the United States.

Other researchers developed in-house assessments based on their classroom and laboratory experiences, sampling questions from class quizzes and exams [9][23]. After informally studying student responses in lectures and and recitation lessons, Kautz developed diagnostic questions optional for students to complete during class lectures, or at the end of their final exam.

Another popular method for observing misconceptions in circuit analysis courses was through student interviews, typically done after the diagnostic test. Biswas identified specific misconceptions students had about AC circuits through a series of interviews with a total of 18 students, who gave walk-through explanations of their circuit analysis steps [9].

Finally, one paper analyzed learning materials to identify potential misconceptions in explanations of concepts. Sangam and Jesiek analyzed circuit analysis concepts and links between the concepts to pinpoint misconceptions common across 5 textbooks [10].

A suggest for future research is to combine a validated assessment, such as DIRECT [5], with an interview to help dive deeper into the misconception. A validated assessment has already been verified to have questions that accurately predict conceptual understanding across a large population. An interview enable a researcher to better explore why the misconception exists.

Interestingly, none of the articles attempted to address the misconceptions, so there exists a need for addressing misconceptions experimentally.

Analysis of Misconception Categories

Many of the misconception topics found shared commonalities in the overall concept being taught, or the type of circuit being analyzed. Thus, we grouped the misconceptions into the following 8 misconception categories:

- Physics: 5 misconceptions pertaining to the fundamentals of physics. Ex: Charge as a property of matter.
- Math: 2 misconceptions pertaining to the use of math in circuit analysis. Ex: Algebraic manipulations.
- Sequential reasoning: 1 misconception pertaining to the failure to consider effects on the circuit as a whole during analysis. Ex: General failure to consider local changes in context of entire circuit.
- Application of Ohm's Law: 2 misconceptions pertaining to the understanding and application of Ohm's Law. Ex: Inappropriate application or blind reliance of Ohm's Law.
- Elements in series and parallel: 2 misconceptions pertaining to identifying and analyzing circuit elements in series and parallel. Ex: Misidentifying if components are in series or in parallel.
- Open and short circuits: 4 misconceptions pertaining to analyzing effects in a circuit when circuits are open or shorted. Ex: Recognizing voltage effects in open and closed circuits.
- Kirchoff's circuit laws: 2 misconceptions pertaining to the application of Kirchoff's Current Law and Kirchoff's Voltage Law. Ex: Belief the direction of mesh currents matter in mesh analysis.
- AC circuits: 2 misconceptions pertaining to analyzing AC circuits. Ex: Identifying what is alternating in an AC circuit.

Table 1 includes each specific misconception organized by misconception categories. Each specific misconception is briefly described. For example, in physics, a misconception is related to charge as a property of matter. Specifically, some students thought that electrons carry positive charge [7] or that a voltage source provides charge [10].

The number of articles per misconception category were:

- Physics: 7 articles
- Application of Ohm's Law: 7 articles
- Sequential reasoning: 6 articles
- Open/short circuits: 5 articles
- Elements in series and parallel: 4 articles
- Math: 3 articles

- Kirchoff's circuit law: 3 articles
- AC circuits: 2 articles

Note: The number of articles may be influenced by which concepts researchers tested. For example, papers focusing on math may not have included tests for AC circuits, so in that case, AC circuits would not be found to have misconceptions because AC circuits were not tested.

To help decide which concept to focus on, we built a dependency graph, as shown in Figure 1. Foundational concepts are toward the top. A solid line means the concept pointed to depends on the concept that points. A dashed line means the concept pointed to is often in conjunction with the concept that points, though these concepts do not have an explicit dependency. Applications of Ohm's Law depend on math because algebraic manipulations are necessary to solve for voltage, resistance, and current. Applications of Ohm's Law also depend on physics because students need to solve for the right physical property. Elements in series and parallel depends on math because appropriate arithmetic rules must be followed to solve. Open and short circuits depend on applications of Ohm's Law because Ohm's Law is used to solve unknowns in such circuits. Kirchoff's circuit laws depend on both applications of Ohm's Law because Ohm's Law is used to solve circuit unknowns, and Kirchoff's circuit laws depend on physics because a common misconception is that current or voltage is used up. Sequential reasoning depends on applications of Ohm's Law because Ohm's Law is used to solve for unknowns. Some misconceptions in sequential reasoning are caused by misconceptions in open and short circuits, or in Kirchoff's circuit laws. Misconceptions for AC circuits did not directly relate to other misconceptions.

