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Teaching and Learning Complex Circuit Concepts: An Investigation of the Intersection of Prior Knowledge, Learning Activities, and Design of Learning Environments

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Abstract

Eliciting students' conceptual understanding of electric circuits has been discussed as challenging to achieve owing to difficulties faced by students when learning circuit concepts. This difficulty has been attributed to the posit that students tend to hold very little formal pre-conceptions of electricity. This then becomes problematic as the level of complexity increases from the most basic to more advanced circuit concepts. This lack of formal prior knowledge has the potential to prevent students from being able to assimilate new material they come in contact with when instructed about electric circuit concepts. Other impeding factors reported have been the influence of students' prior misconceptions, the abstract nature of the content, inadequate instructional strategies to provoke conceptual conflict and inadequate preparation of students from pre-requisite courses. However, a gap that still exists is the direct interaction between: (1) students' prior knowledge, (2) the types of learning activities and (3) the design of the learning environment fueled by the decisions made by professors on how to teach circuit concepts.

This study focused on exploring undergraduate electrical engineering students' conceptual understanding of electric circuits based on the previously noted interaction. This study was conducted using three distinctive approaches: firstly, to investigate the influence of prior knowledge about other circuit phenomena when learning about more complex scientific concepts, secondly to examine the role of learning environments and student activities on students' understanding of these concepts and thirdly to study the design and dissemination of knowledge about electric circuits in an introductory course. The overarching findings of this study deal primarily with the design of introductory courses having alignment between content, assessment and pedagogy. This alignment has direct impact on the decisions made about the teaching and application of content, design of the learning environment and how the content is communicated to the students. Findings have indicated the misalignment that exist between the three core areas of learning in course design. These results have theoretical and practical significance to the field of engineering as well as contribute to the body of literature on complex circuits such as alternating current (AC) circuits and students' conceptual understanding. The core findings of the three studies independently and collectively have the ability to significantly impact the way future engineers are taught introductory concepts in their respective disciplines.

Introduction

Research focused on increasing students' conceptual understanding of electric circuits has discussed this concept as difficult to not only teach but for students to grasp [1], [2]. In introductory circuit courses students are exposed to basic circuit concepts such as direct current (DC) circuits and the more complex concepts such as alternating current (AC) circuits. However, for each type of circuit the requirement for identifying circuit operating conditions, the interaction of voltage, current and resistance among circuit components and the type of circuit design whether series, parallel or series-parallel, remains the same. Yet, alternating current (AC) circuits specifically have been described as more difficult than general direct current (DC) circuits [3]. This difficulty has been attributed to the fact that students tend to hold very little formal prior conception about the abstract nature of electricity with which to assimilate the new material taught in their courses [4]–[6].

Additionally, as the level of complexity increases from simple to complex, students seem to lack the necessary conceptual frames of reference. For example, understanding what is happening in the circuit at a given time, relationships between variables and how components operate individually and holistically. Often times, students' inability to associate this new concept with some pre-existing conception or prior knowledge leads to the development of misconceptions about the nature of electricity [7], [8]. These misconceptions are further compounded by the level of difficulty associated with the dynamic and time-varying nature of alternating current (AC) sources when compared to its static and steady direct current (DC) alternative. This adds another level of complexity especially since students are usually taught DC and AC circuits combined without there being any direct dissociation made between the two in terms of how fundamentally different they are [9], [10]. Despite previous work on the nature of electric circuits and students' understanding in introductory circuit courses [11], [12] there is the need for studies intent on taking a deeper look at the interaction students' prior knowledge, design of learning environment and the strategies used to convey information about complex circuits. The very important gap of exploring the intersection of prior knowledge/experiences, design of learning environment and how the content is taught to mitigate the level of difficulty theorized to be associated with electricity needs to be studied. The goal of this study is to investigate the reasons for the perceived underlying difficulties related to learning and understanding complex circuit concepts such as phasors and sinusoidal steady-state analysis.

Recommendations have been made for the inclusion of innovative teaching strategies aimed at engaging students actively in the process of learning about AC circuits [5], [8], [13], [14]. Similarly, calls for the use of more engaging learning strategies in engineering learning environments suggest that when students are actively involved in the process of learning they are better able to learn and retain the new material [15]. While some studies [16], [17] have been aimed at exploring how innovative teaching strategies are beneficial in increasing students' understanding and learning of complex scientific concepts, the lack of literature in engineering that speaks specifically to complex concepts such as circuits having AC sources makes this study a fruitful venture in engineering [9], [18]. In addition, the complex and abstract concepts associated with AC circuits has been a limiting factor to the number of studies conducted on issues associated with this area of study [19]. The topic of AC circuits has not been studied in depth mainly due to the fact that the concept of AC circuits is one that is quite difficult to understand hence very few researchers have attempted to look more deeply into this issue [8]. It has also been discussed that studies that do focus on AC circuits lean towards studying introductory physics classes at the college or high school level. The simple nature in which AC circuits are discussed at these levels barely address the more high-order classroom material that undergraduate students are usually taught [1], [3].

As part of a larger study, three separate small studies were conducted aimed at answering the broad overarching question of: What are the underlying reasons for students' perceived difficulty in learning complex circuit concepts? The focus of this paper is to share the collective findings of the three studies and their implications for the design of electrical engineering introductory courses.

The central theme guiding these studies was the alignment of prior knowledge, design of learning environments and how concepts are taught. The combined purpose of all three studies was to give a descriptive illustration of the difficulties associated with learning complex circuits in general. The rationale for choosing these three specific studies and method of conducting them stemmed from recommendations made by various researchers. Most prominent among these was having an approach to teaching and learning complex scientific concepts that explores the relationship between the role of learning environments, student' experiences, prior knowledge and how difficult concepts are taught in a classroom [2], [3], [6], [8], [14], [18], [20]. Collectively the findings highlight the cyclical relationship that exists between the knowledge and experiences students bring to the learning environment, decisions made by professors about how concepts are taught and what concepts are emphasized as important.

Methods

Each study was conducted having its own research question, method of inquiry and data set. This approach was chosen specifically so as to create the opportunity to investigate the issue being studied using student individual schema (study one), pedagogy (study two) and cognition (study three) as guiding principles. Table 1 summarizes the methodological approach used for each study.

Table 1. Summary of methods for all three studies.

Methods sections	**Study One - student individual schema**	**Study Two – pedagogy associated with learning circuits**	**Study Three – design of learning environments**
Research questions	How does students' prior knowledge hinder/enhance learning about complex circuit concepts? How do students use analogies and metaphors to explain circuit concepts?	How are engineering learning environments designed to promote students' understanding of electric circuits? What are students' perceptions of the types of activities used in enhancing their understanding of circuit concepts?	How are complex circuit concepts taught to students enrolled in a compulsory introductory circuit course? What decisions are made by professors about how to communicate knowledge about complex circuit concepts to students?
Research approach	Delphi method	Systematic Review	Descriptive single case, multiple embedded units study
Participants	Sophomore, junior and senior EE majors	Published work on electrical engineering circuits courses	Professors of an introductory circuit course
Data collection methods	Think aloud interviews	Engineering database search	Classroom observations, course documents and professor interviews
Data analysis	Deductive content analysis	Thematic analysis	Two rounds of inductive coding

Results

In figure 1, a map of the key findings of each study is illustrated. From the figure it can be seen how the studies, study one (purple concepts), study two (blue concepts) and study three (pink concepts), are connected to each other and influence the design of the other. Additionally, the figure illustrates how individual findings from each study answer the overarching research question (represented by the green concepts). The map also highlights other findings that are specific to each study that did not completely align with the overarching research question. The six common findings across the three studies are summarized in table 2.

Table 2. Common findings across all three studies

Common findings	**Study One**	**Study Two**	**Study Three**
Use of analogical or comparative reasoning	x		x
Dependence on mathematical representation	x	x	x
Importance of students' prior knowledge	x		x
Abstract nature of the content is problematic	x	x	x
Lack of real-life application of content	x	x	x
Lack of multiple representation of content	x	x	x