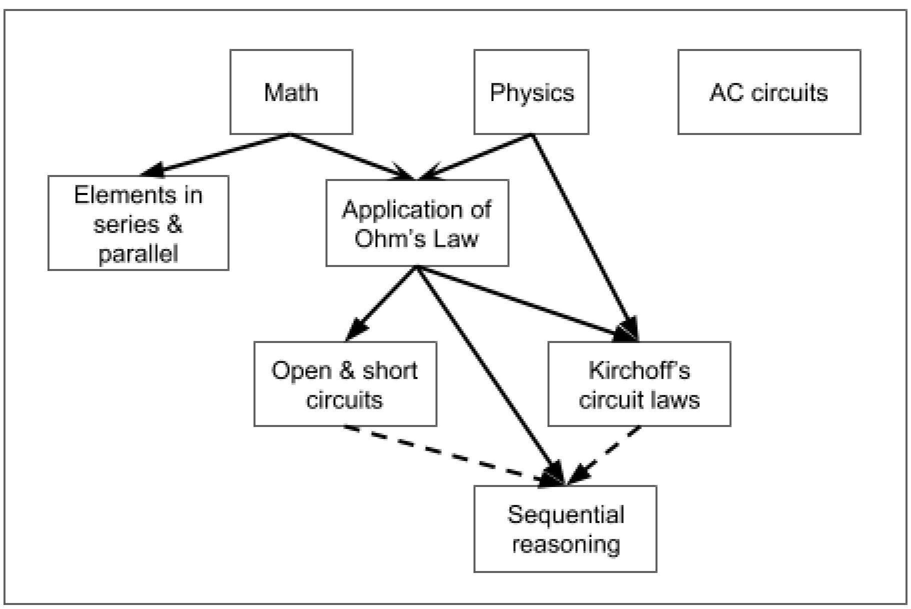

Figure 1: A dependency graph of misconception categories where solid lines represent conceptual dependencies and dashed lines indicate that the parent concept is often included in the concept pointed to, e.g., Sequential reasoning often includes Open and short circuits.

Table 1: List of misconception categories with specific misconceptions (in italics), ordered by top-down of dependency graph. Physics had the most misconceptions and citations.

Misconception categories	**Misconceptions**
Physics	* *Charge as a property of matter*: Electrons carry positive charge [7]; voltage source provides charge [10] * *Conservation of charge*: Charge is used up in a circuit [10]; current is used up in a circuit [23][24][26]; voltage is used up in a circuit [23] * *Electric fields and voltage*: Voltage source supplies current [10][24][26][27]; battery supplies the voltage source which causes current [27] * *Term confusion*: Current related to potential energy [7][27]; voltage and current switch on and off, or positive and negative [9]; current and voltage are confused [26]; current/resistance are confused [26]; voltage is (or like) current that flows or moves [27]; voltage is measure of strength/ size/force of current [27]; voltage is pressure [27] * *Incomplete metaphor*: Current is like water that flows through a pipe [9][10][27]; that metaphor yielded a particular misconception: current pools behind resistors [27]
Math	* *Algebra manipulations*: Incorrect solving of algebra equation [19][20] * *Calculus manipulations*: Believe sinusoidal means sine, calculating wrong cosine angles [7]
Sequential reasoning	* *General failure to consider local changes in context of entire circuit* [10][18][19][20][24][26]
Application of Ohm's Law	* *Inappropriate application or blind reliance of Ohm's Law* [13][15][19][20][23][26] * *Incorrect formula*: I=VR [7]
Elements in series and parallel	* *Misidentifying whether components are in series or parallel* [10][17][20][24] * *Incorrectly calculating series/parallel* [17][20][24]
Open and short circuits	* *Recognizing the effects of resistance* [15][26][28], *voltage* [24], *and current* [19] *across open and closed circuits* * *Confusing open/closed as on/off* [24]
Kirchoff's circuit laws	* *Direction of mesh currents matter in mesh analysis* [7] * *Misapplication of Kirchoff's circuit laws* [23][29]
AC circuits	* *Identifying what is alternating* [9][17] * *Interpreting characteristic phase behavior* [9]

Analysis of Methodologies

Methodologies for finding misconceptions varied amongst the literature. Of the 15 articles included in the review, 9 [7][17][18][19][20][23][24][26][28] analyzed misconceptions only using diagnostic tests, where a multiple choice, short-answer, or a combination test was administered to students and the answers were analyzed. A combination of a diagnostic exam with an interview was used by 4 articles [9][13][15][29], where students took a diagnostic exam, and then a few were selected to discuss their answers in depth. Bledsoe [27] only used interviews, asking students to solve circuits problems while explaining their reasoning. Finally, Sangam and Jesiek [10] analyzed textbooks to discover misconceptions perpetuated across learning materials.