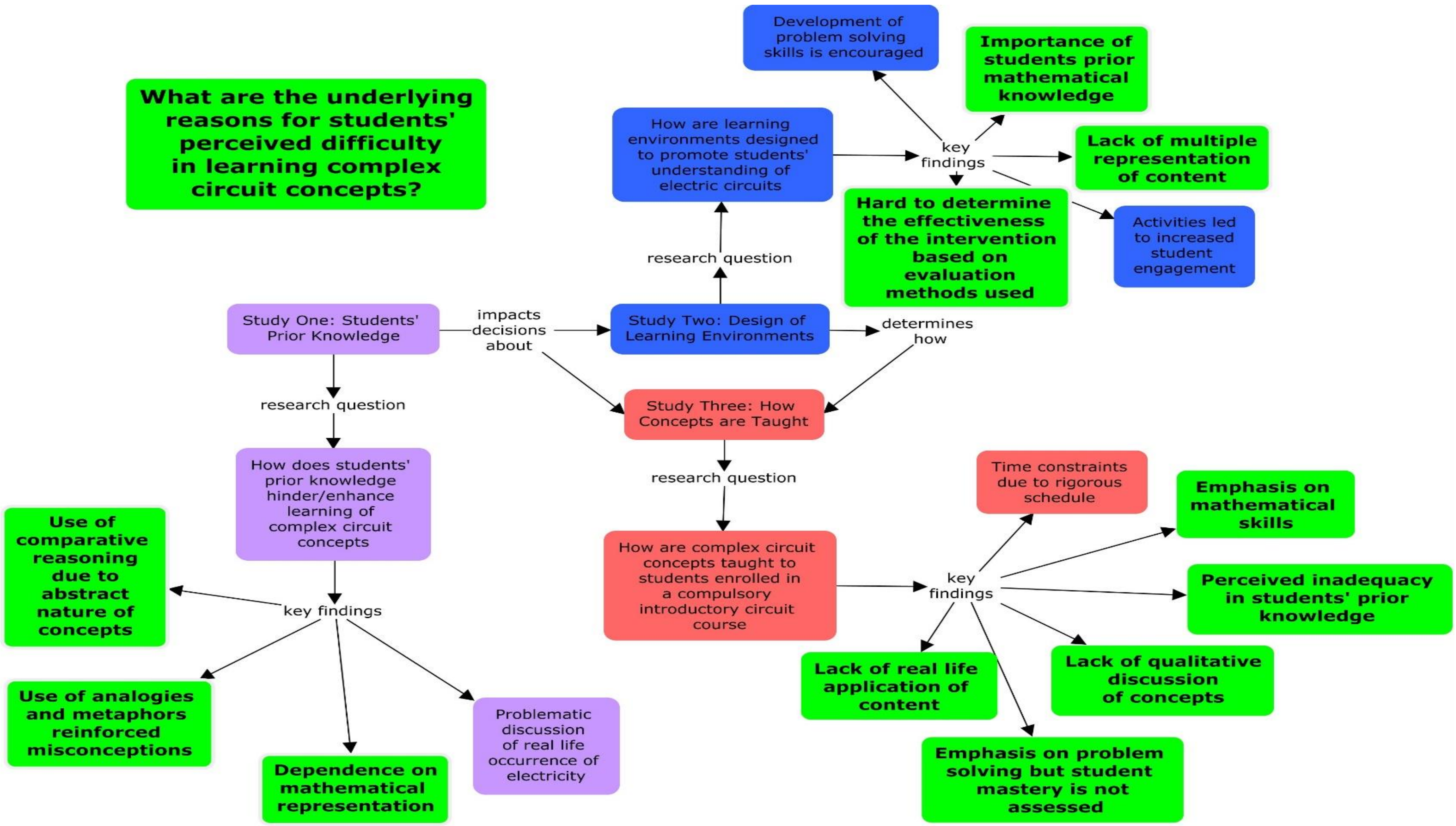
Discussion

The relationship between the three studies, illustrated by figure 1, indicates there were six core findings summarized in table 2. The table also shows how the collective findings were distributed across the studies. The use of analogical or comparative reasoning and importance of students' prior knowledge were the only two findings not common across all three studies.

Use of analogical or comparative reasoning

The focus of study one, indicated by the research question in table 1, was to examine how students use analogies and metaphors spontaneously in their explanation of circuit conditions. In that particular study, it was found that students use a combination of analogies and metaphors when asked to describe the movement of current in a given circuit. The most common example of analogies used was the water flow model. The participants discussed analogies as strategies they were taught to use or had developed for themselves to understand the concept of circuits. This was necessary to be able to relate the otherwise abstract concepts to something that was tangible. Similarly, the professors who participated in study three expressed the sentiment that while analogies can lead to possible misconception it was a necessary evil. This was due to the fact that the nature of the content warrants the use of concepts students have some level of familiarity. However, with this water flow example we found participants discussing current still flowing when the switch was opened (likened to water still flowing when the pipe burst). The implication for the use of analogies by various researchers in that when used, students must also be exposed to the point at which the analogy and the concept being taught are no longer completely aligned.

Figure 1. Concept map showing relationships among studies and alignment of key findings to overarching research questions



Dependence on mathematical representation

In all three studies, the importance of mathematical knowledge and application ability was reinforced. The nature of the content dictated the use of mathematical modeling for understanding. Most commonly was the emphasis on being able to use acquired mathematical skills from previous classes to derive or manipulate applicable formula to arrive at solutions. There was an observed lack of qualitative discussions about the concepts and how relationships among variables were derived. The focus of introductory courses is typically to expose students to the core basics concepts one of which is problem solving through varied strategies. However, research on the teaching and learning of complex scientific concepts such as circuits recommends equal use of qualitative, quantitative and graphical illustrations [2, 3]. Licht's model of teaching electricity suggests students should first be exposed to a purely qualitative approach to the concepts before mathematical representations are introduce [3]. The main benefit of this model is that students come to first understand the operation of the circuit and individual components as well as the underlying relationship among variables before being bombarded by complex mathematical equations.

Importance of students' prior knowledge

According to Ambrose et al. [21, p. 13] "students' prior knowledge can help or hinder learning". This statement resonated through the findings of all studies. Repeatedly, the level of difficulty associated with the teaching of complex circuit concepts was attributed to a lack of or perceived inadequacy of students' prior knowledge. In addition, the presence of misconceptions in students' prior knowledge long after they had learned the introductory material and had progressed in their courses of study was found in the first study. This finding is not surprising since conceptual change researchers study how robust misconceptions associated with prior knowledge and experience will tend to propagate despite exposure to additional and more intense content [22]–[24]. These studies indicated that where difficult and complex concepts such as electric circuits are concerned, the role of prior knowledge in learning new material is very influential. Consequently, it is necessary to assess the status of students' prior knowledge in terms of exactitude and competency in being able to add value or enhance students learning.

Abstract nature of content problematic

Collectively, challenges associated with the learning of circuit concepts were credited to the nature of the content itself especially the interchangeable relationship between current, voltage and resistance. Though each variable serves a very distinct and definite purpose in the circuit, their interaction through the circuit components have significant implications for how the circuit operates and the function it is meant to serve. Findings from our study indicate the interaction of these variables proved most difficult for students to understand. Students' inability to distinguish the three variables independently and collectively as well as their respective function in a circuit has been of significant interest to researchers [25-29]. We also found the interchangeable use of voltage and current and their respective attributes to be another aspect of the content that proved problematic.

Lack of real life-application of content

Instruction focused on AC circuits and other complex circuit concepts should make use of tangible and real life application where possible. Providing students with the ability to engage with the concept in a concrete manner is reported to have lasting impact on their ability to recall and transfer their knowledge from one domain to another [1-2]. The findings from this study have indicated the need for the inclusion of real life application in introductory engineering classrooms. While the argument can be made that students get exposed to design problems when they are assigned their capstone project or are working on internships, the nature of electricity or any other complex concept dictates a measure of applicability. This is based on the fact that abstract concepts are better learned when there is another concept to which it can be compared. In this study it was found that complex concepts and the manner in which they were taught was mostly conceptual with very little to no real life application. The manner in which students are exposed to the concept of electricity in the classroom does not match the actual working environment they will be operating in. Consequently, engineering learning environments should do a better job of preparing students for the workforce and as such there is a need to include more application type activities. In this instance, essential attributes or skills associated with the content of introductory courses could be assessed by students' ability to demonstrate, through given tasks, their mastery of the content.

Lack of multiple representation of content

Use of multiple representational models are proposed to help students have better frames of reference when learning about complex scientific concepts [30]. In addition, students' mental models to problem solving may lead them to assume the knowledge of equation is by itself sufficient to explain and understand circuit phenomena. Consequently, when emphasis is more on the use of formula than the actual underlying structure of the concept this can have a significant impact on students' learning. Collectively, it was found that there was a lack of discussion on the use of multiple modes of representation to convey knowledge of the concept being taught. Across the three studies there was usually a reliance on a particular set of procedures for solving a given problem. Students were expected to learn and follow these steps in order to complete the required tasks. In all the studies there was little or no indication or instruction on the benefits of using multiple formats such as a combination of qualitative discussions, mathematical solutions and/or graphical representations. The most prominent method of conveying knowledge while lecturing, problem solving or answering students' questions was quantitative reasoning through mathematical equations. The disparity between emphasis on mathematical knowledge and skills and the lack of qualitative discussions in the classroom warrants the inclusion of more explanation on not just how to apply formulas but why they are applied.