Of the research papers that used diagnostic tests, questions from 9 tests [9][7][13][18][19][20][23][28][29] were developed in-house by researchers, either based on other research and/or using their own course experiences. Diagnostic questions in the remaining 5 papers were based on validated tests. The Engelhardt test [5] was used in 4 papers [15][17][24][26]. The Circuit Concepts Inventory (CCI) was used in 1 paper [17]. Tests developed by Sabah [16] and Pesman [30] were used in conjunction with the DIRECT diagnostic in 2 papers [15][26].

Discussion

Much research has been done to identify misconceptions in linear circuit analysis. Some research has been conducted to better understand the nature of the misconception, e.g., whether the misconception is due to a conceptual misunderstanding or a mathematical error. More such research may be needed. However, there seems to be a need for research on addressing misconceptions, as in our literature search, we did not come across any such articles.

Most misconception categories depend on the math and physics categories, as shown in the dependency graph (Figure 1). So, addressing misconceptions in math and physics will have the highest-yield toward mitigating misconceptions in other categories. The physics misconception category contains the most misconceptions found by researchers, as well as, the most number of articles (tied with application of Ohm's Law) citing physics misconceptions. So, specifically focusing on physics misconceptions may yield the best results.

Within physics, the term confusion misconception had the most number of instances, such as confusing current and voltage. Also, term confusion seems to be important because the terms are even depended upon by other misconceptions within physics. For example, understanding the nature of current would dispel the incomplete metaphor misconception, i.e., students will no longer believe that current pools behind resistors. So, we might strongly recommend focusing on term confusion within physics.

The application of Ohm's Law misconception category was referenced by 7 articles, predominantly citing an inappropriate application or blind reliance on Ohm's Law. Some researchers suggested that this misconception may be linked to a deficiency in qualitative understanding.

Future work

Future work includes expanding the number of areas searched for articles, such as periodicals, other databases, magazines, and books, as well as, other search methods.

Future work will focus on addressing term confusions in physics, as research indicates that is the most cited and conceptually most depended on misconception. Other high-yield misconceptions to address would be the other misconceptions in physics, math misconceptions, and misconceptions related to the application of Ohm's law.

For math and physics, one idea is to address such misconceptions early in the course by identifying the student's misconceptions with a validated diagnostic test, such as the Englehardt DIRECT test [5], separating out questions that help identify issues specific to understanding current, voltage, and resistance. Then, use results of the test to prioritize an accelerated lesson plan to address the misconceptions. Such a lesson plan might involve lecturing briefly on the misconceptions, then provide additional practice problems to see if the misconception persists.

For the application of Ohm's Law, one suggestion is to ask more qualitative questions, such as how increasing the resistance of 1 light bulb in a series impacts the other light bulbs in the series.

Going forward, the community may converge on a well-validated diagnostic test, such as the Englehardt DIRECT test [5], so that meta-analyses becomes feasible, enabling statistically more comprehensive analyses. Additionally, an interview may supplement the diagnostic test to better explore why the misconceptions exist.

Conclusion

We found 15 relevant articles on circuit analysis misconception from the last 20 years. In total, the articles identified 20 misconceptions; though, none addressed the misconceptions. We grouped the misconceptions into 8 misconception categories. We created a conceptual dependency graph and identified Physics, Math, and Application of Ohm's Law as foundational categories. Physics was the most prominent misconception category, having 5 misconceptions cited across 7 articles. Within the physics misconception category, term confusion was the misconception most frequently cited (4 articles). Math was the second most prominent misconception category, with 2 misconceptions cited by 3 articles. Finally, Application of Ohm’s Law had 2 misconceptions, cited by 7 articles.

From our search, we conclude there is a need for research that experimentally addresses misconceptions. We suggest focusing on physics term confusions and the application of Ohm’s Law, as addressing these misconceptions will likely help address misconceptions that rely on these basic concepts.

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