Implications

The implications of this work are specifically for course instructors and course coordinators. The core findings of the three studies independently and collectively have the ability to significantly impact the way future engineers are taught introductory concepts in their respective disciplines.

The overarching theme that subsumes the findings of these studies deals primarily with the design of introductory courses having alignment between content, assessment and pedagogy which will then influence decisions made about the teaching and application of content, design of the learning environment and how the content is communicated to the students.

Alignment of content, assessment and pedagogy

A course design which incorporates the alignment of content, assessment and pedagogy is reported to have significant benefits to the learning process [31]. Collectively the findings indicate the misalignment between the three core areas of learning in course design. An approach to teaching and learning that takes into consideration the important questions of: What is the desired knowledge students are expected to have at the end of the learning process? What is acceptable evidence of them having garnered this knowledge? How are instruction and learning experiences planned so as to achieve this desired knowledge? [32]. The key to course design is the determination of the enduring outcome for the course. In other words, what is the set of key outcomes one would like for their students to have possessed at the end of the learning experience or even years after they have exited the learning process? For example, in the introductory circuit course used for study three it was evident that students were expected to have developed a certain level of engineering problem solving skills that could be translated to other complex learning experiences. The emphasis on working problems in the class or the use of learning activities meant to provide more class time for working problems were also reflected in studies two and three. However, in most cases students were assessed using multiple choice items. To this end, a deliberate approach to ensuring that the students engage in activities or are assessed using approaches that are directly related to the envisioned outcome is very important. Without alignment of content, assessment and pedagogy complete mastery of the essential attributes of the course cannot be truly determined.

If the intent of the course is the development of problem solving skills aimed at eliciting deep conceptual knowledge that goes beyond simple application of mathematical formula, then there is a need for creating opportunities where students are assessed on their ability to demonstrate these skills. Since the nature of introductory courses is to provide students with the necessary pre-requisite skills and knowledge on which to build their educational model, it is important that content, assessment and pedagogy are properly aligned. The need for alignment between what core concepts are necessary for understanding and future learning, how students' understanding is assessed and how these core concepts are taught is therefore germane.

Conclusion

The first key finding was the impact of students' prior knowledge when they were required to discuss concepts learned in introductory courses after they had completed the course and advance in their academic journey. Misconceptions that developed as a result of the use of analogies and metaphors when the concepts were first introduced, were found to be prevalent when students asked to verbalize their thoughts about basic concepts. It was also found that students were more confident in their responses when the sample problems were the typical textbook circuit problems. This demonstrated students became more uncertain of their knowledge when they had to explain the operation of current and voltage in a real-life concept. This level of difficulty is not surprising as it was found in that students are not exposed during classes to open-ended problems they are likely to encounter in the workplace.

Other findings demonstrate students are expected to develop a certain set of problem solving skills and that these skills are reinforced in the learning environment. However, students' mastery of these skills are not properly assessed. The use of multiple choice items does not provide the opportunity to give detailed illustrations of the process whereby students arrive to the solution. This means professors have no real way of determining how students arrived at a solution nor are they able to identify where students are having difficulties. In addition, there were little to no instances of discussing what to do when the possibility of using the structured problem solving approach led to an incorrect response. The lack of qualitative discussion or other means whereby students are able to communicate what they understand about how concepts are related or how the relationships between concepts are developed was another interesting finding. The nature of the concepts being taught lends itself to heavy reliance on mathematical concepts, symbols and equations. However, students were seldom exposed to why these mathematical formulas or equations were necessary or how they relate to each other. This may lead students to think that the operation of electricity and the interaction between variables are purely quantitative. Not having a qualitative understanding of how concepts relate and why a simple manipulation of a component value can have significant impact on the operation of a circuit contributes to the level of difficulty students face. This difficulty may continue past course completion to challenges in expressing their knowledge in other settings such as more advanced courses.

Our study therefore concludes engineering courses mode of delivery can be transformed to help students better understand and learn these concepts. This can be achieved by using a more structured approach to ensuring alignment between content, assessment and pedagogy. For future study, this work can be extended by looking at the learning environments of other disciplines and how complex concepts within these areas are taught. This would not only create a scholarship of integration but would provide educators with a broad view of how learning can be improved where necessary to increase or elicit conceptual understanding gains.

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